EXHIBIT A

World Health Organization

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Coronavirus disease (COVID-19): How is it transmitted?

23 December 2021 | Q&A

The English version was updated on 23 December 2021.

How does COVID-19 spread between people?

We know that the disease is caused by the SARS-CoV-2 virus, which spreads between people in several different ways.

- **Current evidence suggests that the virus spreads mainly between people who are in close contact with each other, for example at a conversational distance. The virus can spread from an infected person's mouth or nose in small liquid particles when they cough, sneeze, speak, sing or breathe. Another person can then contract the virus when infectious particles that pass through the air are inhaled at short range (this is often called short-range aerosol or short-range airborne transmission) or if infectious particles come into direct contact with the eyes, nose, or mouth (droplet transmission).**
- **The virus can also spread in poorly ventilated and/or crowded indoor settings, where people tend to spend longer periods of time. This is because aerosols can remain suspended in the air or travel farther than conversational distance (this is often called long-range aerosol or long-range airborne transmission).**
- **People may also become infected when touching their eyes, nose or mouth after touching surfaces or objects that have been contaminated by the virus.**

Further research is ongoing to better understand the spread of the virus and which settings are most risky and why. Research is also under way to study virus variants that are emerging and why some are more transmissible. For updated information on SARS-CoV-2 variants, please read the weekly epidemiologic updates.

When do infected people transmit the virus?

What is the difference between people who are asymptomatic or pre-symptomatic? Don't they both mean someone without symptoms?

Are there certain settings where COVID-19 can spread more easily?

How can I reduce my risk of getting COVID-19?

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EXHIBIT B

Centers for Disease Control and Prevention

COVID-19

Science Brief: SARS-CoV-2 and Surface (Fomite) Transmission for Indoor Community Environments

Updated Apr. 5, 2021

> COVID-19 Science Briefs provide a summary of the scientific evidence used to inform specific CDC guidance and recommendations. The Science Briefs reflect the scientific evidence, and CDC's understanding of it, on a specific topic at the time of the Brief's publication. Though CDC seeks to update Science Briefs when and as appropriate, given ongoing changes in scientific evidence an individual Science Brief might not reflect CDC's current understanding of that topic. As scientific evidence and available information on COVID-19 change, Science Briefs will be systematically archived as historic reference materials.
>
> Page First Published March 24, 2021

The principal mode by which people are infected with SARS-CoV-2 (the virus that causes COVID-19) is through exposure to respiratory droplets carrying infectious virus. It is possible for people to be infected through contact with contaminated surfaces or objects (fomites), but the risk is generally considered to be low.

Background

SARS-CoV-2, the virus that causes COVID-19, is an enveloped virus, meaning that its genetic material is packed inside an outer layer (envelope) of proteins and lipids. The envelope contains structures (spike proteins) for attaching to human cells during infection. The envelope for SARS-CoV-2, as with other enveloped respiratory viruses, is labile and can degrade quickly upon contact with surfactants contained in cleaning agents and under environmental conditions. The risk of fomite-mediated transmission is dependent on:

- The infection prevalence rate in the community
- The amount of virus infected people expel (which can be substantially reduced by wearing masks)
- The deposition of expelled virus particles onto surfaces (fomites), which is affected by air flow and ventilation
- The interaction with environmental factors (e.g., heat and evaporation) causing damage to virus particles while airborne and on fomites
- The time between when a surface becomes contaminated and when a person touches the surface
- The efficiency of transference of virus particles from fomite surfaces to hands and from hands to mucous membranes on the face (nose, mouth, eyes)
- The dose of virus needed to cause infection through the mucous membrane route

Because of the many factors affecting the efficiency of environmental transmission, the relative risk of fomite transmission of SARS-CoV-2 is considered low compared with direct contact, droplet transmission, or airborne transmission [1, 2]. However, it is not clear what proportion of SARS-CoV-2 infections are acquired through surface transmission. There have been few reports of COVID-19 cases potentially attributed to fomite transmission [1, 2]. Infections can often be attributed to multiple transmission pathways. Fomite transmission is difficult to prove definitively, in part because respiratory transmission from asymptomatic people cannot be ruled out [3, 4, 5]. Case reports indicate that SARS-CoV-2 is transmitted between people by touching surfaces an ill person has recently coughed or sneezed on, and then directly touching the mouth, nose, or eyes [3, 4, 5]. Hand hygiene is a barrier to fomite transmission and has been associated with lower risk of infection [6].

Quantitative microbial risk assessment (QMRA) studies have been conducted to understand and characterize the relative risk of SARS-CoV-2 fomite transmission and evaluate the need for and effectiveness of prevention measures to reduce risk. Findings of these studies suggest that the risk of SARS-CoV-2 infection via the fomite transmission route is low, and generally less than 1 in 10,000, which means that each contact with a contaminated surface has less than a 1 in 10,000 chance of causing an infection [7, 8, 9]. Some studies estimated exposure risks primarily using outdoor environmental SARS-CoV-2 RNA quantification data. They noted that their QMRA estimates are subject to uncertainty that can be reduced with additional data to improve the accuracy and precision of information that is entered into the models. Concentrations of infectious SARS-CoV-2 on outdoor surfaces could be expected to be lower than indoor surfaces because of air dilution and movement, as well as harsher environmental conditions, such as sunlight. One QMRA study also evaluated the effectiveness of prevention measures that reduce the risk of fomite transmission and found that hand hygiene could substantially reduce the risk of SARS-CoV-2 transmission from contaminated surfaces, while surface disinfection once- or twice-per-day had little impact on reducing estimated risks [9].

Surface survival

Numerous researchers have studied how long SARS-CoV-2 can survive on a variety of porous and non-porous surfaces [10, 11, 12, 13, 14, 15]. On porous surfaces, studies report inability to detect viable virus within minutes to hours; on non-porous surfaces, viable virus can be detected for days to weeks. The apparent, relatively faster inactivation of SARS-CoV-2 on porous compared with non-porous surfaces might be attributable to capillary action within pores and faster aerosol droplet evaporation [16].

Data from surface survival studies indicate that a 99% reduction in infectious SARS-CoV-2 and other coronaviruses can be expected under typical indoor environmental conditions within 3 days (72 hours) on common non-porous surfaces like stainless steel, plastic, and glass [10, 11, 12, 13, 15]. However, experimental conditions on both porous and non-porous surfaces do not necessarily reflect real-world conditions, such as initial virus amount (e.g., viral load in respiratory droplets) and factors that can remove or degrade the virus, such as ventilation and changing environmental conditions [8, 9]. They also do not account for inefficiencies in transfer of the virus between surfaces to hands and from hands to mouth, nose, and eyes [8, 9]. In fact, laboratory studies try to optimize the recovery of viruses from surfaces (e.g., purposefully swabbing the surface multiple times or soaking the contaminated surface in viral transport medium before swabbing). When accounting for both surface survival data and real-world transmission factors, the risk of fomite transmission after a person with COVID-19 has been in an indoor space is minor after 3 days (72 hours), regardless of when it was last cleaned [8, 9, 10, 11, 12, 13, 15].

Effectiveness of cleaning and disinfection

Both cleaning (use of soap or detergent) and disinfection (use of a product or process designed to inactivate SARS-CoV-2) can reduce the risk of fomite transmission. Cleaning reduces the amount of soil (e.g., dirt, microbes and other organic agents, and chemicals) on surfaces, but efficacy varies by the type of cleaner used, cleaning procedure, and how well the cleaning is performed. No reported studies have investigated the efficacy of surface cleaning (with soap or detergent not containing a registered disinfectant) for reducing concentrations of SARS-CoV-2 on non-porous surfaces. From studies of cleaning focused on other microbes, a 90–99.9% reduction of microbe levels could be possible depending on the cleaning method and the surface being cleaned [17, 18]. In addition to physical removal of SARS-CoV-2 and other microbes, surface cleaning can be expected to degrade the virus. Surfactants in cleaners can disrupt and damage the membrane of an enveloped virus like SARS-CoV-2 [19, 20, 21].

To substantially inactivate SARS-CoV-2 on surfaces, the surface must be treated with a disinfectant product registered with the Environmental Protection Agency's (EPA's) List N or technology that has been shown to be effective against the virus [22]. Disinfectant products might also contain cleaning agents, so they are designed to clean by both removing soil and inactivating microbes. Cleaners and disinfectants should be used safely, following the manufacturer guidance. There have been increases in poisonings and injuries from unsafe use of cleaners and disinfectants since the start of the COVID-19 pandemic [23]. Some types of disinfection applications, particularly those including fogging or misting, are neither safe nor effective for inactivating the virus unless properly used [24].

Surface disinfection has been shown to be effective for preventing secondary transmission of SARS-CoV-2 between an infected person and other people within households [25]. However, there is little scientific support for routine use of disinfectants in community settings, whether indoor or outdoor, to prevent SARS-CoV-2 transmission from fomites. In public spaces and community settings, available epidemiological data and QMRA studies indicate that the risk of SARS-CoV-2 transmission from fomites is low—compared with risks from direct contact, droplet transmission or airborne transmission [8, 9]. Routine cleaning performed effectively with soap or detergent, at least once per day, can substantially reduce virus levels on surfaces. When focused on high-touch surfaces, cleaning with soap or detergent should be enough to further reduce the relatively low transmission risk from fomites in situations when there has not been a suspected or confirmed case of COVID-19 indoors. In situations when there has been a suspected or confirmed case of COVID-19 indoors within the last 24 hours, the presence of infectious virus on surfaces is more likely and therefore high-touch surfaces should be disinfected [26].

Response to a case in an indoor environment

When a person with suspected or confirmed COVID-19 has been indoors, virus can remain suspended in the air for minutes to hours. The length of time virus remains suspended and is infectious depends on numerous factors, including viral load in respiratory droplets or in small particles, disturbance of air and surfaces, ventilation, temperature, and humidity [27, 28, 29, 30, 31]. Wearing masks consistently and correctly can substantially reduce the amount of virus indoors, including the amount of virus that lands on surfaces [32].

Based on limited epidemiologic and experimental data, the risk of infection from entering a space where a person with COVID-19 has been is low after 24 hours. During the first 24 hours, the risk can be reduced by increasing ventilation and waiting as long as possible before entering the space (at least several hours, based on documented airborne transmission cases), and using personal protective equipment (including any protection needed for the cleaning and disinfection products) to reduce risk. Certain techniques can improve the fit and filtration effectiveness of masks [32].

After a person with suspected or confirmed COVID-19 has been in an indoor space, the risk of fomite transmission from any surfaces is minor after 3 days (72 hours). Researchers have found that 99% reduction in infectious SARS-CoV-2 on non-porous surfaces can occur within 3 days [8, 9, 10, 11, 12, 13]. In indoor settings, risks can be reduced by wearing masks (which reduces droplets that can be deposited on surfaces), routine cleaning, and consistent hand hygiene.

Conclusion

People can be infected with SARS-CoV-2 through contact with surfaces. However, based on available epidemiological data and studies of environmental transmission factors, surface transmission is not the main route by which SARS-CoV-2 spreads, and the risk is considered to be low. The principal mode by which people are infected with SARS-CoV-2 is through exposure to respiratory droplets carrying infectious virus. In most situations, cleaning surfaces using soap or detergent, and not disinfecting, is enough to reduce risk. Disinfection is recommended in indoor community settings where there has been a suspected or confirmed case of COVID-19 within the last 24 hours. The risk of fomite transmission can be reduced by wearing masks consistently and correctly, practicing hand hygiene, cleaning, and taking other measures to maintain healthy facilities.

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EXHIBIT C

Centers for Disease Control and Prevention

COVID-19

Scientific Brief: SARS-CoV-2 Transmission

Updated May 7, 2021

COVID-19 Science Briefs provide a summary of the scientific evidence used to inform specific CDC guidance and recommendations. The Science Briefs reflect the scientific evidence, and CDC's understanding of it, on a specific topic at the time of the Brief's publication. Though CDC seeks to update Science Briefs when and as appropriate, given ongoing changes in scientific evidence an individual Science Brief might not reflect CDC's current understanding of that topic. As scientific evidence and available information on COVID-19 change, Science Briefs will be systematically archived as historic reference materials.

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SARS-CoV-2 is transmitted by exposure to infectious respiratory fluids

The principal mode by which people are infected with SARS-CoV-2 (the virus that causes COVID-19) is through exposure to respiratory fluids carrying infectious virus. Exposure occurs in three principal ways: (1) inhalation of very fine respiratory droplets and aerosol particles, (2) deposition of respiratory droplets and particles on exposed mucous membranes in the mouth, nose, or eye by direct splashes and sprays, and (3) touching mucous membranes with hands that have been soiled either directly by virus-containing respiratory fluids or indirectly by touching surfaces with virus on them.

People release respiratory fluids during exhalation (e.g., quiet breathing, speaking, singing, exercise, coughing, sneezing) in the form of droplets across a spectrum of sizes.[1-9] These droplets carry virus and transmit infection.

- The largest droplets settle out of the air rapidly, within seconds to minutes.
- The smallest very fine droplets, and aerosol particles formed when these fine droplets rapidly dry, are small enough that they can remain suspended in the air for minutes to hours.

Infectious exposures to respiratory fluids carrying SARS-CoV-2 occur in three principal ways (not mutually exclusive):

1. **Inhalation** of air carrying very small fine droplets and aerosol particles that contain infectious virus. Risk of transmission is greatest within three to six feet of an infectious source where the concentration of these very fine droplets and particles is greatest.
2. **Deposition** of virus carried in exhaled droplets and particles onto exposed mucous membranes (i.e., "splashes and sprays", such as being coughed on). Risk of transmission is likewise greatest close to an infectious source where the concentration of these exhaled droplets and particles is greatest.
3. **Touching** mucous membranes with hands soiled by exhaled respiratory fluids containing virus or from touching inanimate surfaces contaminated with virus.

The risk of SARS-CoV-2 infection varies according to the amount of virus to which a person is exposed

Once infectious droplets and particles are exhaled, they move outward from the source. The risk for infection decreases with increasing distance from the source and increasing time after exhalation. Two principal processes determine the amount of virus to which a person is exposed in the air or by touching a surface contaminated by virus:

1. **Decreasing concentration of virus in the air** as larger and heavier respiratory droplets containing virus fall to the ground or other surfaces under the force of gravity and the very fine droplets and aerosol particles that remain in the airstream progressively mix

with, and become diluted within, the growing volume and streams of air they encounter. This mixing is not necessarily uniform and can be influenced by thermal layering and initial jetting of exhalations.

2. **Progressive loss of viral viability and infectiousness** over time influenced by environmental factors such as temperature, humidity, and ultraviolet radiation (e.g., sunlight).

Transmission of SARS-CoV-2 from inhalation of virus in the air farther than six feet from an infectious source can occur

With increasing distance from the source, the role of inhalation likewise increases. Although infections through inhalation at distances greater than six feet from an infectious source are less likely than at closer distances, the phenomenon has been repeatedly documented under certain preventable circumstances.[10-21] These transmission events have involved the presence of an infectious person exhaling virus indoors for an extended time (more than 15 minutes and in some cases hours) leading to virus concentrations in the air space sufficient to transmit infections to people more than 6 feet away, and in some cases to people who have passed through that space soon after the infectious person left. Per published reports, factors that increase the risk of SARS-CoV-2 infection under these circumstances include:

- **Enclosed spaces with inadequate ventilation or air handling** within which the concentration of exhaled respiratory fluids, especially very fine droplets and aerosol particles, can build-up in the air space.
- **Increased exhalation** of respiratory fluids if the infectious person is engaged in physical exertion or raises their voice (e.g., exercising, shouting, singing).
- **Prolonged exposure** to these conditions, typically more than 15 minutes.

Prevention of COVID-19 transmission

The infectious dose of SARS-CoV-2 needed to transmit infection has not been established. Current evidence strongly suggests transmission from contaminated surfaces does not contribute substantially to new infections. Although animal studies[22-24] and epidemiologic investigations[25] (in addition to those described above) indicate that inhalation of virus can cause infection, the relative contributions of inhalation of virus and deposition of virus on mucous membranes remain unquantified and will be difficult to establish. Despite these knowledge gaps, the available evidence continues to demonstrate that existing recommendations to prevent SARS-CoV-2 transmission remain effective. These include physical distancing, community use of well-fitting masks (e.g., barrier face coverings, procedure/surgical masks), adequate ventilation, and avoidance of crowded indoor spaces. These methods will reduce transmission both from inhalation of virus and deposition of virus on exposed mucous membranes. Transmission through soiled hands and surfaces can be prevented by practicing good hand hygiene and by environmental cleaning.

Summary of Updates

Updates from Previous Content

As of May 7, 2021

- This science brief has been updated to reflect current knowledge about SARS-CoV-2 transmission and reformatted to be more concise.
- Modes of SARS-CoV-2 transmission are now categorized as inhalation of virus, deposition of virus on exposed mucous membranes, and touching mucous membranes with soiled hands contaminated with virus.
- Although how we understand transmission occurs has shifted, the ways to prevent infection with this virus have not. All prevention measures that CDC recommends remain effective for these forms of transmission.

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EXHIBIT D

Feature

WHY THE WHO TOOK TWO YEARS TO SAY COVID IS AIRBORNE

Early in the pandemic, the World Health Organization stated that SARS-CoV-2 was not transmitted through the air. That mistake and the prolonged process of correcting it sowed confusion and raises questions about what will happen in the next pandemic. **By Dyani Lewis**

As 2021 drew to a close, the highly contagious Omicron variant of the pandemic virus was racing around the globe, forcing governments to take drastic actions once again. The Netherlands ordered most businesses to close on 19 December, Ireland set curfews and many countries imposed travel bans in the hope of taming the tsunami of COVID-19 cases filling hospitals. Amid the wave of desperate news around the year-end holidays, one group of researchers hailed a development that had seemed as though it might never arrive. On 23 December, the World Health Organization (WHO) uttered the one word it had previously seemed incapable of applying to the virus SARS-CoV-2: 'airborne'.

On its website, a page titled 'Coronavirus disease (COVID-19): How is it transmitted?' was quietly edited to state that a person can be infected "when infectious particles that pass through the air are inhaled at short range", a process otherwise known as "short-range aerosol or short-range airborne transmission". The website says that transmission can occur through "long-range airborne transmission" in poorly ventilated or crowded indoor settings "because aerosols can remain suspended in the air or travel farther than conversational distance".

"It was a relief to see them finally use the word 'airborne', and to say clearly that airborne transmission and aerosol transmission are synonyms," says aerosol chemist Jose-Luis Jimenez at the University of Colorado Boulder.

The seemingly uncontroversial statement marked a clear shift for the Switzerland-based WHO, which had tweeted categorically early in the pandemic, "FACT: #COVID19 is NOT airborne," casting the negative in capital letters as if to remove any doubt. At that time, the agency maintained that the virus spreads mainly through droplets produced when a person coughs, sneezes or speaks, an assumption based on decades-old infection-control teachings about how respiratory viruses generally pass from one person to another. The guidance recommended distancing of more than one metre — within which these droplets were thought to fall to the ground — along with hand washing and surface disinfection to stop transfer of droplets to the eyes, nose and mouth.

It took until 20 October 2020 for the agency to acknowledge that aerosols — tiny specks of fluid — can transmit the virus, but the WHO said this was a concern only in specific settings, such as indoor, crowded and inadequately ventilated spaces. Over the next six months, the agency gradually altered its advice to say that aerosols could carry the virus for more than a metre and remain in the air.

But this latest tweak is the WHO's clearest statement yet about airborne transmission of SARS-CoV-2. And it places the virus among a select group of 'airborne' infections, a label long reserved for just a handful of the world's most virulent pathogens, including measles, chickenpox and tuberculosis.

The change brings the WHO's messaging in line with what a chorus of aerosol and public-health experts have been trying to get it to say since the earliest days of the outbreak. Many decry the agency's slowness in stating — unambiguously — that SARS-CoV-2 is airborne. Interviews conducted by *Nature* with dozens of specialists on disease transmission suggest that the WHO's reluctance to accept and communicate evidence for airborne transmission was based on a series of problematic assumptions about how respiratory viruses spread.

For example, even in the middle of the fast-moving epidemic, the WHO dismissed field epidemiology reports as proof of airborne transmission because the evidence was not definitive, something that is difficult to achieve quickly during an outbreak. Other criticisms are that the WHO relies on a narrow band of experts, many of whom haven't studied airborne transmission, and that it eschews a precautionary approach that could have protected countless people in the early stages of the pandemic.

Critics say that inaction at the agency led to national and local health agencies around the world being similarly sluggish in addressing the airborne threat. Having shifted its position incrementally over the past two years, the WHO also failed to adequately communicate its changing position, they say. As a result, it didn't emphasize early enough and clearly enough the importance of ventilation and indoor masking, key measures that can prevent airborne spread of the virus. Lidia Morawska, an aerosol scientist at the Queensland University of Technology in Brisbane, Australia, spearheaded several efforts to convince the WHO and other health agencies of the airborne threat. She says that airborne transmission was "so obvious" as far back as February 2020, and that omitting it from official guidelines was disastrous.

But Dale Fisher, an infectious-diseases physician at the National University Hospital in Singapore and chair of the WHO's Global

Public-health advice on COVID-19 in early 2020 focused on sanitizing surfaces more than protecting against airborne transmission.

OZAN KOSE/AFP/GETTY

Outbreak Alert and Response Network steering committee, doesn't think that confusion over whether the virus is airborne has had a defining impact on how the pandemic has played out. "It's not the cause of the catastrophe we've seen," he says.

"So many assumptions that we had about this virus were proven false."

Some other researchers defend the agency's response, given the rapidly evolving situation. "I really don't think anybody dropped the ball, including WHO," says Mitchell Schwaber, an infectious-diseases physician at Israel's ministry of health and an external adviser to the WHO. "So many assumptions that we had about this virus were proven false. We always, we always were learning new things."

Resolving this debate about how to assess the transmission of respiratory viruses matters, say researchers, because a more deadly variant of SARS-CoV-2 could emerge at any time, and new respiratory viruses will almost certainly plague humanity at some point. It's not clear whether the WHO and the world will be ready.

Tension in the air

In the final days of March 2020, Morawska contacted dozens of colleagues — an international mix of aerosol scientists, infectious-disease specialists, and building and ventilation engineers — to get the word out about the airborne threat of SARS-CoV-2. On 1 April 2020, the group sent an e-mail laying out their case to Michael Ryan, head of the WHO's Health Emergencies Programme, and Maria Van Kerkhove, technical lead of the WHO's COVID-19 response.

Within an hour, the agency was on the phone. Two days later, the group attended a video conference with members of the Health Emergencies Programme and the Infection Prevention and Control Guidance Development Group (IPC GDG) — an external group of about 40 clinicians and researchers that advises the WHO on infection containment, especially in hospitals. At the time of the meeting, more than one million people had been infected with SARS-CoV-2, and 54,000 had died. Community spread was rampant in several countries.

Morawska presented what she says was a compelling case for airborne transmission. Two facts stood out. First, there was solid evidence that people were becoming infected even when they were more than one metre — the safe distance recommended by the WHO — from a contagious individual. Second, years of mechanistic studies had demonstrated how mucus in a person's airway can spray into aerosols during speech and accumulate in stagnant rooms. Morawska felt rebuffed by the WHO and its advisers. "I didn't have a feeling that they were trying to see this from our perspective," she says.

She and other people who study aerosols and airborne disease transmission say that the IPC GDG is ill-equipped to assess this type of transmission because most of its members have focused on controlling infections in hospitals and they lack expertise in the physics of how airborne contagions spread. At the time of the 1 April meeting, no one in the IPC GDG had studied this type of disease transmission, say critics.

"If it is a new disease, you better include everyone," says Yuguo Li, a building environment engineer at the University of Hong Kong, whose study of the SARS outbreak in 2002–03 had concluded that the virus responsible, SARS-CoV, probably spread through the airborne route[1]. He suspected that SARS-CoV-2 was also airborne, although he initially thought that only short-range airborne transmission was likely.

Marcel Loomans, an indoor-air-quality physicist at Eindhoven University of Technology in the Netherlands, says that it is often hard to find common ground between the two disciplines. "On the medical side, they were not aware of how aerosols behave in the air and what ventilation can do," he says. People end up "talking past each other".

The disconnect was there even in the use of scientific terms. Infection-control experts have long drawn a hard line between droplet viruses and airborne ones, seeing only the latter as capable of travelling far and lingering in the air. "Dogmatic bias is certainly a big part of it," says Don Milton, an occupational-health physician who studies aerosol transmission of infectious diseases at the University of Maryland in College Park. He says that he was disappointed but not surprised by the WHO's lack of action in addressing the airborne threat after the 1 April meeting. "I'm just familiar with how the medical profession thinks," he says.

But Schwaber, who chairs the IPC GDG, recalls the meeting differently. "We took very seriously the issues that they raised at the meeting, and responded to them," he says. "Nothing was being blown off, nothing was being ignored."

At the time, he says, the available evidence suggested that airborne precautions throughout hospitals – including N95 masks for staff, visitors and patients – were unnecessary. Still, faced with soaring deaths among front-line doctors and nurses, most hospitals and health agencies adopted these precautions on their COVID-19 wards, as well as less-stringent protections such as wearing surgical masks in other areas of the hospital.

"You've got to explain all the data, not just the data that you've picked to support your view."

Mark Sobsey, an environmental microbiologist at the University of North Carolina in Chapel Hill who is a member of the IPC GDG, says that especially in the early days, the concerns brought to the WHO about airborne transmission were "largely unfounded" and lacked credible evidence, such as the isolation of infectious virus particles from air samples. Epidemiological data from outbreak investigations were "especially weak", he says.

According to Trish Greenhalgh, a primary-care health researcher at the University of Oxford, UK, the IPC GDG members were guided by their medical training and the dominant thinking in the medical field about how infectious respiratory diseases spread; this turned out to be flawed in the case of SARS-CoV-2 and could be inaccurate for other viruses as well. These biases led the group to discount relevant information – from laboratory-based aerosol studies and outbreak reports, for instance. So the IPC GDG concluded that airborne transmission was rare or unlikely outside a small set of aerosol-generating medical procedures, such as inserting a breathing tube into a patient.

That viewpoint is clear in a commentary by members of the IPC GDG, including Schwaber, Sobsey and Fisher, published in August 2020 (ref. 2). The authors dismissed research using air-flow modelling, case reports describing possible airborne transmission and summaries of evidence for airborne transmission, labelling such reports "opinion pieces". Instead, they concluded that "SARS-CoV-2 is not spread by the airborne route to any significant extent".

In effect, the group failed to look at the whole picture that was emerging, says Greenhalgh. "You've got to explain all the data, not just the data that you've picked to support your view," and the airborne hypothesis is the best fit for all the data available, she says. One example she cites is the propensity for the virus to transmit in 'superspreader events', in which

CHANGING VIEWS OF HOW COVID SPREADS

Throughout much of 2020, the World Health Organization (WHO) held tight to the idea that SARS-CoV-2, the virus that causes COVID-19, spreads through relatively large 'respiratory' droplets that are expelled by infected people while coughing, sneezing or speaking. These droplets contaminate nearby surfaces or get breathed in, so the WHO stressed the importance of washing hands and disinfecting surfaces.

It took many months for the agency to acknowledge that the virus could travel on tiny particles called aerosols that can spread widely and linger in the air. And nearly two years passed before the WHO clearly stated that the virus is airborne.

2020

23 February

"The disease can spread from person to person through small droplets from the nose or mouth which are spread when a person with COVID-19 coughs or exhales. These droplets land on objects and surfaces around the person. Other people then catch COVID-19 by touching these objects or surfaces, then touching their eyes, nose or mouth. People can also catch COVID-19 if they breathe in droplets from a person with COVID-19 who coughs out or exhales droplets. This is why it is important to stay more than 1 metre (3 feet) away from a person who is sick."

The WHO does not mention transmission by means of aerosols, or that the virus can spread across distances of more than one metre or remain in the air.

28 March

"FACT: #COVID19 is NOT airborne ..."

"The virus that causes COVID-19 is mainly transmitted through droplets generated when an infected person coughs, sneezes or speaks."

"These droplets are too heavy to hang in the air. They quickly fall to the ground."

The agency explicitly states that the virus is not airborne, despite reports at the time suggesting that it could be.

9 July

"Outside of medical facilities, some outbreak reports related to indoor crowded spaces have suggested the possibility of aerosol transmission, combined with droplet transmission, for example, during choir practice, in restaurants or in fitness classes. In these events, short-range aerosol transmission, particularly in specific indoor locations, such as crowded and inadequately ventilated spaces over a prolonged period of time with infected persons cannot be ruled out."

In a detailed 'Scientific Brief', the WHO continues to stress that transmission is through droplets that fall onto surfaces

S.C. LEUNG/SOPA IMAGES/LIGHTROCKET/GETTY

Early WHO advice on masks recommended them only for infected people and their carers.

numerous individuals are infected at a single gathering, often by a single person. "Nothing explains some of these superspreader events except aerosol spread," says Greenhalgh.

Throughout 2020, there was also mounting evidence that indoor spaces posed a much greater risk of infection than outdoor environments did. An analysis of reported outbreaks recorded up to the middle of August 2020 revealed that people were more than 18 times as likely to be infected indoors as outdoors[3]. If heavy droplets or dirty hands had been the main vehicles for transmitting the virus, such a strong discrepancy would not have been observed.

Although the WHO played down the risk of airborne transmission, it did invite Li to become a member of the IPC GDG after he spoke to the group in mid-2020. Had the organization not at least been open to his view that infections were caused by aerosols, especially at short range, "they would not have invited me there as they knew my standing", he says.

Still, Li is disappointed that it took the WHO until October 2020 to acknowledge that aerosols play a part in disease transmission in community settings (see 'Changing views of how COVID spreads'). And in its updated guidelines on mask use, in December 2020, the agency still emphasized shortfalls and gaps in the evidence for aerosol transmission, and the need for more "high quality research" to understand the specifics of how the virus spreads. It wasn't until the end of April 2021 that long-range aerosol transmission was added to a question-and-answer section on the agency's website about how the virus spreads. And the term airborne wasn't officially added until December 2021.

Conservative approach

Some scientists note that the WHO's decision to classify SARS-CoV-2 as airborne, belated as it was, is momentous. That's because it flies in the face of the established view of respiratory virus transmission that held sway when the pandemic began — that nearly all infectious diseases are spread by droplets, not through the air. And researchers say that this change is particularly important because the organization generally takes a conservative approach. "What the WHO says is normally based on a consensus of expert advice and opinion," says Christopher Dye, an epidemiologist who served as the scientific adviser to the agency's director-general until 2018.

And although the WHO has drawn strong

and are spread by surface contamination or by close contact. But, for the first time, it acknowledges that transmission by aerosols might be possible, contradicting its previous statements.

20 October

"Current evidence suggests that the main way the virus spreads is by respiratory droplets among people who are in close contact with each other. Aerosol transmission can occur in specific settings, particularly in indoor, crowded and inadequately ventilated spaces, where infected person(s) spend long periods of time with others, such as restaurants, choir practices, fitness classes, nightclubs, offices and/or places of worship. More studies are under way to better understand the conditions in which aerosol transmission is occurring outside of medical facilities where specific medical procedures, called aerosol generating procedures, are conducted."

The WHO states that aerosol transmission happens outside of medical settings.

2021

30 April

"Current evidence suggests that the virus spreads mainly between people who are in close contact with each other, typically within 1 metre (short-range). A person can be infected when aerosols or droplets containing the virus are inhaled or come directly into contact with the eyes, nose, or mouth.

The virus can also spread in poorly ventilated and/or crowded indoor settings, where people tend to spend longer periods of time. This is because aerosols remain suspended in the air or travel farther than 1 metre (long-range)."

The WHO for the first time mentions that aerosols can stay suspended in the air or travel long distances.

23 December

"Current evidence suggests that the virus spreads mainly between people who are in close contact with each other, for example at a conversational distance ...

The virus can also spread in poorly ventilated and/or crowded indoor settings, where people tend to spend longer periods of time. This is because aerosols can remain suspended in the air or travel farther than conversational distance (this is often called long-range aerosol or long-range airborne transmission)."

Nearly two years into the pandemic, the WHO uses the term 'airborne' for the first time.

criticism for the way in which it assessed SARS-CoV-2 transmission, some researchers don't find the agency's response surprising. The international community looks to the WHO for early warnings of disease outbreaks. But when it comes to science, the agency "sees its role as certifying the current expert consensus, not (usually) advancing new, tentative knowledge", says Peter Sandman, an independent risk-communications specialist based in New Jersey who has worked as a consultant to the WHO.

Schwaber says: "Individuals and governments and public-health bodies are looking to a WHO GDG, not to conjecture. They're looking to a WHO GDG to put out guidance. That everything that we say can be backed by evidence."

The WHO frequently gets attacked, "so you can understand how they'd be risk averse", says Tom Frieden, president of the global-health initiative Resolve to Save Lives and former head of the US Centers for Disease Control and Prevention (CDC). Frieden is critical of some aspects of the WHO's pandemic response, including how slow it was to recommend the use of masks. But he says that the agency is in a difficult position during health crises.

In 2009, for instance, it was accused of being alarmist over the H1N1 swine influenza outbreak that petered out with few lives lost. "WHO got hit hard for that," says Dye, even though he thinks the agency was right to be cautious and declare a public-health emergency of international concern.

Hard line to tread

Virologist May Chu, a member of the IPC GDG at the Colorado School of Public Health in Aurora, says that the WHO treads a difficult line, and tends to be quite conservative in its recommendations to avoid putting out information that later proves to be incorrect. "You can't be backtracking" on advice, adds Fisher, because "then you lose complete credibility".

The gravity of the situation might have made the WHO even more cautious in its pronouncements and less likely to stray from consensus views, according to Sandman's partner Jody Lanard, an independent risk-communications specialist who has also worked with the WHO in the past.

In previous situations — such as during the Ebola outbreak in West Africa, and in polio vaccine campaigns — the WHO was more nimble than it has been during the COVID-19 pandemic, Lanard says. "I've seen them be able to change what their approach was, or try different things," she says. But during the pandemic "it's so tempting to be very, very cautious", because millions of lives will be affected by the agency's recommendations. Loomans and others question why, when concerns were growing that SARS-CoV-2 could be airborne, the WHO didn't adopt a precautionary approach by acknowledging the possibility of different risks, even without definitive proof.

And in May 2021, the Independent Panel for Pandemic Preparedness and Response (IPPPR), a body established by the WHO a year earlier to review the agency's actions at the start of the pandemic, called out the WHO for not applying the precautionary principle to another crucial aspect of COVID-19 transmission — whether it could spread from human to human (see go.nature.com/3iqhfjm). "There is a case for applying the precautionary principle in any outbreak caused by a new pathogen resulting in respiratory infections, and thereby for assuming that human-to-human transmission will occur unless the evidence specifically indicates otherwise," the IPPPR said in its 2021 report.

In practice, applying the precautionary approach to the question of how SARS-CoV-2 — or any newly emerged pathogen — is transmitted would mean initially assuming that all routes of transmission are possible. "That should be your starting point, and then you can strike out routes if you're sure," says Loomans.

But Schwaber says that this approach carries risks. "To say, well, the best interests of the patient and the best interests of the health-care worker involve invoking the precautionary principle would also imply that there's no downside to invoking it," he says. Taking full precautions against airborne transmission would require major changes at hospitals, such as using negative-air-pressure isolation rooms and uncomfortable N95 masks for all staff and visitors. Such changes need to be weighed against the evidence that they are required, he says.

Sobsey says that the WHO did adopt the precautionary principle, in part because of the advice from aerosol scientists. That's why, he says, the agency stated in July 2020 that airborne transmission couldn't be ruled out — and why it started placing more emphasis on ventilation as a protective measure, even though the evidence for airborne transmission was weak at the time.

> **"I think there's been a sea change in thinking at WHO as a consequence of the experience with this virus."**

"They are not totally wrong," says Li of those who claimed there were gaps in the evidence for airborne transmission, especially over larger distances. "It's nothing bad to seek solid scientific evidence," he says, but "when you see the spread so significantly, do you still wait for a nice *Nature* or *Science* article?" he says.

Still, other health organizations moved faster than the WHO despite the uncertainty. In February 2020, Li was contacted by the Chinese Center for Disease Control and Prevention for advice on air conditioning in public buildings and on public transport. At Li's suggestion, he says, the centre recommended maximizing airflow in buildings from the outside, to help flush out any airborne contagion. At the time, Li didn't think that ventilation would substantially reduce infection from a virus that he suspected was airborne only over short distances — an assumption that he later disproved. But he recommended improved ventilation because "I always support a precautionary approach," he says.

Communication problems

One thing that's still missing, says Jimenez, is a clear communication campaign from the WHO. Its director-general, Tedros Adhanom Ghebreyesus, acknowledged the challenges in his opening remarks at the agency's global conference on communicating science during health emergencies, on 7 June 2021. "Scientific processes, decision-making in an emergency context and mass communication do not fit together easily," Tedros said, adding that "high-quality research takes time, but time is something we don't have in an emergency".

During the early months of the pandemic, the WHO was fighting battles on other fronts. While it grappled with shortages of protective equipment and ventilators, it was also contending with misinformation about unproven treatments for COVID-19 and US threats to pull its funding from the organization.

But critics say that even two years into the pandemic, the WHO hasn't clearly communicated the risks from airborne transmission. And, perhaps as a result, governments around the world spent much of the pandemic focusing on hand washing and surface cleaning, instead of ventilation and indoor masking.

"The cacophony of changing messages has undoubtedly contributed greatly to resistance to masks and other measures," says Jimenez.

On 15 December 2021, less than two weeks before the latest change in wording on the WHO's website, Jimenez put out a call on Twitter for evidence of how governments and organizations either "don't know how to protect their citizens, or use @WHO's ambiguity to avoid doing so". He enumerated more than 100 examples in which health advice at the time was at odds with airborne precautions, indicating that the message was not filtering out from the agency.

Jimenez has continued to receive such examples. Now that the agency has changed the wording on its main website, Jimenez can call out these 'COVID Hall of Shame' offenders, as he labels them, for providing advice that is no longer in line with the international health agency.

"That is the arrogance, a bit, of what WHO is," says Chu. "Once you post [new guidance], it's pretty passive. They expect you to come to their website. They don't necessarily broadcast it."

SAM YEH/AFP/GETTY

Schoolchildren in Taipei eat lunch behind partitions to stop the spread of COVID-19 in April 2020, after the WHO stressed the dangers of respiratory droplets that travel short distances.

But that's exactly what's needed, says Jimenez, especially given early communications that still haunt the agency, such as its tweet about COVID-19 not being airborne. "No doubt we owe the persistence of misinformation to that WHO announcement and firm position, at the time in which we were all scared and eager to learn how to protect ourselves, very early in the pandemic," says Jimenez.

The agency defends its actions throughout the pandemic. In a statement to *Nature* last month, a spokesperson said: "WHO has sought the expertise of engineers, architects and aerobiologists along with expertise in infectious diseases, infection prevention and control, virology, pneumology and other fields since the early days of the COVID-19 pandemic. In August 2020, we established the Environment and Engineering Control Expert Advisory Panel (ECAP) for COVID-19 to provide expert contributions for the development of guidance through evaluation and critical interpretation of available evidence (benefits and harm of interventions) related to relevant technical questions including indoor air quality management and ventilation as an engineering control measure in the context of COVID-19."

The organization says that initial guidance covered airborne precautions in health-care settings, but notes that: "As the evidence on the transmission of COVID-19 has expanded, we have learnt that smaller-sized infectious particles known as aerosols also play a role in transmission in community settings, and WHO has adapted its guidance and messages to reflect this in the December 2020 update to our mask guidance."

In response to critics who say that it hasn't adequately highlighted the changes it has made regarding the risks of airborne transmission, the WHO says that it has held about 250 press briefings and hundreds of live social-media events during the pandemic. It adds that it also pushes out information through social-media channels, meetings with doctors and mailing lists to scientists.

That's not enough, according to some researchers. Stephanie Dancer, a microbiologist at the Edinburgh Napier University, UK, says that the WHO needs to be clear about its position so that others follow its lead. "They have to show true strength of character and stand up and say, 'We got it wrong. We're going to get this right. Here are our next set of guidelines. This is where we're going to go. This is what we advise,'" she says.

Off to a bad start

Part of the problem was how emphatic the WHO was at the beginning of the pandemic, says Heidi Tworek, a historian and public-policy specialist at the University of British Columbia in Vancouver. "To say that COVID was definitively not airborne unfortunately meant there was a massive hill to climb to undo that," she says. Right from the beginning, the WHO and other public-health authorities and governments should have emphasized that SARS-CoV-2 was a new coronavirus, and that guidelines would inevitably change, she says. "And when they do, it's a good thing because it means we know more."

"We're really talking here about two failures, not one," says Sandman. "Being reluctant to change your mind, and being reluctant to tell people you changed your mind." Like other public-health and scientific organizations, the WHO "are afraid of losing credibility by acknowledging that they got something wrong", he says.

But when Lanard worked with the WHO in 2005 to draft its risk-communications guidelines, one tenet that she advocated – to admit mistakes and errors when they occur – was removed from the final draft. She says that there were good reasons behind that decision, including that health officials in some countries could have faced imprisonment – or worse – if they had promoted information from the WHO that turned out to be incorrect. Officials and scientific advisers in several countries have received death threats during the pandemic. "Inevitably you'll get it wrong sometimes," says Frieden. And the WHO is in a position that means "whatever they do, they get attacked", he says.

On the science front, questions remain about how much of COVID-19 transmission is airborne. Sobsey says that researchers still need to come up with evidence that the airborne route makes "an important contribution to the overall disease burden". Many on the other side of the aisle, such as Jimenez, are convinced that airborne transmission predominates. The US Office of Science and Technology Policy voiced strong support for this view on 23 March, when its head, Alondra Nelson, issued a statement called 'Let's Clear the Air on COVID', which said "the most common way COVID-19 is transmitted from one person to another is through tiny airborne particles of the virus hanging in indoor air for minutes or hours after an infected person has been there."

Other viruses long suspected of being airborne – including influenza and common cold viruses – will also be scrutinized. In September 2021, the US National Institutes of Health awarded Milton a multimillion-dollar grant to conduct trials that will determine whether airborne or droplet routes lead to influenza infection.

Li says that there's much greater recognition of airborne transmission because of the COVID-19 pandemic, and research over the next few years will probably show that most respiratory viruses can spread in this way. So the whole world will be more alert to the possibility of the airborne threat when old or new infectious diseases start spreading.

In the WHO, too, attitudes have shifted, according to Sobsey. "I think there's been a sea change in thinking at WHO as a consequence of the experience with this virus," he says, "which is – be more precautionary, even if you're not sure."

Dyani Lewis is freelance reporter in Melbourne, Australia.

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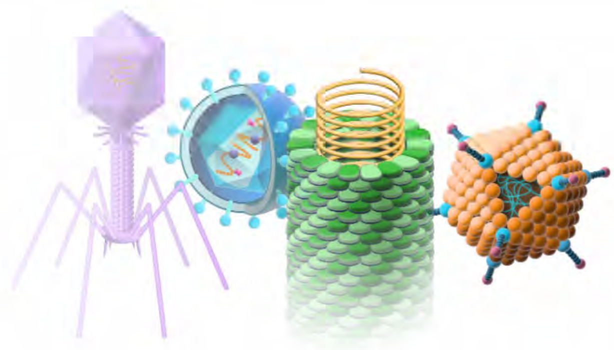
EXHIBIT E

VIRUS

updated: March 24, 2023



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Definition

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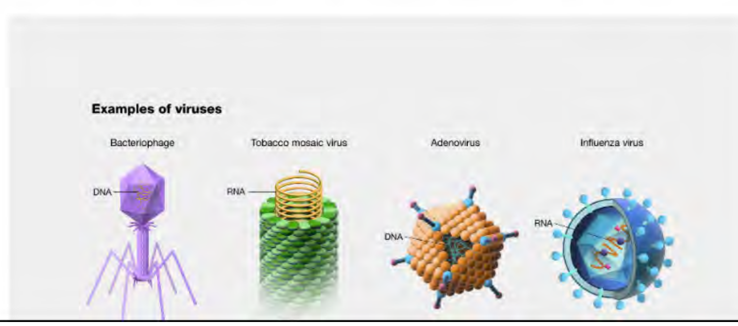
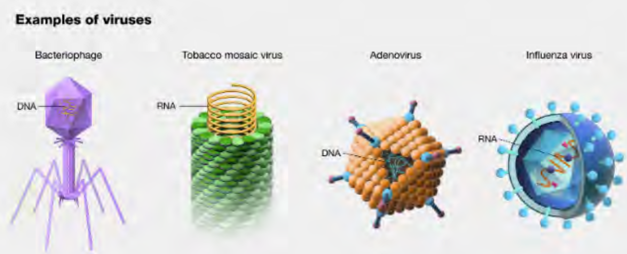
A virus is an infectious microbe consisting of a segment of nucleic acid (either DNA or RNA) surrounded by a protein coat. A virus cannot replicate alone; instead, it must infect cells and use components of the host cell to make copies of itself. Often, a virus ends up killing the host cell in the process, causing damage to the host organism. Well-known examples of viruses causing human disease include AIDS, COVID-19, measles and smallpox.





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Narration

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Virus. Well, we all have learned a lot more about viruses in the last two years with the Covid-19 outbreak/global pandemic. Viruses infect humans. But, in fact, viruses infect many organisms, so you'll have viruses that infect fungi, viruses that infect bacteria, and we can learn a lot about how viruses maintain themselves by studying viruses that infect a whole host of species. That really does help us to understand human disease. But the viruses that infect humans are only a small fraction of the viruses that you find in the world. The greatest abundance of viruses would be those that infect bacteria that are sometimes called phage. And they have shared a lot of the same properties but they are much more abundant. A lot of future research will unravel the ways in which viruses infect humans and what we might find as potential ways of stopping viral replication within human cells.

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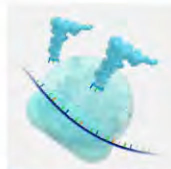
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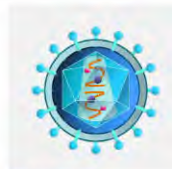
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EXHIBIT F

RESEARCH ARTICLE | CHEMISTRY

The dynamics of SARS-CoV-2 infectivity with changes in aerosol microenvironment

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Significance

The aerosol microenvironment is dynamic, exposing pathogens, such as severe acute respiratory syndrome coronavirus 2 virus, when exhaled in respiratory aerosol to extreme conditions of solute concentration, pH, and evaporative cooling. Yet surviving this environment is a key step in the transmission of such pathogens. Understanding the impact that airborne transport has on pathogens and the influence of environmental conditions on pathogen survival can inform the implementation of strategies to mitigate the spread of diseases such as coronavirus disease 2019. We report changes in the infectivity of the airborne virus over timescales from 5 s to 20 min and demonstrate the role of two microphysical processes in this infectivity loss, namely, particle crystallization and aerosol droplet pH change.

Abstract

Understanding the factors that influence the airborne survival of viruses such as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in aerosols is important for identifying routes of transmission and the value of various mitigation strategies for preventing transmission. We present measurements of the stability of SARS-CoV-2 in aerosol droplets (~5 to 10 μm equilibrated radius) over timescales spanning 5 s to 20 min using an instrument to probe survival in a small population of droplets (typically 5 to 10) containing ~1 virus/droplet. Measurements of airborne infectivity change are coupled with a detailed physicochemical analysis of the airborne droplets containing the virus. A decrease in infectivity to ~10% of the starting value was observable for SARS-CoV-2 over 20 min, with a large proportion of the loss occurring within the first 5 min after aerosolization. The initial rate of infectivity loss was found to correlate with physical transformation of the equilibrating droplet; salts within the droplets crystallize at relative humidities (RHs) below 50%, leading to a near-instant loss of infectivity in 50 to 60% of the

stability is sustained for the first 2 min, beyond which it decays to only 10% remaining infectious after 10 min. The loss of infectivity at high RH is consistent with an elevation in the pH of the droplets, caused by volatilization of CO_2 from bicarbonate buffer within the droplet. Four different variants of SARS-CoV-2 were compared and found to have a similar degree of airborne stability at both high and low RH.

The ongoing coronavirus disease 2019 (COVID-19) pandemic has demonstrated the requirement for an improved understanding of the factors that govern the relative importance of different modes of transmission of respiratory pathogens, including the parameters that influence droplet, fomite, and airborne transmission. Indeed, shortcomings in our understanding have prolonged the debate surrounding the likelihood of airborne transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (1–3), with consequences for the implementation of nonpharmaceutical interventions and mitigation strategies such as physical distancing, the wearing of face coverings, and the use of ultraviolet (UV) germicidal irradiation. Currently, epidemiological evidence (4–7), air sampling studies (8), and animal-model studies (9) are broadly consistent with transmission dominated by the inhalation of infectious aerosol (<100-μm diameter). Transmission over distances beyond 2 m has been documented and tends to be under preventable circumstances (10), such as occurring after prolonged exposure in poorly ventilated rooms (11, 12).

Reports of the airborne stability of SARS-CoV-2 consistently indicate that the half-life associated with the decay in viral infectivity is on the order of hours in surrogates of respiratory aerosols (13–16). However, a detailed understanding of the processes that govern the airborne longevity of viruses, and how infectivity is affected by basic environmental conditions such as relative humidity (RH) and temperature, is required. More specifically, there is little clarity on the impact of environmental conditions on the microenvironment within an airborne droplet and the interplay between this microenvironment and the stability of pathogens. Improved models of the physicochemical properties of respiratory aerosol and the processes that transform particle size, moisture content, composition, and phase are essential to provide clearer insights into the relative risks of airborne transmission in different environments and the potential benefits of mitigation measures to reduce transmission. Indeed, it should be recognized that transformation processes lead to transient changes in properties (e.g., surface enrichment in salts during evaporation following droplet exhalation) that can have impacts on infectivity distinct from the steady state equilibrium properties that persist over longer time periods during airborne transport (e.g., an equilibrated salt concentration).

The microenvironment within an airborne droplet is multifarious and notoriously difficult to study (17) and is further complicated by the presence of organic macromolecules and microorganisms (18). While the vast majority of indoor aerosols originate from sources such as transmitted in exhaled aerosol that can span from 100-nm to 100-μm diameter and have emission rates as low as 10 particles s^{-1} when humans breathe (20, 21). Regardless of the expiratory activity that generates respiratory aerosols [e.g., coughing, speaking (21, 22)], the high surface area-to-volume ratio of the emitted particles facilitates rapid equilibration to the surrounding gas phase composition (*SI Appendix*, Fig. S1*A*) (23). In particular, the equilibration of the water activity within the droplet to the surrounding RH impacts the physicochemical conditions experienced by microorganisms present within the aerosol. Aqueous respiratory droplets at the point of exhalation start with a very high water activity (~0.995) (24) consistent with equilibration with the high RH within the respiratory tract (25) but must adjust to equilibrate with the indoor humidity, which is typically within the range 20 to 60% (26–28). Under most conditions, exhaled aerosol droplets rapidly lose both moisture and heat through evaporation, with large concomitant changes in volume and temperature as they establish an equilibrium with the indoor environment.

Not only does the loss in water lead to an increase in solute concentrations during evaporation but also the absence of heterogenous nucleation sites (i.e., a surface) leads to supersaturated solute concentrations that cannot be achieved in the bulk solution phase or in sessile droplets deposited on surfaces. At sufficiently low RH (e.g., below 45% for saline solution droplets), the supersaturation of solutes can be sufficient to induce homogenous nucleation (29–31) of the salt fraction, leading to efflorescence (crystallization) of the droplet and the formation of a dryer particle. Furthermore, during the initial period of droplet evaporation, the rates of diffusion of microorganisms within the droplet can be significantly slower than the rate at which the droplet surface recedes, leading to their exclusion to the near-surface region of the droplet. Given that the physicochemical conditions at the surface of the droplet can be different to the core (e.g., surface enrichment in solute concentration), establishing the distribution of microorganisms within a particle may be crucial to understanding the impact of aerosol microphysics on their longevity.

Once the moisture content of the aerosol has decreased to establish equilibrium with the ambient environment, the decay in microorganism survival may be regulated by steady-state microphysical properties. In particular, the typical range in ambient RH is consistent with equilibrated solute concentrations that are supersaturated in the exhaled aerosol. Although the mechanism remains unclear, high salt concentrations may inactivate viruses by damaging the viral nucleic acid (32, 33). With high contents of organic macromolecules, phase-separated particles with organic- and inorganic-rich domains or amorphous particles containing trapped moisture may form, potentially enhancing viral and bacterial survival. Furthermore, the pH of aerosol particles is RH, size, and composition dependent, and the pH of aerosol droplet surfaces may be different from the droplet bulk (34). Indeed, predicting the evolving aerosol pH is challenging, particularly when the facile partitioning of water-soluble acidic and basic components from the ambient environment is considered, even before the influence of aerosol pH on microorganism survival is considered (35).

Laboratory strategies to assess the airborne stability of a pathogen must either be capable of simulating every aspect of the real-world environment in which transmission occurs or processes and properties on survival can be assessed independently. Goldberg rotating drums (36) have been widely used over many decades to assess airborne pathogen stability and have been used to investigate the airborne survival of SARS-CoV-2. More specifically, studies have examined the dependence of infectivity on time (20 min to 16 h), RH (40 to 70%), and the presence of UVC light with measurements in aerosols composed of cell culture media (Dulbecco's modified Eagle medium [DMEM] and minimal essential media [MEM]) and artificial saliva (13–16, 37). All studies concentrate on equilibrated particle sizes of ~5 μm (mass median aerodynamic diameter). A nebulizer is used to generate a cloud of aerosolized pathogen that is suspended by the rotation of the drum. The initial environmental conditions within the drum can be controlled by mixing the output of the nebulizer with a flow of humidity- and temperature-controlled air. However, operation with stable environmental conditions can be challenging; for example, as the droplets evaporate and equilibrate to the set humidity, the water they release can cause the humidity within the drum to increase [see for example the report of Smither et al. (14)]. In addition, dynamic changes in liquid water content within the freshly nebulized aerosol cloud do not replicate the very rapid changes that can accompany the extremely low concentrations of the exhaled aerosol. This precludes any study of short-term decreases in pathogen viability that may be critical to understanding close contact transmission and the immediate consequences of exhalation on microbe survival.

We have previously reported a unique approach to the study of infectious aerosol and the interplay between aerosol microphysics and pathogen survival, using complementary aerosol analysis techniques to assess the underlying mechanisms that govern the airborne longevity of pathogens (38, 39). The aerosol stability of viruses and bacteria is investigated using the CELEBS (controlled electrodynamic levitation and extraction of bioaerosols onto a substrate) technique (38–40). In CELEBS (*SI Appendix*, Fig. S1*B*), a small population (<20) of near-identical monodisperse droplets containing bacteria or viruses are trapped within an electric field, while a constant flow of air prevents the accumulation of released water around the droplets. Loading droplets into the CELEBS takes <0.1 s, and there is no physical loss of droplets over time. Thus, an assessment of the viability of suspended microbes within droplets can be made after periods of suspension varying between less than 5 s to many hours. These longevity measurements can then be contextualized with detailed measurements of the dynamic changes in the physicochemical properties of droplets generated the exact same way in an instrument referred to as the comparative kinetic-electrodynamic balance (CK-EDB) (38, 41–45). The CK-EDB uses the same piezoelectric droplet-on-demand dispensers as the CELEBS to generate droplets, with particles captured in the path of a laser within a flow of humidity and temperature-controlled air (*SI Appendix*, Fig. S1*C*). The elastic light scattering pattern can be used to infer the size and structure of these droplets within the same environmental conditions as those used in CELEBS.

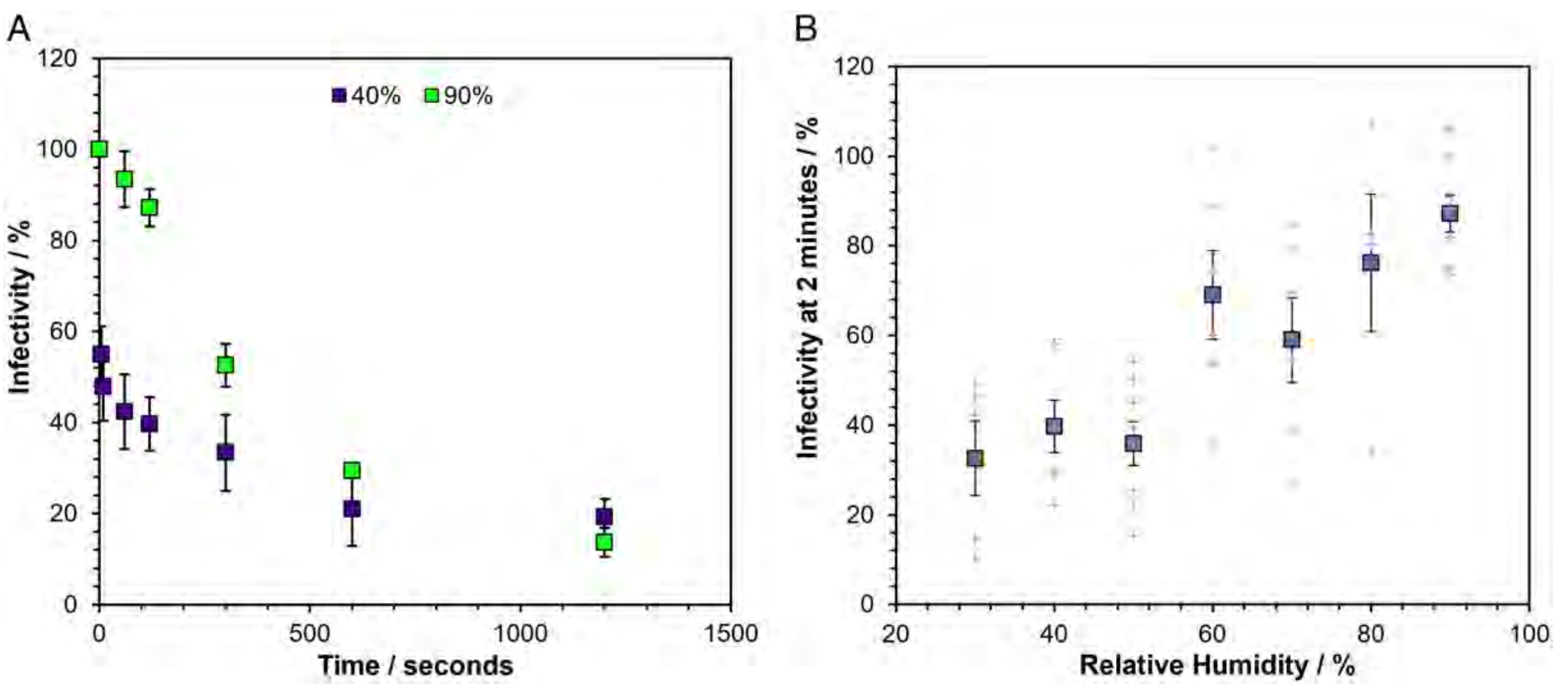
By coupling the time-sensitive measurements of the physicochemical properties of the droplets (CK-EDB) with the downstream biological effects (CELEBS) on the same timescale, the systematic exploration of hypotheses regarding the inactivation mechanisms of viruses and bacteria is possible. In this study, we apply this approach to the study of SARS-CoV-2 survival in studying the physicochemical changes that take place in the droplet and exploring how these changes impact the infectivity of the virus, we elucidate the effect of the airborne environment on SARS-CoV-2. This study provides insights into the potential influence of environmental conditions on COVID-19 transmission.

Results

The Airborne Infectivity of SARS-CoV-2 Declines over the First 20 min following Aerosolization.

The infectivity of SARS-CoV-2 contained in droplets of MEM with 2% vol/vol fetal bovine serum (MEM 2% FBS) was measured over the course of 20 min of levitation in CELEBS at both low (40%) and high (90%) RH (Fig. 1A). A decrease in infectivity (in this work, defined as the proportion of virus remaining able to induce cytopathic effect) at low RH occurs almost immediately, falling to an average of 54% within 5 s of generation. Interestingly, although the initial loss in infectivity at low RH is almost instant, the virus infectivity then remains more stable, only decreasing an average of 19% over the next 5 min. At high RH, the reduction in infectivity following aerosolization is more gradual with a steady loss of infectivity of 48% within the first 5 min. The decay in survival appears to plateau at both RHs after 10 min, and the difference between infectivity in aerosol particles suspended at the two RHs diminishes over time, until survival at the two RHs is indistinguishable after 20 min. Further research will be required to explore for how long the apparent plateau continues, but it is possible that this slowing down of the viral decay is responsible for the longer half-lives reported in previous Goldberg rotating drum studies (15). It is unlikely that the rapid initial decay in virus infectivity would be observable in a rotating drum due to the relatively long times required to load the drum.

Fig. 1.



The short-term airborne decay of SARS-CoV-2. Datapoints are the mean of several measurements (typically >4), and error bars show the standard error. Measurements were carried out at room temperature at 18 to 21°C. (A) The percentage infectivity of SARS-CoV-2 REMRQ0001 as a function of time levitated in CELEBS at 40% RH (purple) and 90% RH (green). (B) Curve showing the impact of RH on the percentage infectivity of SARS-CoV-2 REMRQ0001 after 2 min of levitation in CELEBS. The larger colored square points show the mean, with the error bars showing the standard error. Gray crosses show the results of individual measurements.

To more fully characterize the dependence of the infectivity of SARS-CoV-2 on RH, the RH was reported little dependence of the infectivity decay rate on RH within the uncertainty of the measurements (14, 16). However, we observe a clear relationship between the short-term viability of SARS-CoV-2 and RH (Fig. 1*B*). Between 30 and 50% RH, the infectivity typically declines within this short time frame to between 30% and 40% after 2 min of levitation. At RHs of 80% and above, the virus is far more stable, with infectivity rarely falling below 80% after 2 min. The residual infectivity between 60% and 70% RH is highly variable, sometimes falling to similar levels to those observed at the lower RHs and sometimes showing almost no decrease; we shall return to this variability in a later section.

The rapid decay in infectivity reported here, with an observed half-life of on the order of seconds to minutes, has not been reported previously. However, consistent with the majority of previous studies, these survival decays have been measured in virus culture directly and it should be remembered that the aerosol composition (MEM 2% FBS) is different from real exhaled respiratory fluids, including saliva, alveolar lung fluid, and other respiratory secretions. Thus, we now investigate the causative mechanisms driving the decay of SARS-CoV-2 in airborne MEM 2% FBS in order to better understand the relevance of these measurements to the transmission of SARS-CoV-2.

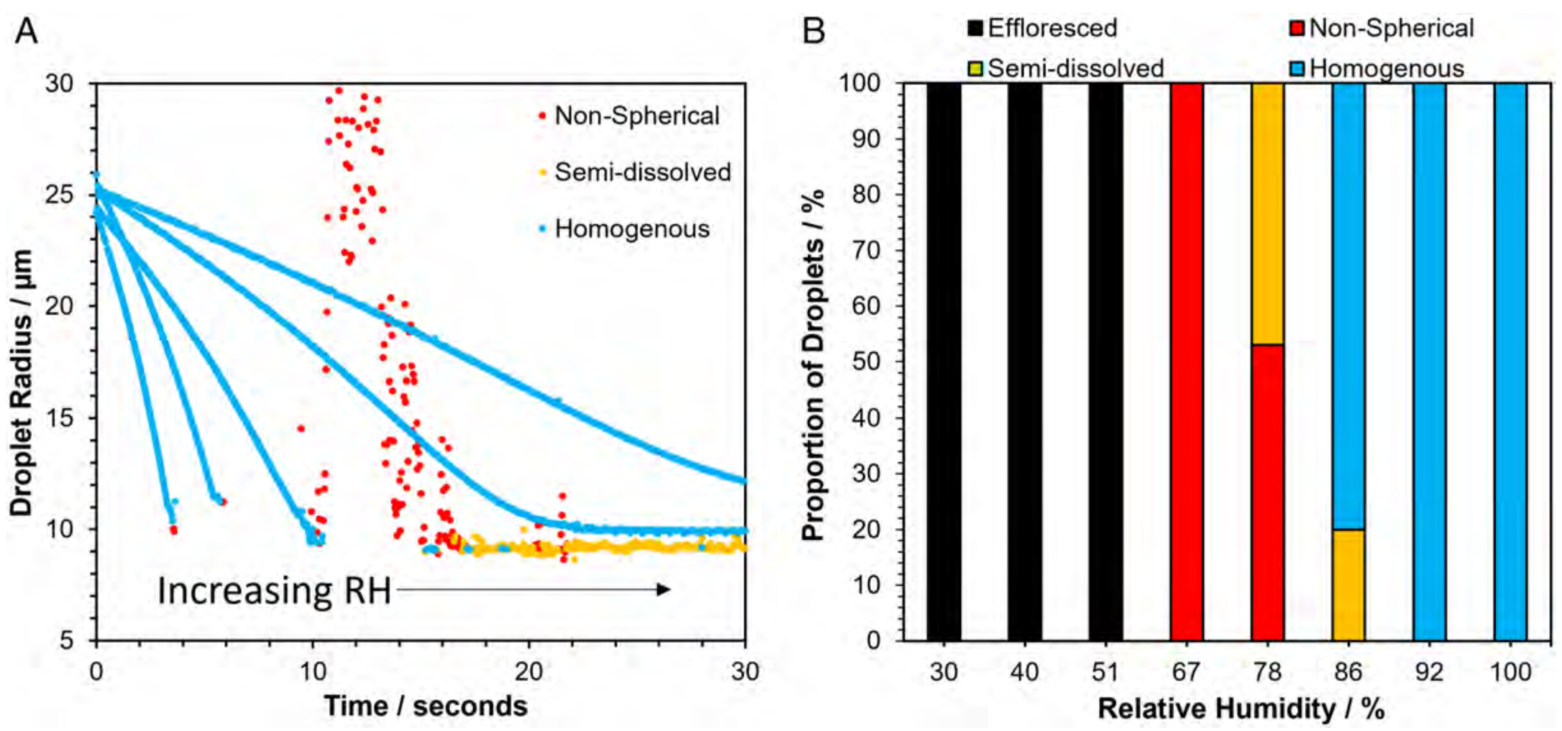
Airborne Droplets of MEM Show Complex Phase Behavior during Evaporation.

To provide insight into the underlying mechanisms that drive the observed airborne loss of SARS-CoV-2 infectivity, the microphysical changes (depicted in *SI Appendix*, Fig. S1*A*) taking place in the droplets hosting the virus were explored in real time and in situ using the CK-EDB with a time resolution of <100 ms (38, 41–45). For context, the phase changes that occur during the evaporation of aqueous sodium chloride at an RH below the efflorescence threshold are shown in *SI Appendix*, Fig. S2. When efflorescence occurs at low RH, the crystallization of the salt is exothermic, resulting in a transient increase in the droplet temperature and a concomitant increase in the evaporation rate. This increase in evaporation rate characteristic of efflorescence is best observed in changes in the intensity of the total light scattered by the particle. By comparison, Mie scattering calculations from the angularly resolved light scattering pattern can be used for precise estimation of the droplet size and can provide other insights into the physical transformations of the particle, such as the formation of numerous submicron crystals dispersed within the host liquid droplet and the point at which the particle ceases to be spherical (46).

For the viral longevity measurements in this study, the virus was suspended in MEM 2% FBS, which was the tissue culture medium used in the initial growth of the virus on Vero cells. The relatively low viral titers obtained with SARS-CoV-2 culture (, 47) prevented dilution into other solutions, constraining longevity experiments to the starting stock solution. We avoided concentrating the virus stocks using methods such as ultracentrifugation and tangential flow filtration to avoid any impact these processes might have on the stability of the virus, which could then introduce ambiguity into the interpretation of the longevity data. MEM is a complex solution containing a range of inorganic salts and organic components such as proteins, amino acids, and various sugars. The composition is made more complicated and uncertain through in MEM. For example, MEM contains 3.3 g/L of sodium, 0.2 g/L of potassium, and 1.6 g/L of bicarbonate. For human saliva, these concentrations range from 0.26 to 5 g/L for sodium (48), 0.1 to 0.7 g/L for potassium (48), and 0.5 to 2 g/L for bicarbonate (49), putting the concentrations in MEM within the expected ranges for saliva. It should be noted though that the composition of saliva can vary significantly from individual to individual, with sampling conditions, and over the course of a respiratory infection (50–54).

To better understand the response of aerosols, formed from the complex mixture of components typical of cell culture media and respiratory secretions, to the airborne environment, the drying kinetics of droplets containing MEM 2% FBS were studied using the CK-EDB. Evaporation curves for droplets of MEM 2% FBS levitated at a range of RHs are shown in Fig. 2*A*. From the evaporation rates reported here, it is possible to estimate that the change in droplet temperature driven by evaporative cooling will not exceed a transient reduction of 5.5 °C, which is unlikely to influence viral infectivity. At an RH of 51% and below, changes in the overall light scatter intensity typical of efflorescence were observed (*SI Appendix*, Fig. S3), with the droplets crystallizing in less than 5 s from generation. At a measurement RH of 67%, efflorescence was not observed, although the recorded Mie scattering profile indicates that the particles are no longer spherical, potentially forming inhomogeneous amorphous semisolid particles (Fig. 2*A*). Indeed, at 78% RH, variability in the outcome of the dynamics and phase transformation of the aerosol was observed; particles initially underwent a phase change (possibly with the formation of inclusions) that was sometimes reversible, reforming a homogenous spherical particle at a later time. At RHs of 85% and above, particles mostly remained homogenous aqueous spheres. The dependence of the apparent final particle structure on RH is summarized in Fig. 2*B*. At the extremes of RH, particles of consistent phase were formed following drying and equilibration, with crystalline or spherical homogenous solution droplets resulting at low and high RH, respectively. At intermediate RHs, variability in the physical state of the equilibrated particle was observed, mirroring the greater variability in the remaining infectivity of SARS-CoV-2 at 2 min across these RHs (Fig. 1*B*). We shall return to a fuller explanation of the phase behavior of the droplets at these intermediate RHs in a later section.

Fig. 2.



The microphysics of airborne MEM droplets. (A) Mie scatter evaporation profiles of MEM 2% FBS generated droplet, and red indicates a nonspherical particle (note that size estimates become inaccurate for nonspherical particles). (B) Proportion of particle morphologies formed by MEM 2% FBS at different RHs. The frequency of the formation of each particle type is shown for the RHs studied, with black indicating efflorescence, red indicating a nonspherical particle, yellow indicating a semi dissolved particle, and blue indicating an aqueous homogenous particle.

The relationships between the RH, the rate of evaporation, and the volume change during drying for aqueous MEM droplets are shown in *SI Appendix*, Fig. S4. The solute molarities increase from their initial values by around 10-fold when droplets evaporate into a gas phase at 92% RH and 25-fold at 78.2%, as reflected by the change in droplet radius and, thus, volume. Below this RH, inclusion formation (likely by some of the solute components crystallizing from solution) precludes an accurate estimation of the degree of supersaturation achieved within the remaining liquid phase. Although equilibration timescales are size dependent (smaller droplets would be expected to reach equilibrium much faster), the overall increase in solute concentration is size independent.

During equilibration to the ambient RH, the surface of an evaporating droplet can become enriched with larger solutes and suspended matter if the rate at which the surface is receding (κ, $m^2\ s^{-1}$) is faster than the rate of diffusional mixing (reflected in the diffusion constant, D_i, $m^2\ s^{-1}$) (55, 56). This competition is characterized by the Peclet number, Pe_i, for component i:

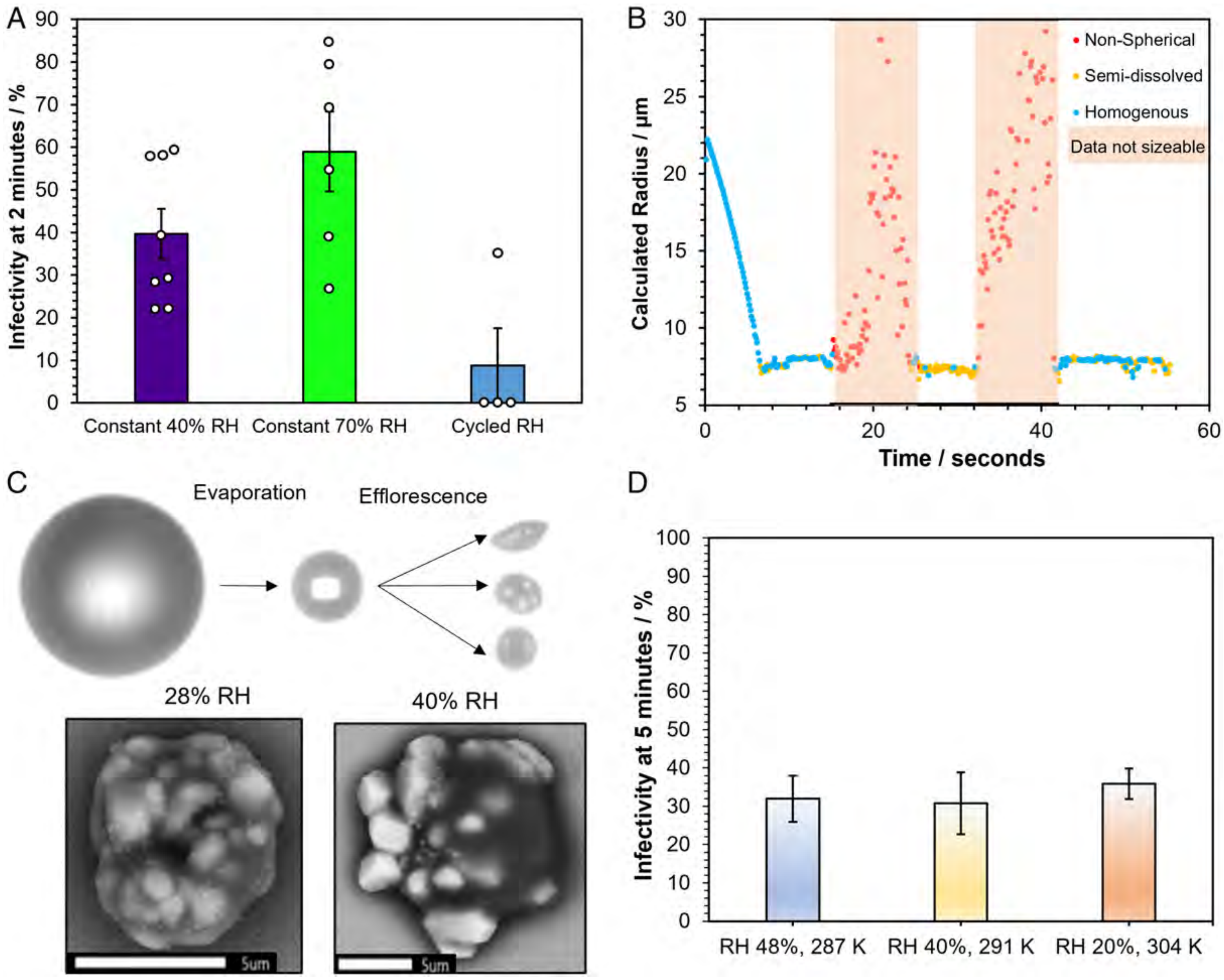
$$Pe_i = \frac{\kappa}{8D_i}. \quad [1]$$

By comparing the evaporation rates reported in Fig. 2A (and *SI Appendix*, Fig. S4) with the previously reported diffusion coefficient for a typical virus in water (57, 58), the Pe_i for SARS-CoV-2 in MEM 2% FBS can be estimated. In all cases and for all temperatures studied here, the initial Pe_i for SARS-CoV-2 at the starting droplet water activity can be assumed to be in the range 0.5 to 5, showing marginal surface enrichment at most (59). As the water content diminishes during evaporation, particularly when drying into low RH, the increasing solute concentrations may slow the diffusion of the virus and may lead to surface segregation, although we do not account for this here. Indeed, Pe_is for more highly diffusing solutes will be $\ll$1 and can be assumed to show only marginal surface enrichment at the lowest RHs and highest temperatures; for example, at a Pe_i of 0.2, drying aqueous sodium chloride droplets show a transient enrichment in surface salt concentration of ~20% above the droplet core concentration for similarly sized droplets (60).

Efflorescence Enhances the Loss of Infectivity in Aerosol at Low RH.

The loss of infectivity at low RHs appears to be consistent with observations of a change in phase state for the airborne droplet with a reproducible decrease in infectivity observed when efflorescence occurs. However, it remains unclear whether the efflorescence event itself impacts the infectivity of the virus. To confirm the correlation with phase behavior, the RH was cycled above (75% RH) and below (40% RH) the efflorescence threshold twice during a 2-min levitation (Fig. 3A). The infectivity for three out of the four levitations fell below the detection limit, indicating a >90% loss of infectivity. This loss of infectivity was far greater than during 2-min levitations where the RH was maintained at either a constant 40% RH, resulting in a single would occur, which resulted in an average infectivity of 59%. A more detailed account of this measurement can be seen in *SI Appendix*, Fig. S5, with infectivity measured before and after each efflorescence event.

Fig. 3.



The role of efflorescence in SARS-CoV-2 airborne loss of infectivity. (A) Comparison of the infectivity from Fig. 1B after 2-min levitations at constant 40% RH (purple bar) and 70% RH (green bar) with levitations where the RH has been cycled between 75 and 40% RH in one levitation (blue bar labelled cycled RH). The bars show the average % infectivity with error bars showing the standard error; the white circles show the % infectivity from the individual measurements. (B) CK-EDB measurements showing the phase behavior of levitated MEM droplets as the RH is cycled between 75 and 40%. RH is initially set at 75%, lowered to 40% at 14 s, raised to 75% at 24 s, lowered to 40% at 32 s, and finally raised to 75% at 41 s. Structural information about the droplet is denoted by the color of the data points as per Fig. 2A. (C) Images showing the changes in particle morphology that take place while MEM 2% FBS is airborne. The Top images are from the falling droplet column and showing the initial droplet generated by the dispenser on the Left, the droplet after 1.6 s of evaporation at 28% RH in the Center, and three different particles after they have undergone phase change on the Right. The Bottom shows two SEM images of droplets effloresced at 28% RH (Left) and 40% RH (Right). The scale bar is 5 µm long. (D) Percent Infectivity of SARS-CoV-2 (REMRQ0001) measured after levitation for 5 min at three different temperatures and RHs. Bars show the mean of five measurements with error bars showing the standard error.

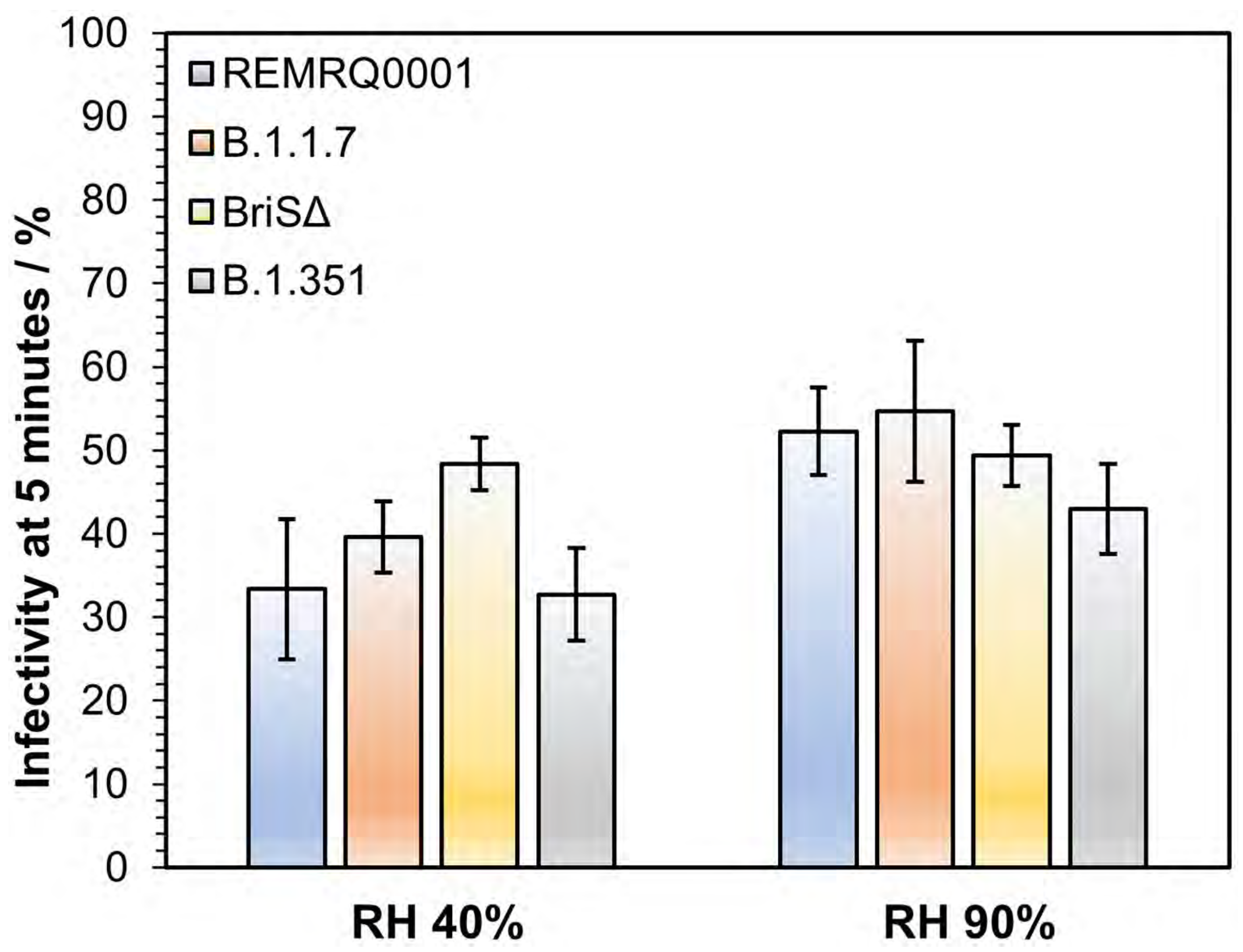
A CK-EDB measurement of a levitated MEM droplet, in which the RH was cycled between the same values as in the CELEBS survival measurement, is shown in Fig. 3*B*. These data confirm that a cycle of evaporation and efflorescence, redissolution, efflorescence, and redissolution occurs as the RH is cycled between 75, 45, 75, 45, and 75%. As in previous CK-EDB measurements of MEM, the particles were predominantly aqueous at the higher RH but with some solid inclusion content. For the cycled RH measurements in Fig. 3*A* (and *SI Appendix*, Fig. S5), the droplets were deposited at high RH ensuring they were in a dissolved solution phase on sampling. This indicates that the efflorescence-driven loss in infectivity did not arise from a physical sequestration of the virus in nondissolving salt crystals but reflected an infectivity

The consistency in the infectivity reduction induced on efflorescence, even when multiple efflorescence events take place in the same droplet population, demonstrates that there is no inherent property of individual virions that protects them from the crystallization event. The factor that determines whether an individual virion retains infectivity postefflorescence must instead depend on the local conditions in the vicinity of each individual virion. It was possible to image the evaporation and efflorescence of airborne MEM 2% FBS at 40% RH using a falling droplet column (Fig. 3*C*). In flight, there is considerable variability in the morphology of the MEM particle immediately after crystallization, which is apparent also in the dried MEM 2% FBS droplets collected and imaged with scanning electron microscopy (SEM) (also Fig. 3*C*). These images of the effloresced media reveal that some of the particle is crystalline while some is not. Thus, it is possible that whether or not the virus is in the crystallized fraction of a particle determines its stability following efflorescence. Interestingly, the salt crystals formed are smaller and more numerous as the RH is lowered (*SI Appendix*, Fig. S6), consistent with previous work that has shown that there is a greater propensity for nucleation when droplets are dried at higher rates leading to more nucleation events and smaller final crystals forming a larger composite particle (61).

Changing the temperature of the air around the droplets while maintaining the RH below the efflorescence point does not significantly impact the observed loss of infectivity (Fig. 3*D*). This provides further evidence that the mechanism driving the loss of infectivity is a physical process such as efflorescence rather than a thermodynamically driven chemical process, such as the rate at which the solute concentrations increase during the evaporation process. The temperature change marginally alters the timepoint at which efflorescence occurs, but the droplets all effloresce within 25 s for all three temperatures reported here, well before the 5-min point at which droplets were sampled and infectivity measured.

Airborne Longevity Appears Similar for Different SARS-CoV-2 Variants.

Most measurements in this study were carried out using SARS-CoV-2 isolated early in the pandemic (SARS-CoV-2/human/Liverpool/REMRQ0001/2020 [REMRQ0001]). We compared the data from this variant with CELEBS measurements with three others to determine if changes in the structure of SARS-CoV-2 could have an impact on its response to the airborne environment. At 5 min, a decrease in infectivity was observed both at 40 and 90% RH for REMRQ0001, providing the optimum time to resolve any differences in aerostability. At both 40 and 90% RH, no significant difference was observed between REMRQ0001, B.1.1.7 (the Alpha variant), a mutant of the SARS-CoV-2 isolate England/2/2020 that has the same Spike protein sequence as REMRQ0001 except that the furin cleavage site is deleted (designated BriSΔ) (62, 63), and B.1.351 (the Beta variant) (Fig. 4). It is possible that if this comparison is expanded to cover a broader range of times and conditions, differences between these variants will be observable. However, based on these measurements, it does not appear that the deletion in BriSΔ, or the array of mutations throughout B.1.1.7 and B.1.351, result in readily observable changes in the airborne longevity of the virus when compared with REMRQ0001. There is no reason to believe that the measurements in this study using REMRQ0001 are not representative of later-circulating variants of the virus.



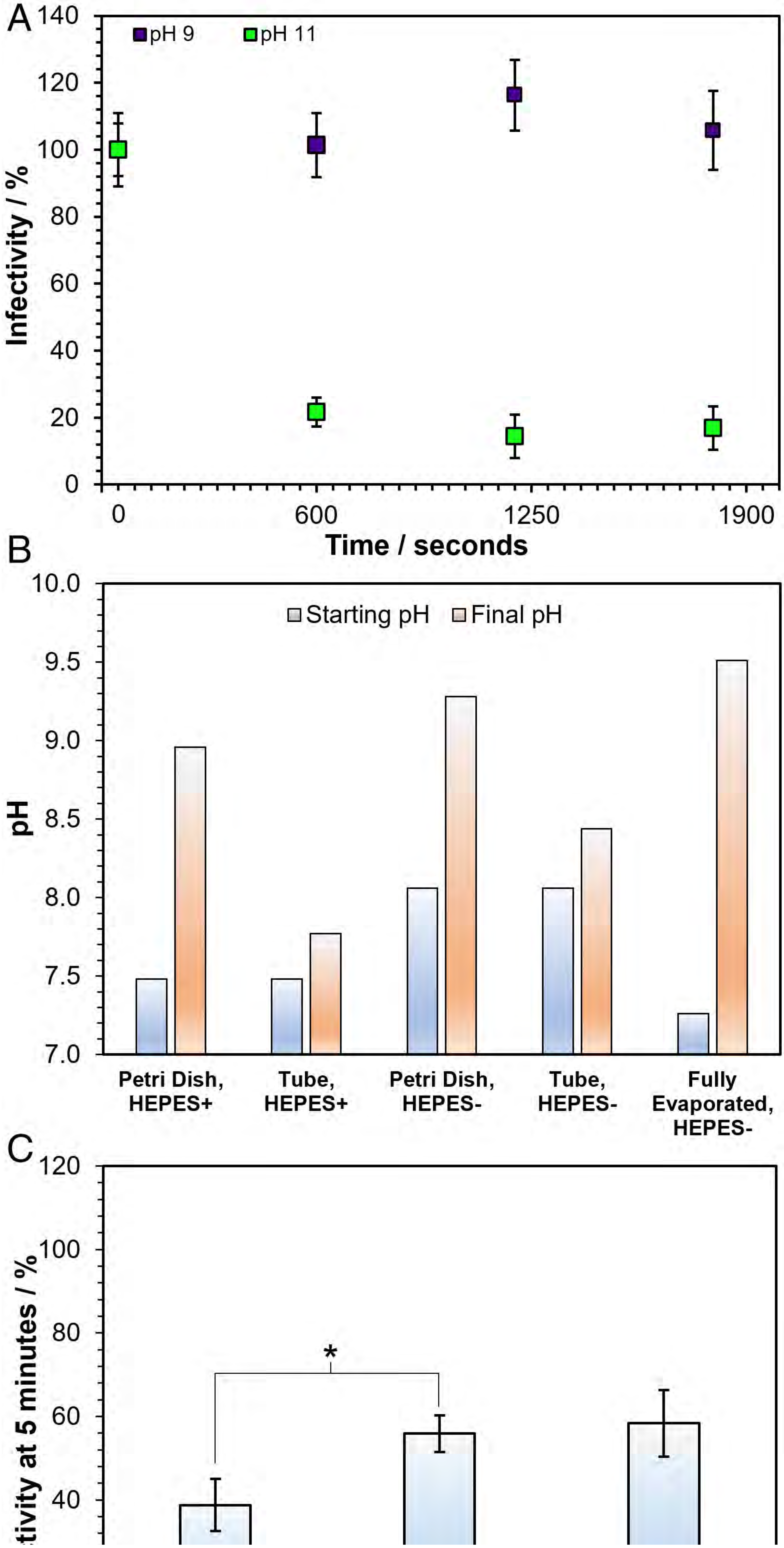
The influence of SARS-CoV-2 strain on airborne stability. Infectivity of four different variants of SARS-CoV-2 (blue bars for REMRQ0001, orange bars for B.1.1.7, yellow bars for BriSΔ, gray bars for B.1.351). Infectivity is compared after 5 min of levitation at 40 and 90% RH, 18°C. At 40% RH, N = 5 for REMRQ0001, N = 8 for B.1.1.7, N = 4 for BriSΔ, and N = 10 for B.1.351. At 90% RH, N = 7 for REMRQ0001, N = 11 for B.1.1.7, N = 7 for BriSΔ, and N = 13 for B.1.351. Bars show the mean; error bars show the standard error.

Droplet pH, Carbon Dioxide Partitioning, and the Rate of the Loss of Infectivity at High RH.

Replicating the physicochemical conditions that exist in the aerosol phase through bulk phase measurements is not possible except for conditions equivalent to the very highest RH. Under typical ambient conditions in the range 20 to 60% RH, solute concentrations are heavily supersaturated in equilibrated aerosols. In addition, the high surface-to-volume ratio in aerosol cannot be replicated, diminishing the potentially significant role of surface processes at the gas–liquid boundary and ignoring the influence of the rapid microphysical dynamics including the coupling of heat and mass transfer. However, certain elements of the airborne change in droplet composition can be replicated in the bulk phase by simulating the concentrations of various components in the droplet at concentrations equivalent to equilibration at high RH. The steady concentrations of solutes when the aerosol is equilibrated at 90% RH are approximately a factor of 10 higher than in the starting droplets at a water activity of 0.995 (*SI Appendix*, Fig. S4), which is a concentration that can be replicated in the bulk. However, exposing SARS-CoV-2 to a 10-fold higher MEM concentration did not result in any observable loss of viral infectivity within 20 min (*SI Appendix*, Fig. S7). This suggests that this increased concentration of culture medium solutes is unable to account for the rate of the loss of infectivity in the aerosol phase.

In addition to changes in the concentration of solutes that occur on equilibration to the ambient RH, it is possible that the pH of aerosol droplets containing MEM can change rapidly. Although the sensitivity of SARS-CoV-2 infectivity both to high and to low pH has been reported infectivity with the change in pH on a similar timescale, SARS-CoV-2 was suspended in tissue culture media at varying pH for 20 min, before dilution into neutral media and plating onto cells for infectivity quantification (*SI Appendix*, Fig. S8). Although no significant decrease in infectivity was observed after 20 min at pH ranging from 5.6 to 9, the average infectivity was diminished considerably above pH 9.5 so that only 7% of the virus remained infectious after 20 min at pH 11.2. The effect of pH was further explored by suspending SARS-CoV-2 in solutions of pH 9 and 11 for 30 min (Fig. 5*A*), with neutralization and quantification being carried out every 10 min. In this experiment, the virus remained stable in the pH 9 solution, but at pH 11, the infectivity fell to a similar level as in the 90% RH levitations, also seeming to plateau once 90% of the virus had been deactivated. These bulk phase studies suggest that the pH would have to increase to around 11 to explain the deactivation observed in the aerosol phase at 90% RH after 20 min. We therefore considered whether such a high pH could be present in the aerosol droplets at high RH conditions.

Fig. 5.


A
pH 9
pH 11
Infectivity / %
140
120
100
80
60
40
20
0
0
600
1250
1900
Time / seconds
B
Starting pH
Final pH
pH
10.0
9.5
9.0
8.5
8.0
7.5
7.0
Petri Dish, HEPES+
Tube, HEPES+
Petri Dish, HEPES-
Tube, HEPES-
Fully Evaporated, HEPES-
C
tivity at 5 minutes / %
120
100
80
60
40
*

*The role of pH in SARS-CoV-2 airborne loss of infectivity. (A) Bulk % infectivity of SARS-CoV-2 (B.1.351) after a 30-min incubation in DMEM 2% FBS altered to either pH 9 (purple datapoints) or 11 (green datapoints), diluted back into neutral media and plated onto cells every 10 min. Datapoints are the mean of three measurements for pH 11 and five measurements for pH 9, with error bars showing the standard error. (B) The pH changes that tissue culture media (in this case DMEM) underwent when exposed to open air. DMEM was left in an open petri dish or 50-mL tube both with and without HEPES and the initial pH (blue bar) and the pH after 20 min (orange bar) was measured. The same measurement was carried out using thin layers of DMEM that were allowed to evaporate to 10% of their original volume over the course of 24 h (labelled fully evaporated). (C) The 5-min levitations were carried out with SARS-CoV-2 (B.1.351) at 90% RH with varying CO_2 concentrations mixed into the gas flow. Bars show the mean of 15 measurements for 0% CO_2, 16 measurements for 5% CO_2, and 6 measurements for 10% CO_2 with the error bars showing the standard error. *P < 0.03 between 0% and 5% CO_2.*

The equilibration between dissolved bicarbonate anions and gaseous CO_2 is particularly important to consider for many respiratory secretions as well as the tissue culture media often used in experimental studies of airborne viral survival (65). A set of coupled equilibria is established with a bicarbonate concentration that responds to changes in the level of gas phase CO_2, typically at an elevated gas phase concentration for cell culture and 50,000 ppmv in exhaled air, specifically,

$$\mathrm{CO_{2(g)}} + \mathrm{H_2O_{(l)}} \rightleftharpoons \mathrm{CO_2.H_2O_{(l)}},$$

$$\mathrm{CO_2.H_2O_{(l)}} \rightleftharpoons \mathrm{HCO_3}^-{}_{\mathrm{(aq)}} + \mathrm{H}^+{}_{\mathrm{(aq)}},$$

$$\mathrm{HCO_3}^-{}_{\mathrm{(aq)}} \rightleftharpoons \mathrm{H}^+{}_{\mathrm{(aq)}} + \mathrm{CO_3}^{2-}{}_{\mathrm{(aq)}}.$$

Cell culture media typically contain 20 to 50 mM bicarbonate (50, 51) to buffer the aqueous solution at a pH ~7.4 when gas phase CO_2 is at an elevated concentration, 4 to 5% by volume. For bicarbonate in exhaled salivary aerosol (66), the lower gas phase CO_2 concentration in the environment after exhalation (0.04%) results in a change in the equilibrium concentration of bicarbonate in the aerosol by shifting the equilibria toward $CO_2{\cdot}H_2O_{(l)}$ and eventually $CO_{2(g)}$, leading to particle-to-gas phase partitioning of CO_2. Indeed, for laboratory studies of airborne survival, the aerosol is often generated in an environment devoid of CO_2, as is the case here, leading to irreversible evaporation of dissolved CO_2 into the gas phase. As evaporation occurs, the available H^+ concentration diminishes, and the pH can be expected to rise.

As a bulk analog experiment, bulk tissue culture medium was exposed to ambient air for an extended time period (Fig. 5*B*). After 20 min in an open petri dish, the pH of DMEM (formulated with the same concentration of bicarbonate as the MEM used in the levitations) rises from 8 to 9.3. Adding HEPES reduces the initial pH of the medium, but the pH was still found to increase significantly after exposure to air, increasing from 7.4 to 9. When the DMEM solution was kept in an open 50-mL tube rather than a petri dish, decreasing the surface area for interaction, the rate of the rise in pH also decreased. A final experiment was carried out in which thin layers of DMEM were placed in petri dishes and allowed to evaporate to 10% of the starting volume over the course of 24 h, replicating both the CO_2 and H_2O equilibration that takes place in airborne droplets. The combination of CO_2 equilibration and volume loss resulted in the greatest pH rise, increasing from 7.25 to 9.5. The particle-gas partitioning can be expected to occur more rapidly than in any of these bulk examples because of facile transport across a droplet surface decrease in the concentration of dissolved bicarbonate through the irreversible loss of CO_2 following their aerosolization will cause droplets to become more alkaline.

Sodium bicarbonate accounts for ~20% of the solute mass in MEM with ~65% sodium chloride by mass. With the loss of bicarbonate from MEM solution droplets, through irreversible evaporation of CO_2, the reduction in solute mass should lead to a reduction in the wet equilibrated size of the droplet with less solute able to sustain less water in the condensed phase. Indeed, it was possible to observe a long-time slow loss of CO_2 and dissolved solute using the CK-EDB for MEM solution droplets (*SI Appendix*, Fig. S9) and for mixtures of NaCl and $NaHCO_3$ (*SI Appendix*, Fig. S10), the two dominant salts. Droplets of both MEM and sodium bicarbonate continue to decrease in size for longer than the time required for the water activity to equilibrate to the gas phase RH. Indeed, the vapor pressures inferred from the data in *SI Appendix*, Fig. S10 with varying RH (0.0092, 0.014, and 0.052 Pa at 60, 75, and 90% RH) are consistent with calculations using the E-AIM model (www.aim.env.uea.ac.uk/aim/aim.php) (67) for the vapor pressure of CO_2 above supersaturated carbonate solutions at the same water activities (~0.01 Pa and increasing with increase in RH). By contrast, the vapor pressure of CO_2 from bicarbonate solutions at the same RHs are considerably higher (~100 kPa) and the particle-gas partitioning can be expected to occur extremely rapidly in ≪1 s following aerosol droplet exhalation or generation, a process that can be expected to already be completed by the time the aerosol droplets are captured by CELEBS or the CK-EDB.

During the evaporation of water, as the moisture content of the aerosol equilibrates, the solutes surpass solubility limits for various salts. The initial water activity of the starting droplets can be estimated as 0.9952 by considering the dominant ionic species alone (Na^+, Ca^{2+}, Cl^-, and HCO_3^-) using the E-AIM model (67). Calcium carbonate is particularly insoluble and becomes supersaturated from very early on in the evaporation process, successively followed by other binary and mixed salts, specifically $CaNa_2(CO_3)_2 0.5H_2O(s)$, $Na_2Ca(CO_3)_2 0.2H_2O(s)$, $NaHCO_3(s)$, and finally NaCl(s) as water activity decreases. The droplet becomes saturated with respect to the first two salts above a water activity of 0.9, sodium bicarbonate at ~0.9, and NaCl below 0.8. Indeed, we observe the precipitation of salts during the droplet equilibration process as the water activity transitions through to the final equilibrated value, with significant supersaturation required for each before crystallization occurs (Fig. 2*B*). Until the crystallization of NaCl(s), which only occurs at the very lowest RHs of 50% and below, a partially deliquesced particle containing crystalline inclusions along with an aqueous phase leads to considerable variability in the remaining infectivity of the virus (Fig. 1*B*).

It can be hypothesized that increasing the concentration of $CO_{2(g)}$ around the droplet would reduce the irreversible loss of bicarbonate from the droplet and could mitigate a pH-driven loss of infectivity. $CO_{2(g)}$ was added to the airflow during CELEBS levitations at high RH and the infectivity of SARS-CoV-2 measured after 5 min (Fig. 5*C*). The elevation to a gas phase concentration of 5% by volume CO_2 (equivalent to 50,000 ppmv) around the droplet at 90% RH results in a small but significant increase in the remaining infectivity of SARS-CoV-2 after 5 min when compared with ambient $CO_{2(g)}$ (0.04%). Increasing the steady $CO_{2(g)}$ concentration around the trapped droplet cannot mitigate the loss of infectivity from pH changes during the initial droplet may have other physicochemical effects on the droplet in addition to decreasing the pH, this measurement provides further evidence that increased droplet pH is at least partly responsible for the observed falls in viral infectivity at high RH.

The influence of pH on infectivity is expected to be relevant in respiratory aerosols as the underlying physicochemical properties of exhaled aerosol (saliva) and MEM are similar, and numerous studies have demonstrated that exhaled breath condensate is alkaline (68–71). This dynamic is in stark contrast to environmental aerosols such as sea spray where, following generation, the pH of the sea spray droplets become more acidic through the uptake of acidic gases such as HCl and SO_x (72). Exhaled aerosol is generated in an environment with an extremely high concentration of an acidic gas (4 to 5% by volume CO_2) that can only be reduced once exhaled. This contrast in pH behavior following generation is clear when comparing studies of collected sea spray pH (72, 73) with those of collected exhaled breath condensate (69–71, 74). In short, while the vast majority of ambient aerosol may be acidic, exhaled aerosol can be expected to be alkaline. The pH of exhaled and model respiratory aerosols is an area in need of further study, with a need for measurements across a broad range of timescales, droplet compositions (saliva, sputum, MEM, DMEM), and environmental conditions (RH, [$CO_{2(g)}$]).

Comparison with Rotating Drum Studies of SARS-CoV-2.

A motivation of our combined approach using CELEBS and CK-EDB is to identify the fundamental physicochemical parameters that dictate viral infectivity in the aerosol phase, progressing beyond general associations such as those between RH and infectivity, and to address the more challenging and informative questions allowing the identification of mechanistic causation rather than just correlation. By taking this approach, it has been shown that SARS-CoV-2 undergoes a rapid deactivation in the first few minutes following droplet generation and that this deactivation occurs on efflorescence at low RH and possibly by an increase in droplet pH at high RH resulting from irreversible partitioning of CO_2 into the gas phase. There have been several reports of the aerostability of SARS-CoV-2 using the Goldberg rotating drum (14–16). However, given the relatively short timescale over which the majority of this deactivation occurs, which drum experiments cannot observe, and the importance of the physicochemical properties of the droplet in driving the deactivation, it is unsurprising that data collected from rotating drums report a longer lifetime for the virus in the aerosol phase.

Rotating drums have a poorly defined time-zero, meaning that the benchmark infectivity to which later time data are compared is poorly defined. The number of droplets suspended, their initial size, and viral units per droplet are both variable and uncontrolled and thus must be inferred offline. RH profiles, while they appear to be commonly collected in rotating drum experiments, are rarely reported in their entirety, with many drum studies only reporting a single RH value for each measurement (15). The location of the RH probe within the experiment, and whether the value is taken at a particular time or is an average across their experiment, is not always reported. Regardless, the RH recorded by a probe is likely unrelated to the RH trajectory that an aerosol droplet experiences as it passes from the nebulization value that would be typical of the very low respiratory aerosol concentrations actually generated (21). These uncertainties may make the influence of processes such as efflorescence on infectivity challenging to infer.

Comparisons of the time dependence and precision of the CELEBS measurements with those from rotating drum studies are reported in *SI Appendix*, Figs. S11 and S12. The time-resolution of the drum measurements make the initial decrease in infectivity challenging to identify. Indeed, the times of the indicated points (*SI Appendix*, Fig. S11) should not be taken as the time-resolution as discussed above. In addition, the average relative SD (RSD) from the CELEBS measurements is 0.37 (*SI Appendix*, Fig. S12), compared with 0.66 from van Doremalen et al. and 1.03 from Smither et al. (14) Two further papers do not report sufficient information to estimate RSDs (15, 16). The smaller RSD from the CELEBS is likely the result of the more stable environmental conditions, a more reproducible monodisperse droplet generation process, and improved methodology for viral infectivity quantification (39). Furthermore, CELEBS experiments are more straightforward to perform, allowing for more repeat measurements for each condition and leading to a high degree of confidence in the mean percentage infectivity values reported.

The nebulization of bicarbonate-buffered solutions into a confined volume results in the elevation of the CO_2 gas concentration (*SI Appendix*, Fig. S13). The magnitude of this elevation is dependent on many variables, including the pH of the nebulized solution, the nebulization time, and the drum volume. A survey of the literature failed to identify a single article where the CO_2 levels within a rotating drum was reported. As reported (Fig. 5*C*), CO_2 in the gas phase reduces the degradation of the virus likely by limiting the rise in droplet pH. CO_2 cannot be removed selectively during a rotating drum study, and the conditions likely support greater SARS-CoV-2 longevity. Accumulation of CO_2 is not an issue in CELEBS due to the constant flow of compositionally controlled air being maintained over the trapped droplets. In addition to potential issues with the pH of the airborne droplets in the rotating drum, it is also possible that the pH of the solution within the nebulizer may increase during the nebulization process (*SI Appendix*, Fig. S14), directly affecting the viral infectivity prior to nebulization (Fig. 5*A*).

Discussion

A combination of measurement strategies to probe the changes in airborne viral infectivity with time and the physicochemical transformation dynamics of the host aerosol is crucial to improve our understanding of the influence of environmental (such as RH, temperature) and biological (such as spike protein mutations) parameters on the transmission of viruses in the aerosol phase. While the current consensus is that the half-life of SARS-CoV-2 in the aerosol phase is between 1 and 2 h, if not longer, we report an initial rapid decline in infectivity within a few seconds to minutes of aerosol generation. Under all conditions measured, the majority of SARS-CoV-2 is inactivated within 10 min of aerosolization. Further research is required to determine for how long the remaining fraction persists, how this may depend on the viral load in the aerosol, and the influence of chemical composition. The high-time resolution infectivity measurements reported here are uniquely accessible to the CELEBS technology and can only same characteristics of real respiratory secretions, particularly the high concentration of inorganic ions that dominate the phase behavior and water content of the aerosol, along with bicarbonate ions that partition CO_2 into the gas phase on aerosolization. In addition, the initial water activity of the aerosol is consistent with the high RH of the respiratory tract, and the aerosol generation process generates isolated droplets that must respond rapidly to the surrounding environmental conditions, which is typical of the very low concentrations of aerosol exhaled in infected individuals.

The aerostability data reported here are consistent with a view that the risk of SARS-CoV-2 transmission is greatest closer to the source of infection. Often, the assumption is that short distance transmission is caused by large droplets that fall to the ground more quickly and therefore do not travel as far. The rapid loss of infectivity demonstrated in these measurements provides an alternative explanation for a short transmission distance, with rapid airborne losses of viral infectivity possibly making transmission decreasingly likely as distance from the particle source is increased, even if the particles that contain the virus are small and able to travel long distances. This loss in infectivity is compounded by the considerable dilution in aerosol concentration that results following exhalation and transport beyond the short range. However, the rapid loss of infectivity must also be considered in combination with the large variability in aerosol emission rate between individuals [up to a factor of 10^3 between individuals when breathing (75)] and viral titer in the exhaled aerosol [which could be as much as 10^4 if variations in sampled saliva are indicative (76)].

We do not observe the characteristic "V-shape" relationship between RH and virus stability, where maximum virus loss occurs around RH = 50%. Rather, the largest loss of infectivity was observed at the lowest RHs. Previously, Goldberg drum studies have not identified a strong dependence for SARS-CoV-2 survival on RH (14). However, following the initial loss of infectivity, the virus within the now dry particle appears to be somewhat stable when compared with the higher RH. Thus, if the initial rapid decrease in infectivity is not accounted for when reporting RH stability data, a V-shape relationship may be identifiable. However, not accounting for changes in viral infectivity that take place immediately after particle generation prevents the accurate coupling of airborne stability measurements with measurements of initial virus shedding, limiting the value of the V-shape relationship.

The rapid loss of SARS-CoV-2 infectivity through droplet efflorescence at an RH of <45% suggests that dry air may help to limit overall exposure. However, investigation of the impact that lowering RH has on particle transport in the exhalation jet is required to confirm this. The large impact of efflorescence on SARS-CoV-2 infectivity indicates that measuring the impact of environmental conditions on phase change in respiratory secretion aerosols may provide useful insights into COVID-19 transmission. Further research is needed to confirm with more certainty the degree to which pH is involved in the airborne loss of SARS-CoV-2 infectivity at high RH and to determine the exact mechanism by which the pH rise is deactivating the virus. The importance of elucidating of the role of pH in the survival of SARS-CoV-2 in the aerosol phase cannot be understated. A literature survey found no manuscripts indicating that the alkaline nature of exhaled aerosol may affect viral infectivity. Contrarily, it has been reported

Elevation of CO_2 levels within a room is taken as a clear sign of occupancy and poor ventilation. There has been increasing discussion surrounding the use of CO_2 monitors as a means of determining the relative risk of COVID-19 transmission in various settings. The data from this study give further credence to this approach. Not only is elevated CO_2 an indication of a densely occupied, poorly ventilated space but it could also be indicative of an environment in which SARS-CoV-2 is more stable in the air. The precise elevation in CO_2 required for an observable increase in SARS-CoV-2 transmissibility is unknown and requires further investigation (5% CO_2 is not a concentration reached in typical indoor environments), but it is possible that this is an additional risk presented by poorly ventilated, densely occupied settings. If so, CO_2 monitors may present an immensely valuable means of assessing the relative risk of different indoor environments. Additionally, the apparent role of pH elevation in the deactivation of airborne virus suggests a currently unexplored role of condensable acid vapors, such as nitric acid (78, 79), in the role of infectivity. It is possible that the condensation of acidic components into exhaled aerosol may help to neutralize the initial rapid pH increase, lowering the pH and increasing the airborne stability of the virus.

The approach taken here has clearly demonstrated the value of a combined approach that considers both the aerosol microphysics and biological processes in tandem and on the same timescale, demonstrating that underlying parameters that drive SARS-CoV-2 inactivation in the aerosol phase are particle phase and pH. In further research, we intend to explore these processes over an even wider range of times, conditions, and virus variants. There also remain unanswered questions as to exactly how phase change and high pH deactivate the virus. Do these processes rupture the viral envelope or impart an irreversible modification to the spike protein? Is the effect of pH the result of direct deprotonation of viral molecules or is it an indirect effect caused by alterations to the solubility of other components within the droplet? Answering such questions would provide key insights into the physicochemical and biomolecular processes governing SARS-CoV-2 transmission and airborne pathogen transmission more broadly. It is only by pushing the limits of aerobiology to this deeper level that we can hope to understand how best to prevent the airborne spread of disease.

Materials and Methods

Details of virus strains and methodologies for virus and cell culture, viral infectivity quantification, bulk stability measurements, CK-EDB measurements, and falling droplet column measurements can be found in *SI Appendix, Extended Materials and Methods*.

Generation and Trapping of Droplets.

The reservoir of a droplet-on-demand dispenser (MicroFab) is filled with MEM 2% FBS. The application of a square waveform to the piezoelectric crystal results in a compression wave that passes through the dispenser's orifice and initiates the formation of a jet that forms droplets of uniform size with each pulse. A direct current voltage is applied to an induction electrode, positioned 2 to 3 mm from the dispenser tip, which leads to an ion imbalance in the jet, resulting in a droplet with a net charge (~5 fC). Using the Gouy-Chapman model (80), a salt containing droplets with this level of net charge can be predicted to have an electric field an electric field strength of 3 V/m. The presence of this net charge interacting with the electrodynamic field of the CELEBS/CK-EDB leads to confinement of the droplet within the null field point.

CELEBS Airborne Longevity Measurements.

The environmental conditions were set by adjusting the Peltier voltage and polarity to set the temperature and the ratio of dry to wet air to set the humidity. SARS-CoV-2 suspension is drawn into a 1-mL syringe which is then attached to the instrument and used to feed the virus solution to the droplet dispenser via a remotely operated motor. Droplets are then generated and trapped as described above. Once the desired time is reached, an isolation plate is retracted causing the electric field to be set to zero; then, the droplets are pulled down into a plate containing 5 to 10 mL of DMEM 2% FBS so that the remaining virus can be quantified (*SI Appendix, Extended Materials and Methods*). For each measurement, two levitations are carried out. First, a short levitation of <5 s at 90% RH was used to measure the initial infectious unit per droplet number, and then a second levitation was used for which the droplets are kept in the trap for the conditions and length of time being investigated. Infectious units per droplet are normalized to the average of the short, high humidity levitations from that experiment, such that the levitation data can be presented as percentage infectivity.

Data Availability

The txt file data has been deposited in data.bris, the University of Bristol Research Data repository (81).

Acknowledgments

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Supporting Information

Appendix 01 (PDF)

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air, mixture of gases comprising the Earth's atmosphere. The mixture contains a group of gases of nearly constant concentrations and a group with concentrations that are variable in both space and time. The atmospheric gases of steady concentration (and their proportions in percentage by volume) are as follows:

nitrogen (N_2)	78.084
oxygen (O_2)	20.946
argon (Ar)	0.934
neon (Ne)	0.0018
helium (He)	0.000524
methane (CH_4)	0.0002
krypton (Kr)	0.000114
hydrogen (H_2)	0.00005
nitrous oxide (N_2O)	0.00005
xenon (Xe)	0.0000087

The uniformity of composition is maintained by mixing associated with atmospheric motions; but, above a height of about 90 km (55 miles), diffusional processes become more important than mixing, and the lighter gases (hydrogen and helium, in particular) are more abundant above that level.

Britannica Quiz

Wind and Air: Fact or Fiction?

Of the gases present in variable concentrations, water vapour, ozone, carbon dioxide, sulfur dioxide, and nitrogen dioxide are of principal importance. The typical concentration ranges of these gases (in percentage by volume) are as follows:

water vapour (H_2O)	0 to 7
carbon dioxide (CO_2)	0.01 to 0.1 (average about 0.032)
ozone (O_3)	0 to 0.01
sulfur dioxide (SO_2)	0 to 0.0001
nitrogen dioxide (NO_2)	0 to 0.000002

Although present in relatively small amounts, these variable constituents may be very important for maintaining life on Earth's surface. Water vapour is the source for all forms of precipitation and is an important absorber and emitter of infrared radiation. Carbon dioxide, besides being involved in the process of photosynthesis, is also an important absorber and emitter of infrared radiation. Ozone, which is present mainly in the atmospheric region 10 to 50 km (6 to 30 miles) above the Earth's surface, is an effective absorber of ultraviolet radiation from the Sun and effectively shields the Earth from all radiation of wavelengths less than 3,000 angstroms.

ozone layer

atmospheric science

Alternate titles: ozonosphere

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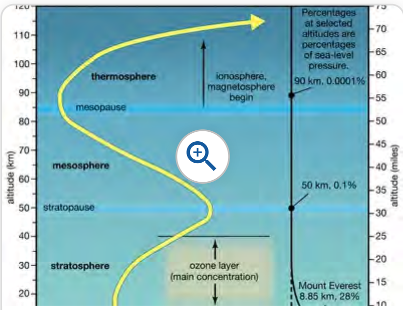

layers of Earth's atmosphere

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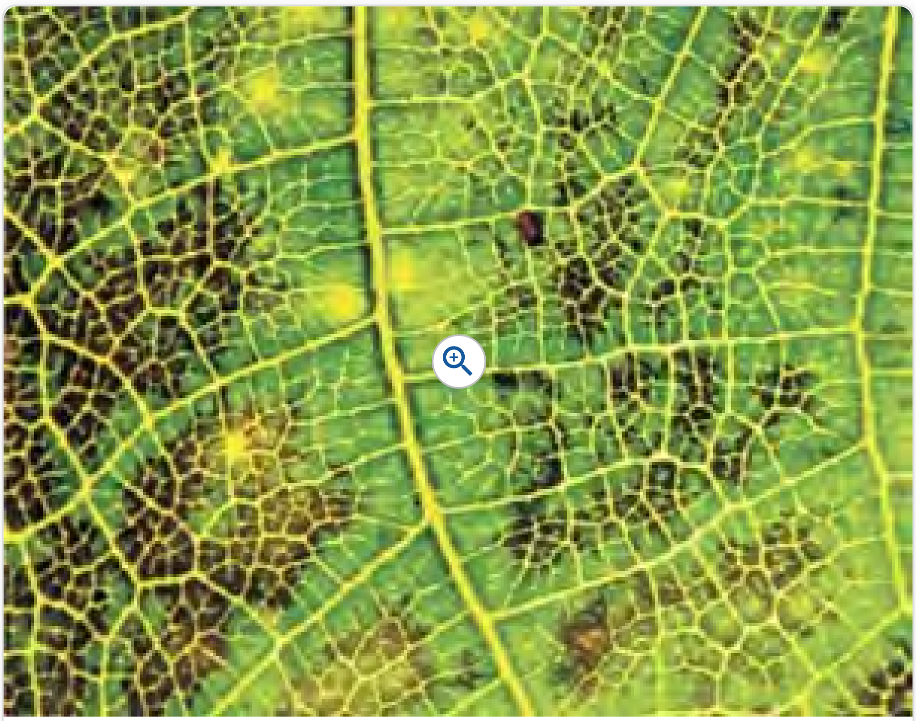
ozone layer, also called **ozonosphere**, region of the upper atmosphere, between roughly 15 and 35 km (9 and 22 miles) above Earth's surface, containing relatively high concentrations of ozone molecules (O_3). Approximately 90 percent of the atmosphere's ozone occurs in the stratosphere, the region extending from 10–18 km (6–11 miles) to approximately 50 km (about 30 miles) above Earth's surface. In the stratosphere the temperature of the atmosphere rises with increasing height, a phenomenon created by the absorption of solar radiation by the ozone layer. The ozone layer effectively blocks almost all solar radiation of wavelengths less than 290 nm from reaching Earth's surface, including certain types of ultraviolet (UV) and other forms of radiation that could injure or kill most living things.

Location in Earth's atmosphere

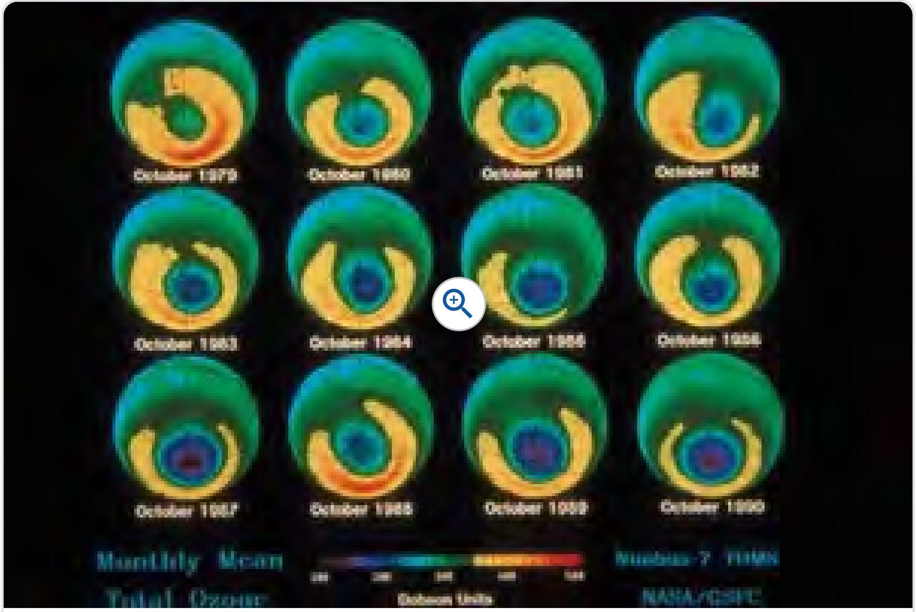
In the midlatitudes the peak concentrations of ozone occur at altitudes from 20 to 25 km (about 12 to 16 miles). Peak concentrations are found at altitudes from 26 to 28 km (about 16 to 17 miles) in the tropics and from about 12 to 20 km (about 7 to 12 miles) toward the poles. The lower height of the peak-concentration region in the high latitudes largely results from poleward and downward atmospheric transport processes that occur in the middle and high latitudes and the reduced height of the tropopause (the transition region between the troposphere and stratosphere).



ozone damage on leaf

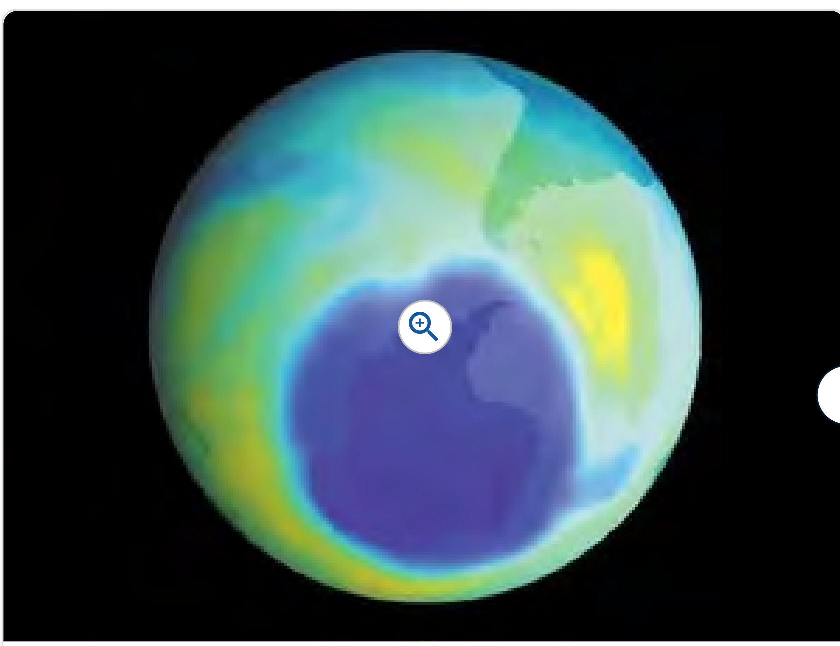
Most of the remaining ozone occurs in the troposphere, the layer of the atmosphere that extends from Earth's surface up to the stratosphere. Near-surface ozone often results from interactions between certain pollutants (such as nitrogen oxides and volatile organic compounds), strong sunlight, and hot weather. It is one of the primary ingredients in photochemical smog, a phenomenon that plagues many urban and suburban areas around the world, especially during the summer months.

Ozone creation and destruction



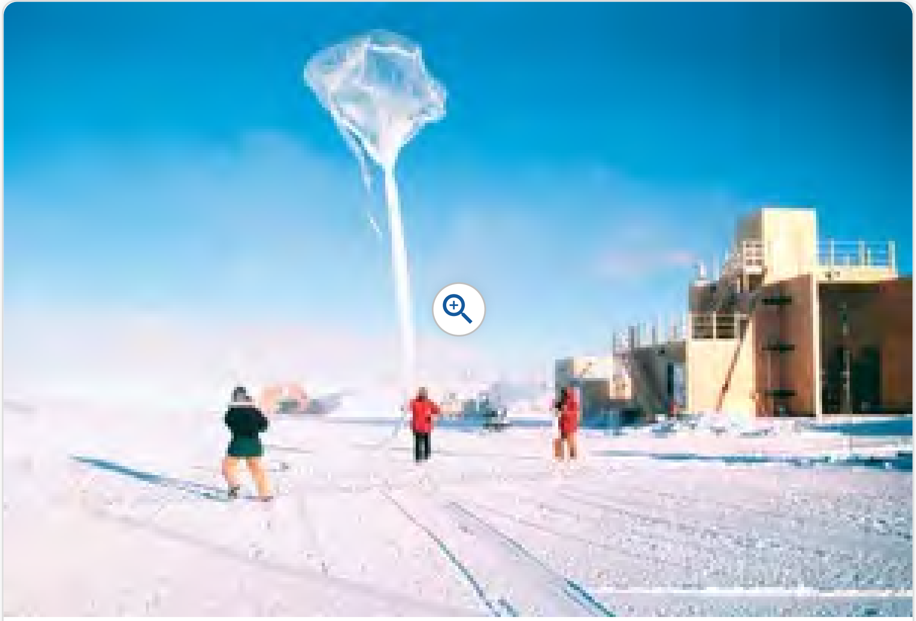
ozone: hole

The production of ozone in the stratosphere results primarily from the breaking of the chemical bonds within oxygen molecules (O_2) by high-energy solar photons. This process, called photodissociation, results in the release of single oxygen atoms, which later join with intact oxygen molecules to form ozone. Rising atmospheric oxygen concentrations some two billion years ago allowed ozone to build up in Earth's atmosphere, a process that gradually led to the formation of the stratosphere. Scientists believe that the formation of the ozone layer played an important role in the development of life on Earth by screening out lethal levels of UVB radiation (ultraviolet radiation with wavelengths between 315 and 280 nm) and thus facilitating the migration of life-forms from the oceans to land.



ozone depletion

The amount of ozone in the stratosphere varies naturally throughout the year as a result of chemical processes that create and destroy ozone molecules and as a result of winds and other transport processes that move ozone molecules around the planet. Over the course of several decades, however, human activities substantially altered the ozone layer. Ozone depletion, the global decrease in stratospheric ozone observed since the 1970s, is most pronounced in polar regions, and it is well correlated with the increase of chlorine and bromine in the stratosphere. Those chemicals, once freed by UV radiation from the chlorofluorocarbons (CFCs) and other halocarbons (carbon-halogen compounds) that contain them, destroy ozone by stripping away single oxygen atoms from ozone molecules. Depletion is so extensive that so-called ozone holes (regions of severely reduced ozone coverage) form over the poles during the onset of their respective spring seasons. The largest such hole—which has spanned more than 20.7 million square km (8 million square miles) on a consistent basis since 1992—appears annually over Antarctica between September and November.



ozonesonde

As the amount of stratospheric ozone declines, more UV radiation reaches Earth's surface, and scientists worry that such increases could have significant effects on ecosystems and human health. The concern over exposure to biologically harmful levels of UV radiation has been the main driver of the creation of international treaties such as the Montreal Protocol on Substances That Deplete the Ozone Layer and its amendments, designed to protect Earth's ozone layer. The Montreal Protocol has been a success: some 99 percent of the ozone-depleting chemicals regulated by the treaty have been phased out since its adoption in 1987. Compliance with international treaties that phased out the production and delivery of many ozone-depleting chemicals, combined with upper stratospheric cooling due to increased carbon dioxide, is thought to have contributed to the shrinking of the ozone holes over the poles and to slightly higher stratospheric ozone levels overall. Studies note that continued reductions in ozone-depleting chemicals that follow the schedule proposed by the Montreal Protocol and its follow-up agreements are expected to result in a return to 1980-level ozone concentrations above the poles by as early as 2040, with the closure of the ozone holes above Antarctica by about 2066

Ctesibius Of Alexandria

Greek physicist and inventor

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Alternate titles: Ktesibios of Alexandria

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Ctesibius of Alexandria

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Ctesibius Of Alexandria, Ctesibius also spelled **Ktesibios**, (flourished *c.* 270 BC), Greek physicist and inventor, the first great figure of the ancient engineering tradition of Alexandria, Egypt.

Ctesibius was the son of a barber. The discovery of the elasticity of air is attributed to Ctesibius, as is the invention of several devices using compressed air, including force pumps and an air-powered catapult. His most famous invention, however, was an improvement of the clepsydra, or water clock, in which water dripping at a constant rate raised a float that held a pointer to mark the passage of the hours. Another notable invention was a hydraulis, or water organ, in which air was forced through the organ pipes by the weight of water rather than by falling lead weights. Ctesibius' writings have not survived, and his inventions are known only from references to them by Vitruvius and Hero of Alexandria, but he laid the foundations for the engineering tradition that culminated in the works of Hero of Alexandria and of Philo of Byzantium.

Britannica Quiz

Inventors and Inventions

This article was most recently revised and updated by Amy Tikkanen.

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Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards

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Evidence suggests that SARS-CoV-2, as well as other coronaviruses, can be dispersed and potentially transmitted by aerosols directly or via ventilation systems. We therefore investigated ventilation openings in one COVID-19 ward and central ducts that expel indoor air from three COVID-19 wards at Uppsala University Hospital, Sweden, during April and May 2020. Swab samples were taken from individual ceiling ventilation openings and surfaces in central ducts. Samples were subsequently subjected to rRT-PCR targeting the N and E genes of SARS-CoV-2. Central ventilation HEPA filters, located several stories above the wards, were removed and portions analyzed in the same manner. In two subsequent samplings, SARS-CoV-2 N and E genes were detected in seven and four out of 19 room vents, respectively. Central ventilation HEPA exhaust filters from the ward were found positive for both genes in three samples. Corresponding filters from two other, adjacent COVID-19 wards were also found positive. Infective ability of the samples was assessed by inoculation of susceptible cell cultures but could not be determined in these experiments. Detection of SARS-CoV-2 in central ventilation systems, distant from patient areas, indicate that virus can be transported long distances and that droplet transmission alone cannot reasonably explain this, especially considering the relatively low air change rates in these wards. Airborne transmission of SARS-CoV-2 must be taken into consideration for preventive measures.

Abbreviations

ACH	Air changes per hour
CoV	Coronavirus
COVID-19	Coronavirus infectious disease 2019
Ct	Cycle threshold
HFNC	High flow nasal cannula
Hpi	Hour post infection
HVAC	Heating Ventilation Air-condition
MERS	Middle eastern respiratory syndrome
RNA	Ribonucleic acid
rRT-PCR	Real time reverse transcriptase polymerase chain reaction
SARS	Severe acute respiratory syndrome

During the coronavirus infectious disease 19 (COVID-19) pandemic, droplet transmission has been considered the most significant transmission route for severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), although other routes such as aerosol, fecal–oral, and indirect transmission via fomites may contribute to the rapid global dissemination of the virus[1,2]. The relative importance of aerosols versus droplets in the transmission of respiratory infections is difficult to distinguish, since particles of both aerosol and droplet size are generated for example when talking[3,4]. Aerosols are smaller than droplets, traditionally defined as smaller than 5 µm in diameter, and are thought to remain airborne longer, enabling transmission at greater distances and over longer periods of time[5]. This definition has been challenged and may very well be an over-simplification and it may be precarious to rigidly differentiate the two categories[3,6,7].

Previously, other coronaviruses have been shown to disperse via aerosols and ventilation, and have been determined to cause HVAC (heating, ventilation, air conditioning) associated and nosocomial infections as well as extensive hospital outbreaks[8–13]. In recent studies, extensive environmental contamination of SARS-CoV-2 in

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A B

Figure 1. (**A**) Overview of the 19 investigated COVID-19 ward rooms (ward 1). Dots indicate approximate placing of ceiling vent openings. Red dots indicate openings that where SARS-CoV-2 RNA was detected in at least one of two samplings, blue dots openings negative in both samplings. (**B**) Lateral view of the hospital building. Ward levels: red; COVID-19 outpatient clinic, yellow and blue; COVID-19 wards 1 and 2, with 19 rooms each, purple; eighth floor with central ventilation fans and HEPA filters. Individual ceiling vent openings were investigated on the second-floor ward (yellow) seen in (**A**).

hospital settings has been demonstrated, and viral RNA has been found both in air samples and in samples from air vent openings in isolation rooms[14–18]. Also, the potential for the aerosol transmission route of SARS-CoV-2 is supported by other recent studies[17,19–21]. The increased risk for infection in indoor environments, as well as superspreading events, could be explained by airborne transmission[22–26]. In this context it is therefore vital to understand the amount of SARS-CoV-2 in confined spaces and the distances at which virus can be passively dispersed. Hospital rooms where COVID-19 patients are treated are obviously venues in which airborne transmission is both of great importance to understand, as well as a suitable environment to study this phenomenon. In this study from a COVID-19 infectious disease ward at Uppsala University Hospital, Sweden, we investigated if SARS-CoV-2 RNA could be detected in and near air vent openings in isolation rooms and in filters in the central ventilation system situated on the eighth (top) floor of the hospital building. As RNA was detected at substantial distances from patient areas, fluid sample collections were performed in an attempt to determine the potential infective ability of SARS-CoV-2 detected in the systems. Our findings may suggest both airborne dispersal of SARS-CoV-2 and possible long-distance dissemination of SARS-CoV-2 via ventilation air flow.

Materials and methods

Sampling strategy. Sampling was performed on separate occasions during April and May 2020. In the first two occasions, 17 and 28 April, surfaces of exit vent openings in all 19 patient rooms in ward 1 (Fig. 1a) were swabbed as described below. When repeated on April 28, the internal surfaces of the central ventilation ducts, on the top floor were also swabbed and filter sections removed, as described further below. Due to the detection of SARS-CoV-2 RNA in the ventilation system (see "Results"), a further sample collection was performed using fluid traps, both at the terminal end of the ducts prior to the exhaust filters (at the same area where swabs were taken on April 28) as well as under the ceiling vent openings in the ward rooms (ward 1, see Fig. 1b), in an attempt to determine the infective ability of any collected virus.

Swab samples. Surfaces were swabbed using sterile nylon flocked swabs (Copan eSwab, Copan Italia SpA, Italy) moistened in sterile viral transport medium (VTM), containing Hank's balanced salt solution (Gibco, UK) supplemented with 2% fetal bovine serum (Gibco, USA), 100 µg/ml Gentamicin, and 0.5 µg/ml Amphotericin B[27]. Round ceiling vent openings were swabbed around the inside of the entire opening (circumference ca 25 cm). Swabs were placed in tubes containing 750 µl viral transport medium and stored at 4 °C until analysis within 24–72 h. Sampling was performed on April 17 and 28, 2020. Indoor relative air humidity and temperature were 30–31% and 20–21 °C, respectively.

Filter samples. Exit ventilations from each of the eight stories in the investigated hospital building, (Fig. 1b), lead to separate HEPA filter systems, located on the eighth (top) floor. Consequently, we could identify ducts and exhaust filters collecting air from individual floors not merging airflows. We chose to examine exhaust filters from three floors in the building that had been specifically designated for COVID-19 patients; two COVID-19 wards and a COVID-19 out-patient clinic. In addition, we examined exhaust filters from one story with per-

Corresponding floor	Exit airflow from ward (m^3/s)	Approximate distance from ward to top floor filters (m)	Sample	PCR results (Ct value)	
				N gene	E gene
Top floor air vent samples					
Covid-19 outpatient clinic	2.45	56	Ventilation shaft swab	Negative	Negative
			Air vent filter sample 1	37.13	37.30
			Air vent filter sample 2	Negative	Negative
			Air vent filter sample 3	38.79	36.96
			Cell medium in petri dish	Negative	Negative
Covid-19 ward 1	2.27	53	Ventilation shaft swab 1	Negative	Negative
			Ventilation shaft swab 2	Negative	Negative
			Air vent filter sample 1	36.86	34.91
			Air vent filter sample 2	36.31	34.87
			Air vent filter sample 3	35.32	35.41
			Cell medium in petri dish	Negative	33.00
Covid-19 ward 2	2.55	49	Ventilation shaft swab	Negative	Negative
			Air vent filter sample 1	37.42	38.70
			Air vent filter sample 2	35.72	33.85
			Air vent filter sample 3	36.72	36.08
			Cell medium in petri dish	35.32	33.16
Ground level non-patient care area	3.48	60	Air vent filter sample × 3 (negative control)	Negative	Negative

Table 1. rRT-PCR analysis of samples from filters and swabs in the ventilation system at the 8th floor, top level of the hospital building. Samples not exhibiting fluorescence above threshold level after 45 PCR cycles are labeled "negative". Ct: cycle threshold, N gene: SARS-CoV-2 Nucleocapsid gene, E gene: SARS-CoV-2 Membrane Small Envelope gene.

sonnel areas and a cafeteria, as a negative control. The distance between the COVID-19 wards and the exhaust filters and inspection hatches was 49, 53 and 56 m respectively for each COVID-19 ward (Table 1). The four stories located between the COVID-19 wards and the central ventilation in the top of the building (Fig. 1b) only sporadically harbored COVID-19 patients and were therefore not investigated. Adjacent inspection hatches upstream from (prior to) the HEPA filters were opened, and internal 30 × 30 cm surfaces swabbed as described above. Furthermore, one (out of six) 60 × 60 cm laminate F7 HEPA filter sections was removed from each system (filtering air from one ward or floor) and three filter samples (3 × 3 cm) were randomly cut out of the filters using sterilized scissors, placed in vials containing 2.5 ml of viral transport medium (described above), and stored at 4 °C until analysis within 72 h. The removed filters had been routinely replaced one month prior to collection.

Fluid samples. Fluid sample collection was performed near air entrances (ward rooms) and exits (directly prior to exhaust filters) in the ventilation system by placing open, 10 cm diameter petri dishes with 10 ml of DMEM (Dulbecco's Modified Eagle's medium (cell medium); Gibco) diluted 1 to 5 with autoclaved water, suspended 15 cm below ceiling vent openings (in ward rooms) for 24 h, or placed within central vent ducts via inspection hatches for 3 h. DMEM was diluted to ensure appropriate salt balance for the cells and no osmotic effect on the virus after evaporation of water during the collection process. We used DMEM instead of water only to be able to add the whole volume of sample onto cells without a dilution effect of the cell medium. These points were chosen in an attempt to determine if virus found entering and/or exiting the ventilation ducts retained infective ability, in response to the PCR results from vent opening and exhaust filters. The suspended petri dishes in the ward rooms were placed within what we expected to be the normal air flow to ventilation ducts, as well as placing the dishes as far from the patients as possible, in order to avoid contamination by coughing induced droplets or other patient or personnel activity in the rooms. An open petri dish containing cell medium was exposed to air in the biosafety level (BSL)-2 area of the laboratory for 24 h and used as a negative control, along with non-exposed DMEM and viral transport medium. DMEM and VTM spiked with synthetic oligonucleotides (gBlocks, IDT, Belgium) based on N and E gene sequences with introduced 5 base pair deletions were used as positive controls (Suppl. Table 1). DMEM exposed to air in 19 ward rooms were combined to three pools. Pooling was performed when we could establish that a large number of rooms were occupied by non-contagious patients (seven rooms), patients with suspected COVID-19 but not confirmed (five rooms) and only six rooms were occupied by contagious COVID-19 patients (May 13, 2020) (Suppl. Table 1). Due to evaporation during collection, the final concentration of DMEM in the petri dishes after collection was equivalent to undiluted cell medium. The entire pooled volume ranging from 5 to 10 ml was subsequently applied to Vero E6 cells in T25 flasks and incubated up to 13 days. Samples were subsequently collected and subject to rRT-PCR. Petri dishes with 10 ml DMEM exposed to air outside of patient areas for 24 h were used as negative control.

Ward conditions. All exit vent openings in the ward rooms are situated in the ceiling and are approximately 3 to 5 m from the head end of the beds (fresh air input openings are at 0 to 50 cm above floor level). Seven of the 19 openings are situated in adjacent washing rooms (see Fig. 1a) and are up to approximately 5 to 6 m from beds. Total air changes per hour (ACH) for each patient room varied between 1.5 and 2.6 in ward 1, and 2.1 to 2.7 in ward 2, between 2.8 and 3.2 in the outpatient clinic, (measured December 2017). Air flow in the central ventilation shafts, from each story, ranged between 2.27 and 3.48 m^3/s (Table 1). Pressure differences in rooms in ward 1 varied, − 6 to − 8.1 Pa between corridor and anterooms and + 5.5 to + 18 Pa between anterooms and patient rooms (measured March 2020). Hence, the anterooms were under negative pressure compared to the adjacent ward corridor as well as patient rooms.

RNA extraction and rRT-PCR. RNA was extracted using 280 µl of samples and QIAamp viral RNA kit (Qiagen, Hilden, Germany), according to manufacturer's protocol. Portions of the SARS-CoV-2 nucleocapsid (N) and envelope small membrane protein (E) genes were amplified by rRT-PCR, using primers (Thermo Fisher Scientific, Waltham, MA, USA) previously described[28–30] and the SuperScript III OneStep RT-PCR System with Platinum Taq DNA Polymerase kit (Invitrogen, Carlsbad, CA, USA). In brief, the two reaction mixtures (25 µl) contained 12.5 µl reaction buffer (a buffer containing 0.4 mM of each dNTP, 3.2 mM $MgSO_4$), 1 µl of enzyme solution (SuperScript III RT/Platinum Taq Mix), 1.25 µl of probe primers solution (10 µM stock concentration) 3 µl magnesium sulfate (50 nM), and 7.25 µl of RNA. The cycling conditions were as follows: cDNA synthesis at 55 °C for 30 min (min) and 50 °C for 2 min followed by 45 cycles of denaturation at 95 °C for 15 s (s), extension at 57 °C for 30 s and collecting the fluorescence signal at 68 °C for 30 s. Target 1 (E gene) forward primer ACA GGTACGTTAATAGTTAATAGCGT; reverse primer TGTGTGCGTACTGCTGCAATAT; and probe 5′-FAM-ACACTAGCCATCCTTACTGCGCTTCG-TAMRA-3′. Target 2 (N gene) forward primer GGGGAACTTCTC CTGCTAGAAT; reverse primer CAGCTTGAGAGCAAAATGTCTG; and probe 5′-FAM-TTGCTGCTGCTT GACAGATT-TAMRA-3′. As positive controls, double stranded DNA fragments (gBlocks, IDT, Belgium) with a five-nucleotide deletion in the targeted part of the E (10^2 copies/µl) and N (10^3 copies/µl) gene were used. Positive control Ct vales were 31.67 ± 0.68 and 28.07 ± 2.66 respectively. All PCR products with a Ct value < 45 were confirmed by Sanger sequencing (Macrogen, the Netherlands). Negative controls (swabs) were performed on non-exposed VTM (Suppl. Table 1).

Inoculation. Vero E6 cells (green monkey kidney cells (ATCC CRL-1586)) were seeded into T-25 flasks and grown in DMEM (Gibco, 41966) supplemented with 10% FBS (Gibco, USA) and 1 × Penicillin–Streptomycin (Sigma-Aldrich, PA333). The flasks were incubated (37 °C, 5% CO2) until cells confluency reached approximately 90%, after which the cell media was substituted with 9 ml of pooled samples supplemented with 2% FBS and 1 × Penicillin–Streptomycin. Potential cytopathic effect (CPE) was observed daily. Increase in viral load was determined by rRT-PCR, using 100 µl of supernatant from each T-25 flask at 0 (base line for comparison), 24 and 120 h post infection (hpi). rRT-PCR was also performed on DMEM exposed to air in a BSL-2 laboratory for 24 h (see section "Fluid samples"), non-exposed DMEM and DMEM spiked with SARS-CoV-2 synthetic oligonucleotide control sequence as negative and positive controls, respectively (Suppl. Table 1). Eleven days post inoculation, supernatants from the pooled samples (1 ml) were passed once into new flasks seeded with Vero E6 cells and containing 4 ml of cell media. Two days after the passage, samples were taken as described above for quantification by rRT-PCR. All procedures involving live virus were performed in a BSL-3 laboratory.

Ethical approval. Approval for accessing patient information was granted from the Swedish Ethical Review Authority DNR 2020-01787. As this retrospective data collection was considered completely anonymized by the Ethics committee, the need for patient consent was waived by the Swedish Ethical Review Authority. The study was conducted according to good clinical and scientific practices and following the ethical principles of the Declaration of Helsinki.

Results

SARS-CoV-2 RNA detection from ward samples. In two consecutive surface sampling rounds, performed on April 17 and 28, 2020, both SARS-CoV-2 N and E gene RNA were detected in seven (36.8%) out of 19 vent openings, while 11 days later, four vents (21%) were positive for both genes. Ct values varied between 33.77 and 39.78 (Table 2) and sequences were confirmed by Sanger sequencing. All three pooled cell medium samples from patient room ceilings were positive for both genes; Ct values ranged between 33.41 and 36.64. Pool 1 (Fluid traps from 7 rooms occupied by confirmed COVID-19 patients) N gene 35.47 and E gene 36.4, Pool 2 (6 suspected COVID-19 patient rooms) N gene 33.41 and E gene 36.64; Pool 3, (5 suspected non-contagious patient rooms), N gene 34.07 and E gene 36.64). Despite the attempt to arrange the potentially most infective samples in pools 1 and 2, a retrospective overview of patient diagnostics revealed that PCR-positive patients occupied rooms generating samples in all three pools (Suppl. Table 2).

SARS-CoV-2 RNA detection in central ventilation samples. Samples extracted from the main exhaust filters, located on the eighth (top) floor of the investigated hospital building (Fig. 1b), from each separate ventilation system for the three investigated COVID-19 wards were positive for both genes in eight (88.9%) out of nine samples (Table 2). Swabs taken from internal surfaces of three central ventilation channels at the top floor were all negative (Ct values > 45) (Table 1). Petri dishes containing cell medium, placed in inspection hatches in the central ventilation system prior to the exhaust filters, were found to contain SARS-CoV-2 RNA (both N and E genes) in one (33.3%) out of three specimens from ward 2 (Ct values 35.32 and 33.16 for N and E

Room	Sample set	Patient details						Ventilation opening	
			SARS-CoV-2 PCR			Respiratory support		PCR results (Ct value)	
				PCR results (Ct value)					
		Days since onset of symptoms	Patient sample date	N gene	E gene	Current	Last 24 h	N gene	E gene
1	1	17	April 1, 2020	23.51	22.22	Oxygen	Oxygen	Negative	Negative
	2	8	April 21, 2020	19.14	18.64	HFNC	HFNC	Negative	Negative
2	1	11	April 15, 2020	31.68	32.55	Oxygen	Oxygen	35.33	33.77
	2	12	April 18, 2020	13.3	13.91	Oxygen	Oxygen	Negative	Negative
3*	1	10	April 12, 2020	16.89	16.86	Oxygen	Oxygen	37.94	37.90
		Unoccupied							
	2	16	April 15, 2020	25.47	25.43	None	Oxygen	38.82	37.76
		9	April 21, 2020	14.96	14.98	HFNC	Oxygen/HFNC		
4*	1	15	April 7, 2020	25.98	25.33	HFNC	HFNC	39.55	38.71
		Unoccupied							
	2	20	April 13, 2020	19.72	19.11	Oxygen	Oxygen/HFNC	Negative	Negative
		29	April 5, 2020	17.16	16.59	None	Oxygen		
5*	1	*Unoccupied*						Negative	Negative
		7	April 14, 2020	25.38	25.33	HFNC	HFNC		
	2	*Unoccupied*						Negative	Negative
		8	April 23, 2020	Negative	Negative	Oxygen	Oxygen		
6*	1	8	April 11, 2020	17.91	16.88	Oxygen	Oxygen	36.24	36.70
		20	March 31, 2020	25.18	24.1	HFNC	HFNC		
	2	5	April 25, 2020	Negative	Negative	None	None	Negative	36.78
		Unoccupied							
7*	1	7	April 16, 2020	22.84	22.5	None	None	39.28	Negative
		Unoccupied							
	2	*Unoccupied*						Negative	Negative
		16	April 22, 2020	32.19	Negative	Oxygen	Oxygen		
8*	1	*Unoccupied*						Negative	Negative
		1	April 17, 2020	Negative	Negative	None	None		
	2	*Unoccupied*						Negative	Negative
		15	April 21, 2020	16.09	15.99	None	Oxygen		
9	1	8	April 16, 2020	17.22	17.88	Oxygen	Oxygen	Negative	Negative
	2	12	April 24, 2020	23.76	23.7	None	None	Negative	Negative
10	1	20	April 5, 2020	21.95	21.57	HFNC	HFNC	Negative	Negative
	2	8	April 27, 2020	Negative	Negative	Oxygen	Oxygen	Negative	Negative
11	1	12	April 11, 2020	10.08	9.65	HFNC	Oxygen/HFNC	Negative	Negative
	2	*Unoccupied*						38.61	37.55
12	1	*Unoccupied*						39.77	38.95
	2	12	April 21, 2020	16.09	15.99	None	Oxygen	39.78	Negative
13	1	5	April 15, 2020	24.87	25	Oxygen	Oxygen/HFNC	Negative	Negative
	2	11	April 28, 2020	30.74	Negative	HFNC	HFNC	Negative	Negative
14	1	7	April 17, 2020	Negative	Negative	Oxygen	Oxygen	Negative	Negative
	2	8	April 26, 2020	23.55	22.04	HFNC	HFNC	38.75	38.45
15*	1	*Unoccupied*						Negative	Negative
		Unoccupied							
	2	15	April 20, 2020	14.95	14.83	Oxygen	Oxygen	Negative	Negative
		Unoccupied							
16*	1	13	April 13, 2020	15.95	15.47	Oxygen	Oxygen	37.26	36.14
		Unoccupied							
	2	23	April 14, 2020	17.91	17.58	HFNC	HFNC	Negative	Negative
		Unoccupied							
17*	1	18	April 16, 2020	31.03	36.18	None	None	Negative	Negative
		8	April 13, 2020	16.94	15.95	None	Oxygen		
	2	15	April 18, 2020	29.23	28.38	HFNC	HFNC	Negative	38.63
		30	April 8, 2020	25.31	25.44	Oxygen	Oxygen		

Continued

		Patient details						Ventilation opening	
			SARS-CoV-2 PCR			Respiratory support		PCR results (Ct value)	
				PCR results (Ct value)					
Room	Sample set	Days since onset of symptoms	Patient sample date	N gene	E gene	Current	Last 24 h	N gene	E gene
18*	1	*Unoccupied*						Negative	37.76
		18	April 6, 2020	19.02	17.62	Oxygen	Oxygen		
	2	*Unoccupied*						Negative	Negative
		Unoccupied							
19	1	14	April 6, 2020	14.28	13.58	Oxygen	Oxygen	37.56	35.28
	2	19	April 18, 2020	17.16	15.87	HFNC	HFNC	36.78	35.31

Table 2. Overview of results from the 19 investigated COVID-19 ward rooms (ward 1), including patient details regarding duration of symptoms, date when clinical sample was collected for PCR-diagnosis, PCR-result from clinical sample and ongoing oxygen therapies when ventilation samples were collected. Rooms marked with an * can accommodate two patients, and thus patient data is supplied for two patients for each sample occasion. Sample set 1: April 17, 2020. Sample set 2: April 28, 2020. Samples not exhibiting fluorescence above threshold level after 45 PCR cycles are labeled "negative". No O_2: No ongoing patient oxygen therapy, O_2: conventional nasal cannula or mask, HFNC: High Flow Nasal Cannula, Ct: cycle threshold, N gene: SARS-CoV-2 Nucleocapsid gene, E gene: SARS-CoV-2 Membrane Small Envelope gene.

genes respectively), while one (33.3%) of the three specimens from ward 1 contained only the E gene (Ct value 33.00) (Table 1).

Infectivity in Vero E6 cells. No significant CPE nor decrease in rRT-PCR Ct values were seen compared to baseline values (see "Results" above for Ct values) after 24 or 120 hpi on Vero E6 cells from samples retrieved from ward vent openings or central ventilation ducts or filters.

Discussion

Several aspects during the COVID-19 pandemic support the risk of aerosol transmission of SARS-CoV-2. First, mounting evidence for pre- and asymptomatic transmission, where the spread of droplets through coughing and sneezing cannot be a major factor, must raise questions about aerosol transmission[31]. Second, aerosols generated by speech could theoretically contain enough SARS-CoV-2 virus particles to support transmission, and these aerosols can remain airborne for up to ten minutes[20]. In addition, coronaviruses can be emitted in aerosols through normal breathing[32]. Third, field studies in hospital wards have detected SARS-CoV-2 RNA both in vent openings and in the air[14–17]. These findings are not unexpected seeing as similar observations have been made for both SARS and Middle East Respiratory Syndrome (MERS)[8,33,34].

In this study, we found SARS-CoV-2 RNA in vent openings in ward rooms harboring COVID-19 patients. Viral RNA was also detected in fluid placed in open dishes suspended below vent openings. Similar levels of viral RNA were detected in exhaust filters and open petri dishes with cell medium at least 44 to 56 m from the three investigated COVID-19 wards. Only a small fraction of each filter was analyzed implying that a large number of particles emanating from COVID-19 wards can disperse to greater distances than can be explained by droplet transmission routes. In previous studies, the effect of ventilation has not shown any obvious impact on the risk for spread of droplet-transmitted diseases, probably since droplets are more governed by gravity[35]. Furthermore, the ventilation system in the investigated hospital building has a relatively low air flow; between 1.7 and 3 total air changes per hour (ACH) for each room, depending on room volumes. The recommendation for airborne infection isolation rooms is 12 ACH in most guidelines[35]. Notably, the relative air humidity in the investigated environment was low, between 30 and 31%. Low air humidity has recently been suggested to increase the risk of airborne SARS-CoV-2 dispersal[36,37].

We initiated this study by performing rRT-PCR on numerous surface and filter samples. Detection of SARS-CoV-2 as well as other coronavirus RNA in ventilation openings has been reported before[10,15,38]. However, the detection of viral RNA in the exhaust filters over 50 m from patient care areas was unexpected. In response to these findings, we found it vital to rapidly address the question of infective ability in order to determine the immediate risk of infection for uninfected patients, personnel working in the investigated wards and service personnel that might be exposed while working with the ventilation systems. We therefore employed the ad hoc methods described above in an attempt to determine the infective ability of the samples. We are aware that there are several potential limitations to the employed sampling methods in fluid traps; the likelihood of viral particles being deposited in fluids by gravity, the length of time the viral particles retain infective ability, concentration and increased osmolarity of the cell medium by evaporation as well as pH increase due to oxygen exposure during sampling. We have not determined whether the detected RNA could be from viral particles that have been inactivated by antibodies, seeing as a majority of the patients admitted to at least one of the wards were in later phases of COVID-19 disease at both collection dates (Table 2), and may have likely developed an immune response. Even though we could not determine infective capability of virus collected in cell medium, we repeatedly detected

SARS-CoV-2 RNA using this method. The placement of the petri dishes, either just below the ceiling in ward rooms or at distances around at least 50 m from patients in central vent ducts indicates that dispersal by means other than larger droplets must occur, since larger droplets are considered to precipitate by gravity within one or two meters from a source[5]. Although RNA could be detected in samples from ward rooms and central ventilation ducts, no infectivity was seen after inoculating samples on susceptible cells. This collection method was adopted in order to rapidly address the question as to what threat the RNA findings may infer in a clinical setting. Several explanations for these results may be identified. First, the Ct values are close to the detection limit, indicating that there were few viral copies in theses samples. Also, many of the admitted patients at this time point (later than other samplings in this study) were in late phases of COVID-19 or cleared of infection. We chose to report this as we could detect SARS-CoV-2 RNA in these samples, and that droplets do not appear to be a plausible explanation for these findings as droplets could unlikely follow a ballistic pathway from patient into the petri dished at 2.5 m height, and in all three pools. It is important to continue to develop effective sampling methods in order to determine infective ability of SARS-CoV-2 as well as differentiating between patients in early and late phases of disease. Since we are aware of these technical limitations, we have recommended service personnel to take adequate protective measures while working with the ventilation systems as we cannot definitively repudiate the risk of infection from contaminated air.

Ongoing oxygenation therapies, such as High Flow Nasal Cannula (HFNC) oxygenation, in each room did not apparently correlate to detection, or Ct values, of SARS-CoV-2 RNA in vent openings (Table 2). This raises the question if the risk for airborne transmission should be considered in more situations than during potentially aerosol generating procedures such as HFNC[6]. This is further corroborated by the studies on aerosols generated when speaking and breathing[20,32]. Results differed in ward rooms between the two samplings of vent openings, which could be due to varying disease progression for the occupying patients. Some vent openings were positive for both N and E genes despite the rooms having been evacuated and routinely cleaned (Table 2). This suggests that detection also could result from viral shedding by previous patients and calls for further studies on how long SARS-CoV-2 RNA can be detected in the environment, with the accompanying risk for transmission via fomites. Alternatively, detection of viral RNA in the ventilation systems could arise from such activities as handling bed linens or cleaning which may disturb viral particles from textiles or surfaces and displace them into the air, and that these virions have dried and been rendered inactive. On the other hand, RNA deterioration after inactivation could limit the extent of this source of RNA found in HVAC systems.

In this study we could not demonstrate infectious capability of the virus, when inoculated on Vero E6 cells, from samples in either vent openings, exhaust filters or by collection directly in cell medium. This is likely due to the pathogens rapidly drying in the vents or inadequate amounts of virus collected near vent openings or in front of exhaust filters. Also, collection directly in cell medium does not appear to have been performed previously and these results should be interpreted cautiously. Furthermore, admitted patients in the ward were between day 5 and 23 after symptom onset (Table 2). There is accumulating evidence that COVID-19 contagiousness peaks shortly prior to symptom onset[2,31,39]. This implies that the patients in this study may be in a less contagious phase of COVID-19 disease, which is consistent with the findings that SARS-CoV-2 infectivity appears to be low eight days after symptom onset[39,40]. Nevertheless, during dispersal from a patient to ventilation, and over considerable distances, the virus may still retain infective capability. RNA was also detected in containers placed at ceiling level, demonstrating that viral particles were airborne during these specific periods, at not only deposited on fomites over longer, uncertain duration. We speculate that the risk of infection by exposure to ventilation system air is presumably very low, due to dilution of viral load and drying. Nevertheless, the apparent capability of the virus to be transported in air, as we present here, should raise concerns for the risk of infection in smaller, confined spaces in close proximity to contagious patients, i.e. all air in patients rooms, intensive care units, etc. during care for COVID-19 patients[41]. This may be even more important concerning patients in earlier phases of disease, in which contagiousness may be high. This includes both symptomatic and asymptomatic SARS-CoV-2 infected persons in any confined space, such as homes, public transportation, restaurants, etc. The presented findings indicate airborne dissemination of SARS-CoV-2, especially considering the distance SARS-CoV-2 RNA was dispersed. However, further investigations, preferably discriminating between patients in early and later phases of SARS-CoV-2 disease as well as direct sampling of expiratory air from COVID-19 patients will be needed to resolve this question.

Conclusions

Detection of coronavirus RNA, including SARS-CoV-2, in hospital and other ventilation systems has been reported, as well as nosocomial and HVAC associated outbreaks[8–13]. In particular, MERS coronavirus, closely related to SARS-CoV-2, has caused major hospital associated outbreaks[9–12]. Also, growing concern about aerosol transmission of SARS-CoV-2 has recently been ventilated[42]. Here we present further evidence for SARS-CoV-2 ability to disperse from patients to ward vent openings as well as detection of viral RNA in ventilation exhaust filters located at least 50 m from patient room vent openings. Although we could not conclude that the viral samples in this collection retained infective ability, the distance at which we detected RNA suggests that there may be a risk for airborne dissemination and transmission, especially at much closer distances to contagious persons in confined spaces, both in and outside hospital environments. We therefore find it reasonable to take precautionary measures against airborne transmission and that further investigations are necessary.

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EXHIBIT I

Long distance airborne transmission of SARS-CoV-2: rapid systematic review

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Abstract

OBJECTIVES

To evaluate the potential for long distance airborne transmission of SARS-CoV-2 in indoor community settings and to investigate factors that might influence transmission.

DESIGN

Rapid systematic review and narrative synthesis.

DATA SOURCES

Medline, Embase, medRxiv, Arxiv, and WHO COVID-19 Research Database for studies published from 27 July 2020 to 19 January 2022; existing relevant rapid systematic review for studies published from 1 January 2020 to 27 July 2020; and citation analysis in Web of Science and Cocites.

ELIGIBILITY CRITERIA FOR STUDY SELECTION

Observational studies reporting on transmission events in indoor community (non-healthcare) settings in which long distance airborne transmission of SARS-CoV-2 was the most likely route. Studies such as those of household transmission where the main transmission route was likely to be close contact or fomite transmission were excluded.

DATA EXTRACTION AND SYNTHESIS

Data extraction was done by one reviewer and independently checked by a second reviewer. Primary outcomes were SARS-CoV-2 infections through long distance airborne transmission (>2 m) and any modifying factors. Methodological quality of included studies was rated using the quality criteria checklist, and certainty of primary outcomes was determined using the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) framework. Narrative synthesis was themed by setting.

RESULTS

22 reports relating to 18 studies were identified (methodological quality was high in three, medium in five, and low in 10); all the studies were outbreak investigations. Long distance airborne transmission was likely to have occurred for some or all transmission events in 16 studies and was unclear in two studies (GRADE: very low certainty). In the 16 studies, one or more factors plausibly increased the likelihood of long distance airborne transmission, particularly insufficient air replacement (very low certainty), directional air flow (very low certainty), and activities associated with increased emission of aerosols, such as singing or speaking loudly (very low certainty). In 13 studies, the primary cases were reported as being asymptomatic, presymptomatic, or around symptom onset at the time of transmission. Although some of the included studies were well conducted outbreak investigations, they remain at risk of bias owing to study design and do not always provide the level of detail needed to fully assess transmission routes.

CONCLUSION

This rapid systematic review found evidence suggesting that long distance airborne transmission of SARS-CoV-2 might occur in indoor settings such as restaurants, workplaces, and venues for choirs, and identified factors such as insufficient air replacement that probably contributed to transmission. These results strengthen the need for mitigation measures in indoor settings, particularly the use of adequate ventilation.

SYSTEMATIC REVIEW REGISTRATION

PROSPERO CRD42021236762.

WHAT IS ALREADY KNOWN ON THIS TOPIC

The risk of SARS-CoV-2 transmission is likely to be greatest when in close proximity (<2 m) to someone who is infected

The potential for long distance airborne transmission (>2 m) is unclear, although widespread reporting of superspreader events suggests it may occur

Emission rates of respiratory particles released vary considerably between individuals but are generally higher for singing and speaking compared with breathing and tend to increase with loudness of vocalisation

WHAT THIS STUDY ADDS

The findings from this rapid systematic review suggest that long distance airborne transmission of SARS-CoV-2 might happen in indoor settings such as restaurants, public transport, workplaces, or choir venues

These results show that factors such as insufficient air replacement, directional air flow, and activities associated with increased emissions of respiratory particles (eg, singing or speaking loudly) might contribute to long distance airborne transmission

Well conducted epidemiological investigations can provide critical insight into transmission routes, especially when other types of studies are not feasible; the question of what level of public health evidence is sufficient to support decision making for a novel infection warrants further consideration

Introduction

Since the early stages of the covid-19 pandemic and the first reports of superspreader events,[1 2] the body of evidence suggesting airborne transmission of SARS-CoV-2 in the absence of aerosol generating procedures has grown. However, despite the publication of numerous opinion pieces and narrative reviews in support of airborne transmission of SARS-CoV-2,[3-9] scientific consensus on the relative importance of this route of transmission is lacking. Part of the controversy arises from differences in terminology, definitions, and size thresholds for respiratory particles.[10]

Traditionally, close contact transmission was assumed to occur through droplets with ballistic trajectory that directly deposit on mucous membranes, whereas airborne transmission was assumed to occur over longer distances via smaller particles (aerosols) that remained suspended in the air and were subsequently inhaled.[10 11] Limitations of this dichotomy are well illustrated by the challenge in defining a size range to characterise particles that are droplets or aerosols.[6 7 10 12] For example, the World Health Organization threshold is set at 5-10 microns[13] whereas in the UK the threshold is based on the work by Milton[14] and set to 100 microns.[15] This is also complicated by the role of evaporation, as a particle will get smaller as it moves from human sources.

Regardless of terminology and definitions, it is now understood that short range transmission can occur through both droplets and aerosols and that the concentration of respiratory particles is higher at short range than over longer distances.[7 11 16 17] Consensus is, however, still lacking on the risk for long distance airborne transmission in indoor settings in the community such as hospitality venues, leisure facilities, workplaces, or apartment blocks. This lack of consensus also reflects the challenging nature of the evidence base, and high quality review level evidence is still needed; some systematic reviews have relied on environmental sampling studies, which only provide indirect evidence of the potential risk of airborne transmission,[18-20] whereas systematic reviews that have included a wider range of study designs (epidemiological, environmental, and modelling) and settings (healthcare and community) remain inconclusive.[21-24]

This gap needs to be addressed from a public health perspective, focusing on long distance transmission (>2 m) in indoor community settings. As evidence on the biological plausibility of long distance airborne transmission is available from environmental and experimental studies,[18 21 22] we focused on epidemiological observational studies to assess where and when human-to-human transmission are likely to occur. In this rapid review we systematically identified and examined such studies to evaluate the potential for long distance airborne transmission of SARS-CoV-2 in indoor community settings and to assess the impact of potential modifying factors.

Methods

We used a rapid systematic review approach, following streamlined systematic methodologies to accelerate the review process,[25] and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines.[26] The protocol for this review was registered on PROSPERO before screening took place.[27]

Data sources and searches

We identified primary studies through two sources. Firstly, we screened studies included in the rapid systematic review by Comber et al for those published from 1 January 2020 to 27 July 2020.[21] This systematic review, assessed to be of moderate quality using the AMSTAR 2 (A MeaSurement Tool to Assess systematic Reviews, revised) critical appraisal tool,[28] contains a comprehensive search strategy and wider inclusion criteria than the current rapid review (studies related to all airborne transmission of SARS-CoV-2) and was the only relevant review available at the time we wrote our protocol.

Secondly, we conducted electronic searches in Ovid Medline, Ovid Embase, medRxiv, Arxiv, and WHO COVID-19 Research Database for studies published from 27 July 2020 to 19 January 2022. The initial search was conducted on 8 February 2021 and last updated on 19 January 2022. The search strategy was drafted by an information scientist and peer reviewed by a second information scientist. Supplementary material 1 (section 1) shows the full search strategy.

Using the studies that met our inclusion criteria, we performed a citation analysis on 1 February 2022 on Web of Science and Cocites (co-citation analysis, forward and backwards snowballing). Although this was not part of the search strategy outlined in the protocol, it was agreed a posteriori by the review team to increase the chance of additional relevant studies being retrieved.

Eligibility criteria for study selection

Our eligibility criteria for study selection were published articles, accepted manuscripts, and preprints reporting on the potential for airborne transmission of SARS-CoV-2 in indoor community (non-healthcare) settings at a distance >2 m (the 2 m threshold is based on UK regulations; we also considered for inclusion non-UK studies that used thresholds based on their respective national recommendations, such as 1.5 m or 6 feet/1.8 m). The aim was to include all observational studies (outbreak investigations and epidemiological case series, cohort, case-control, and cross sectional studies) of any human population in non-healthcare settings. We excluded systematic or narrative reviews, guidelines, opinion pieces, intervention studies, modelling studies, environmental sampling studies without epidemiological investigation, laboratory or virology studies, and animal studies. We also excluded observational studies in which close contact or fomite were the most likely transmission routes (eg, studies reporting on transmission in households).

Screening was performed using Rayyan Systems, a freely available online screening tool.[29] Two reviewers independently screened the first 10% of records retrieved from the initial search on title and abstract, with substantial agreement (97.7%; Cohen's κ=0.61). A single reviewer screened the remainder, and two reviewers independently screened a further 10% (of the total number of records), with almost perfect agreement (99.6%; Cohen's κ=0.92). All records selected were screened at full text by one reviewer and checked by a second reviewer, with any discrepancies resolved by discussion with a third reviewer.

Outcomes

The primary outcomes were SARS-CoV-2 infections through long distance airborne transmission (at a distance >2 m), and any factors that might have modified the risk of transmission under these conditions. Included measures for SARS-CoV-2 infections were number of covid-19 cases; secondary attack rates; risk, rate, or odds of transmission over the stipulated distances; or any other reported measure related to transmission rate. For the modifying factors, we considered narrative on the type of effect and any potentially relevant information to be acceptable.

Additional outcomes extracted, when available, were time spent in the setting and distance over which airborne transmission was thought to have occurred.

Data extraction and synthesis

We developed a data extraction table to gather information on methods, participants, settings, outcomes, key findings, and any additional relevant information (eg, whether participants wore face coverings). Data extraction was completed for each included study by one reviewer and independently checked by a second reviewer, with discrepancies resolved by discussion. Only evidence directly relevant to the review question was extracted. For example, if studies reported on different outbreaks or on onward transmission that might have happened in different settings, we only extracted the results of outbreaks or settings when distance and transmission routes could be assessed.

A narrative summary of results according to indoor setting was produced.

Quality assessment and certainty of evidence

We used a quality criteria checklist for primary research to assess the methodological quality of each included study.[30] This checklist tool is composed of 10 questions, four of which are considered critical (questions on selection bias, group comparability, description of exposure/assessment of transmission routes, and validity of outcome measurements). Strict criteria were used to assess the two critical questions related to exposure and outcome assessment. In particular, a cluster of covid-19 cases in the setting of interest had to be confirmed with viral genomic sequencing to be considered as low risk of bias for validity of outcome measurements. Supplementary material 1 (section 2) lists the 10 questions of the quality criteria checklist.

A study was rated as high methodological quality if the answers were yes to the four critical questions plus at least one of the remaining questions. A study was rated as low methodological quality if answers were no to ≥50% of the critical questions. Otherwise, the study was rated as medium methodological quality. Each study was assessed independently in duplicate, with disagreements resolved by consensus.

Certainty of the evidence was assessed using a variation of the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) framework for systematic reviews without meta-analysis.[31] We assessed each of the five GRADE domains (methodological limitations of the studies, indirectness, imprecision, inconsistency, and likelihood of publication bias) and classified them as no limitation or not serious (not important enough to warrant downgrading), serious (downgrading the certainty rating by one level), or very serious (downgrading the certainty rating by two levels). We then classified the body of evidence for a specific outcome as high certainty, moderate certainty, low certainty, or very low certainty.

Patient and public involvement

Patients and members of the public were not involved in this rapid systematic review mainly because of time restrictions. The review question was, however, developed with the input of several public health experts and stakeholders.

Results

Study selection

After removal of duplicates, 7439 records were screened for relevance on title and abstract, with 90 reports assessed for eligibility (fig 1). Fifty six additional reports identified from the Comber et al rapid review[21] and by citation analysis were also assessed. From these 146 reports, 124 were excluded (see supplementary material 1 (section 3) for list of reasons for exclusion), and 22 reports[1 32-52] relating to 18 studies were included. When two or more reports related to the same study, we considered the most comprehensive report as the main publication.

All the studies investigated outbreaks of clusters of SARS-CoV-2 infections, and one study had an analytical component.[36] Eight studies were conducted in Asia,[34-40 45] five in Europe,[41 43 44 47 48] three in Oceania,[32 33 46] and two in the United States.[1 42] Three studies reported on transmission between flats in apartment blocks,[38-40] two in quarantine hotels,[32 33] two in restaurants,[34 35] two in buses,[36 37] one in a food processing factory,[41] one in a courtroom,[43] one in an office,[44] one in a fitness facility,[42] one in a department store,[45] and four during singing events.[1 46-48] All the outbreaks occurred in 2020, except for one in January 2021 in South Korea[40] (before vaccine rollout started in this country) and one in July 2021 in a quarantine hotel in New Zealand.[33]

Table 1 and table 2 summarise the studies by setting. Supplementary material 2 provides detailed information on each study.

Quality assessment

Figure 2 provides details of the methodological quality ratings: three studies were rated as high quality,[33 35 46] five as medium quality,[32 34 36 41 47] and 10 as low quality.[1 37-40 42-45 48] These ratings represent the methodological quality of descriptive studies.

Transmission settings

Quarantine hotels

Two outbreaks of covid-19 in quarantine hotels were identified, both in New Zealand and involving cases part of the same genomic cluster who had quarantined

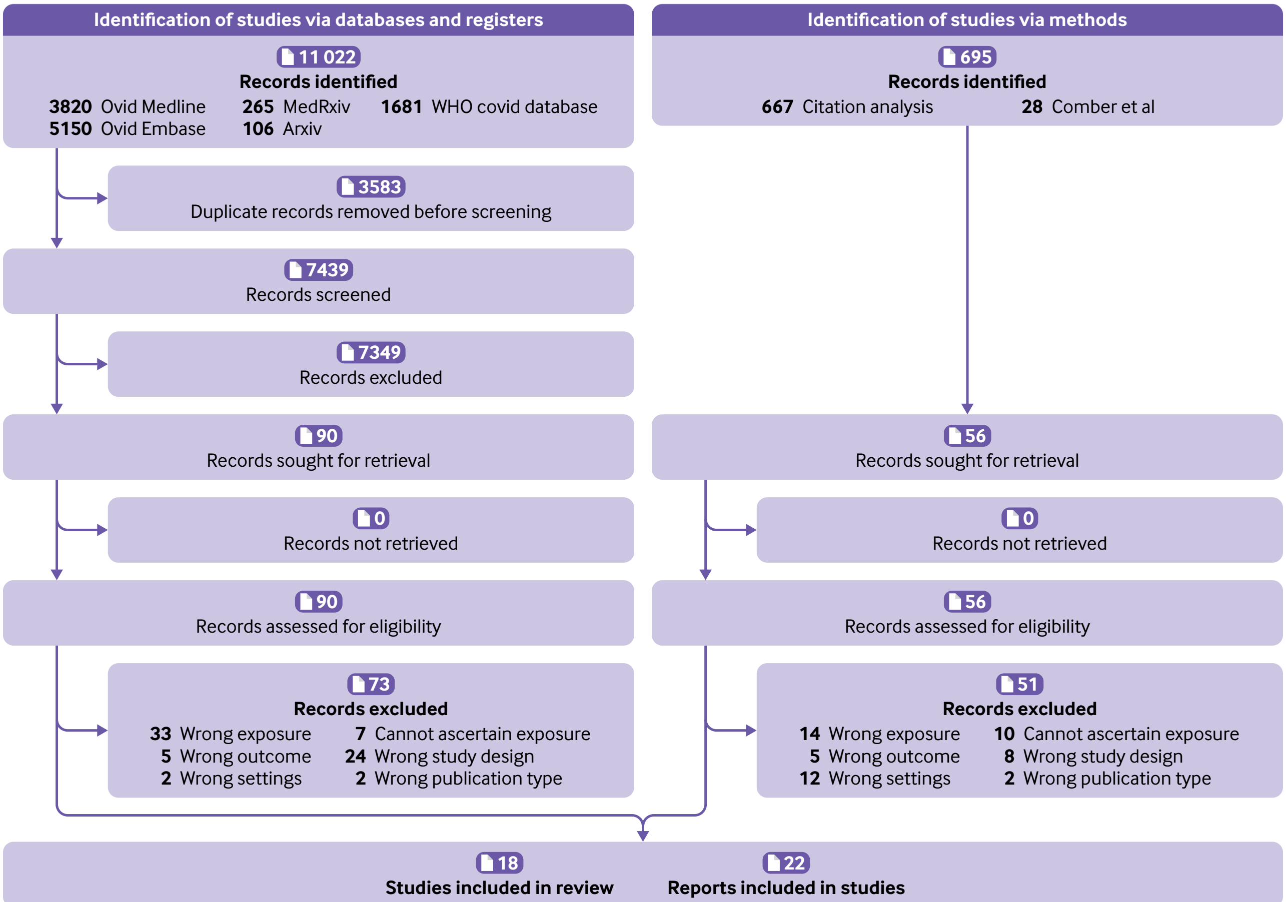

Fig 1 | Flow of articles through the review

in separate rooms. The first outbreak, reported by Eichler et al[32] (rated as medium methodological quality) occurred in September 2020, and although primary and secondary cases had travelled on the same flight, transmission is believed to have happened in the hotel on day 12 of quarantine, after the primary case had developed symptoms on day 10. No information was provided on the measures in place at this quarantine hotel (eg, use of face coverings). The second outbreak, reported by Fox-Lewis et al[33] (rated as high methodological quality) occurred in July 2021. The primary case (asymptomatic) and secondary cases had travelled on different flights and arrived at the hotel on different days. Staff members, all vaccinated, wore full personal protective equipment and were regularly tested. Participants were asked to wear surgical masks when opening doors, but this could not be validated in the investigation. None of the cases (primary or secondary) were vaccinated; the only person who was vaccinated tested negative despite being part of the same travel group as the secondary cases.

Close contact and fomite transmission were ruled out by video analysis in both studies, although in the outbreak reported by Eichler et al[32] fomite transmission through a communal bin—although unlikely, cannot be ruled out. Video analysis showed that in both outbreaks the doors of the rooms had been opened simultaneously for a short period during which infected respiratory particles could have moved between rooms. Both investigations included a review of the ventilation systems and found that pressure differences between rooms and corridors could support this hypothesis. Long distance airborne transmission between a primary case and at least one secondary case was therefore considered to be the most likely route in both outbreaks.

Restaurants

Two separate outbreaks of covid-19 in restaurants were identified. The first outbreak, in China in January 2020, was mainly reported by Li et al[34] (rated as medium methodological quality), with additional evidence provided in two other reports.[49 50] This outbreak involved a primary case (with symptom onset later that day) and at least two secondary cases who were seated on tables between 1.4 and 4.6 m away from the primary case. The second outbreak, reported by Kwon et al[35] (rated as high methodological quality), occurred in June 2020 in South Korea and involved three people with confirmed covid-19 who belonged to the same genomic cluster. The primary case, which was presymptomatic at the time, sat 6.5 m from one secondary case for five minutes, and 4.8 m from the other secondary cases for 21 minutes, all at different tables.

Table 1 | Summary of included studies, in chronological order by setting: quarantine hotels, restaurants, buses, and apartment blocks

Reference (quality rating)	Transmission event, setting, date	No of cases	Outcome and exposure assessment	Potential for other transmission routes	Potential for airborne transmission >2 m*	Modifying factors
Li et al,[34] Lu et al,[49] Zhang et al[50] (medium)	Restaurant, China, January 2020	Ten confirmed cases from three tables	No genomic sequencing. Epidemiological data, video recording, on-site visit, design of air conditioning and ventilation system, experiments to assess airflow and ventilation rates	Close contact or fomite transmission unlikely (except for cases in same household). Transmission from outside event possible for some cases	Possible airborne transmission between primary case and at least two secondary cases; up to 1.4 m (53 min) and 4.6 m (75 min) from primary case	Insufficient air replacement. Directional air flow through air circulation units
Shen et al[36] (medium)	Buses, China, January 2020	Twenty four confirmed cases	No genomic sequencing. Questionnaires and interviews, contact tracing data, bus design, and ventilation system	Close contact, fomite transmission, or transmission from outside event possible for some cases	Possible airborne transmission >2 m from primary case (50 min)	Insufficient air replacement. Directional air flow from central heating system
Luo et al,[37] Ou et al[51] (low)	Buses, China, January 2020	Nine confirmed cases	No genomic sequencing. Epidemiological data, information on loading and unloading stops of all passengers, and seating positions, ventilation systems, tracer gas experiments	Close contact unlikely. Fomite transmission or transmission from outside event possible for some cases	Possible airborne transmission >2 m for some cases (1 hour to 2.5 hours)	Insufficient air replacement. Directional air flow due to exhaust system
Lin et al[38] (low)	Apartment block, China, January 2020	Nine confirmed cases from three households	No whole genome sequencing (partial S gene only). Interviews with cases, CCTV of lift, tracer gas and wind speed experiments	Close contact or fomite transmission unlikely (except for cases in same household); transmission from outside event possible for some cases	Possible airborne transmission between cases in one flat to two different flats (up to 10 floors from flat of primary case)	Insufficient air replacement. Directional air flow through drainage and exhaust system
Kwon et al[35] (high)	Restaurant, South Korea, June 2020	Three confirmed cases	Genomic sequencing. Contact tracing, interviews, credit card records, video recording, mobile phone location data, on-site visits, air flow measurement, environmental sampling	Close contact, fomite transmission, or transmission from outside event unlikely	Possible airborne transmission between cases seated 4.8 m (21 min) and 6.5 m (5 min) from the primary case	Insufficient air replacement. Directional air flow through air circulation units
Hwang et al[39] (low)	Apartment block, South Korea, August 2020	Ten confirmed cases from seven households	No genomic sequencing. Epidemiological data, surface sampling, building assessment	Close contact or fomite transmission unlikely (except for cases in same household). Transmission from outside event possible	Possible airborne transmission through ventilation ducts across floors for some secondary cases	Directional air flow through vertical air duct or floor drain. Insufficient air replacement (unclear)
Eichler et al[32] (medium)	Quarantine hotel, New Zealand, August-September 2020	Nine confirmed cases, with one secondary case considered for long distance transmission	Genomic sequencing. Epidemiological data, surveillance video, review of ventilation system in hotel	Close contact or fomite transmission unclear. Transmission from outside event unlikely	Possible airborne transmission from hotel room of the primary case to doorway or corridor for one secondary case	Insufficient air replacement. Directional air flow
Han et al[40] (low)	Apartment block, South Korea, January 2021	Five secondary cases (three households) considered for long distance transmission	Genomic sequencing. Epidemiological data, interviews, mobile phone location tracking, surface sampling	Close contact or fomite transmission unlikely (except for cases in same household). Transmission from outside event unlikely	Possible airborne transmission through floor drains across three floors for two secondary cases	Insufficient air replacement. Directional air flow through vertical floor drain
Fox-Lewis et al[33](high)	Quarantine hotel, New Zealand, July 2021	Five confirmed cases in two rooms	Genomic sequencing. Epidemiological data, surveillance video, review of ventilation system in hotel	Close contact, fomite transmission, or transmission from outside of event unlikely	Possible airborne transmission from hotel room of primary case to hotel room for at least one secondary case (2.1 m)	Insufficient air replacement. Directional air flow

This review's assessment of likelihood of airborne transmission of SARS-CoV-2 over distances >2 m is based on likelihood of it occurring in some, but not necessarily all, transmission events.
*Exposure distance and time are stated when known; if not stated they are categorised as not clear or not specified.

After extensive epidemiological and environmental investigations, both studies suggested that the most plausible route was long distance airborne transmission, which could have been facilitated by air circulation units generating a directional air flow from the primary to secondary cases combined with lack of air replacement. In both outbreaks close contact and fomite transmission were ruled out based on video surveillance analysis.

Buses and coaches

Two separate outbreaks of covid-19 on buses in China in January 2020 were identified, one on a journey to and from a worship event among lay Buddhists[36] and one on a long distance journey using a public coach and minibus.[37 51]

The outbreak at a worship event was reported by Shen et al[36] who conducted a retrospective epidemiological investigation with an analytical component (rated as medium methodological quality). Thirty one of the 300 participants tested positive for SARS-CoV-2 of whom seven were likely to have been infected by close contact transmission during the religious event. The other 23 cases had travelled to the event in the same bus as the primary case and were thought to have been mainly infected during the bus journey, throughout

Table 2 | Summary of included studies, in chronological order by setting: department store, singing events, meat processing plant, fitness facility, courtroom, and office

Reference (quality rating)	Transmission event, setting, date	No of cases	Outcome and exposure assessment	Potential for other transmission routes	Potential for airborne transmission >2 m*	Modifying factors
Jiang et al[45] (low)	Department store, China, January 2020	Twenty four cases, with 12 secondary cases considered for long distance transmission	No genomic sequencing. Epidemiological data, surveillance video, assessment of ventilation conditions	Close contact, fomite transmission, or transmission from outside event all possible	Unclear airborne transmission across different sections of the store	Not applicable
Hamner et al,[1] Miller et al[52] (low)	Singing event, USA, March 2020	Fifty two: 32 confirmed cases, 20 probable cases	No genomic sequencing. Telephone interviews	Close contact or transmission from outside event possible for some cases. Fomite transmission unlikely	Possible airborne transmission >2 m for some cases, owing to high secondary attack rate (2.5 hours)	Insufficient air replacement. Increased aerosol emission—singing
Charlotte et al[48] (low)	Singing event, France, March 2020	Nineteen: seven confirmed cases, 12 probable cases	No genomic sequencing. Questionnaire and telephone interviews	Close contact possible for some cases. Fomite transmission unlikely. Transmission from outside event possible for at least two cases	Possible airborne transmission >2 m for some cases, owing to high secondary attack rate (2 hours)	Insufficient air replacement. Increased aerosol emission—singing
Gunther et al[41] (medium)	Meat processing plant, Germany, May-June 2020	Thirty one confirmed cases	Genomic sequencing. On-site visit (work condition and ventilation system) and information provided by employer on housing, commuting, and workplaces of employees	Close contact and fomite transmission possible for some cases. Transmission from outside event unlikely	Possible airborne transmission for some cases on the production line, up to 12 m from the primary case	Insufficient air replacement. Directional air flow from air circulation system. Increased aerosol emission—physical work (unclear)
Groves et al[42] (low)	Fitness facility, USA, June 2020	Twenty one confirmed cases, with10 secondary cases considered for long distance transmission	No genomic sequencing. Questionnaire and on-site assessment	Close contact possible for some cases. Fomite transmission unclear. Transmission from outside event unlikely	Possible airborne transmission >2 m for some cases, owing to high secondary attack rate (1 hour)	Insufficient air replacement. Directional air flow from air fan. Increased aerosol emission—shouting
Katelaris et al[46] (high)	Singing event, Australia, July 2020	Thirteen confirmed cases	Genomic sequencing. Interviews with cases, video recording, on-site visit (ventilation system)	Close contact or fomite transmission unlikely (except for five cases in same household). Transmission from outside event unlikely	Possible airborne transmission with secondary cases seated 1-15 m from the primary case (1 hour)	Insufficient air replacement. Increased aerosol emission—singing
Vernez et[43] (low)	Courtroom, Switzerland, September 2020	Five confirmed cases	No genomic sequencing. Court records, contact tracing data, and field measurements	Close contact cannot be ruled out, especially for the two secondary cases at 1.5 m from the primary case. Fomite transmission unlikely. Transmission from outside event likely for one secondary case	Possible long distance airborne transmission for three secondary cases (1.5-3 m; 3 hours)	Insufficient air replacement
Shah et al[47] (medium)	Five singing events, Netherlands, September-October 2020	Fifty: 48 confirmed cases and two probable cases	Genomic sequencing for seven cases. Phone and email correspondence, questionnaires, epidemiological data, aerosol transmission model	Close contact possible for some cases. Fomite transmission unlikely (except for one event). Transmission from outside event possible for some cases, but unlikely in others	Possible airborne transmission >1.5 m for some cases (1 hour to 2.5 hours)	Increased aerosol emission—singing. Directional air flow (unclear). Insufficient air replacement (unclear)
Sarti et al[44] (low)	Office, Italy, November 2020	Five confirmed cases	No genomic sequencing. Telephone interviews	Close contact, fomite transmission, or transmission from outside event possible	Unclear airborne transmission between coworkers	Not applicable

The review's assessment of likelihood of airborne transmission of SARS-CoV-2 over distances >2 m is based on likelihood of it occurring in some, but not necessarily all, transmission events.
*Exposure distance and time are stated when known; if not stated they are categorised as not clear or not specified.

which no one wore face coverings. Those travelling on the bus with the primary case were 11 times more likely to develop covid-19 compared with the other participants (relative risk 11.4, 95% confidence interval 5.1 to 25.4; P<0.01) and 42 times more likely compared with those travelling in the other bus (42.2, 2.6 to 679.3; P<0.01). Close contact transmission, fomite transmission, and transmission from outside the event cannot be ruled out for some of the cases but are unlikely to have accounted for all 23 secondary cases.

The second outbreak, reported by Luo et al[37] (rated as low methodological quality) with additional environmental investigations conducted by Ou et al,[51] involved one primary case (symptom onset occurred on the day of the event) who had travelled without wearing a face covering on a coach for 2.5 hours with 48 other individuals and then on a minibus for one hour with 12 other individuals. Nine secondary cases were identified, resulting in a secondary attack rate of 15% (95% confidence interval 6% to 24%), with most seated >2 m from the primary case: up to 4.5 m based

Reference	QCC questions* 1	2†	3†	4	5	6†	7†	8	9	10	Quality rating
Charlotte 2020[48]	Yes	Yes	Not applicable	Yes	Not applicable	No	No	Not applicable	Yes	Yes	Low
Eichler 2021[32]	Yes	Yes	Not applicable	Not applicable	Not applicable	Unclear	Yes	Not applicable	No	Yes	Medium
Fox-Lewis 2022[33]	Yes	Yes	Not applicable	Not applicable	Not applicable	Yes	Yes	Not applicable	Yes	Yes	High
Groves 2021[42]	Yes	Yes	Not applicable	Unclear	Not applicable	No	No	Not applicable	Yes	Yes	Low
Gunther 2020[41]	Yes	Yes	Not applicable	Yes	Not applicable	Unclear	Yes	Not applicable	Yes	Yes	Medium
Hamner 2020[1,52]	Yes	Yes	Not applicable	Yes	Not applicable	No	No	Not applicable	Yes	Yes	Low
Han 2022[40]	Yes	No	Not applicable	Unclear	Not applicable	No	Yes	Not applicable	No	Yes	Low
Hwang 2021[39]	Yes	Yes	Not applicable	Yes	Not applicable	No	No	Not applicable	Yes	Yes	Low
Jiang 2021[45]	Yes	Unclear	Not applicable	Not applicable	Not applicable	No	No	Not applicable	No	Yes	Low
Katelaris 2021[46]	Yes	Yes	Not applicable	Yes	Not applicable	Yes	Yes	Not applicable	Yes	Yes	High
Kwon 2020[35]	Yes	Yes	Not applicable	Unclear	Not applicable	Yes	Yes	Not applicable	Yes	Yes	High
Li 2021[34,49,50]	Yes	Yes	Not applicable	Not applicable	Not applicable	Yes	No	Not applicable	Yes	Yes	Medium
Lin 2021[38]	Yes	No	Not applicable	Unclear	Not applicable	Unclear	Unclear	Not applicable	Yes	Yes	Low
Luo 2020[37,51]	Yes	Yes	Not applicable	Yes	Not applicable	No	No	Not applicable	Yes	Yes	Low
Sarti 2021[44]	Yes	Yes	Not applicable	Yes	Not applicable	No	No	Not applicable	No	Yes	Low
Shah 2021[47]	Yes	Yes	Not applicable	Yes	Not applicable	Unclear	Unclear	Not applicable	Yes	Yes	Medium
Shen 2020[36]	Yes	Yes	Yes	Yes	Not applicable	Unclear	No	No	Yes	Yes	Medium
Vernez 2021[43]	Yes	Yes	Not applicable	Not applicable	Not applicable	No	No	Not applicable	Yes	Yes	Low

Yes Unclear No Not applicable

Fig 2 | Quality assessment. *Assessments using quality criteria checklist (QCC) for primary research (see supplementary material 1). †Critical questions: 2 on selection bias, 3 on group comparability, 6 on description of exposure/assessment of transmission routes, and 7 on validity of outcome measurements

on one report[37] and up to 9.5 m based on the other report.[51] Genomic sequencing was not performed and, based on symptom onset dates, it is plausible that more than one primary case was present, reducing our confidence in the distances reported. However, even taking into account all potential primary cases, it is possible that airborne transmission occurred for some secondary cases seated >2 m from a primary case. Some passengers wore face coverings, but none of the secondary cases did.

In both outbreaks, insufficient air replacement and directional airflow from the heating system were hypothesised as promoting long distance airborne transmission, supported by tracer gas experiments in the buses involved in one of the outbreaks.[51]

Apartment blocks

Three outbreaks of covid-19 in three separate residential apartment blocks were identified. The study by Lin et al[38] (rated as low methodological quality) investigated an outbreak involving nine people who tested positive for SARS-CoV-2 in three flats of a 29 storey apartment block in China. The nine cases, identified between 27 January and 13 February 2020, lived in flats that shared drain and sewer pipes connected via an exhaust pipe to the roof. Except for cases in the same household, close contact and fomite transmission were ruled out based on interviews with the cases and partial video analysis (lift only). Some but not all of the cases reported wearing face coverings in the communal areas of the building.

The two other outbreaks were in South Korea. The first, reported by Hwang et al[39] (rated as low methodological quality), occurred in August 2020 in an apartment block of 267 flats and involved 10 cases from seven households located around two ventilation ducts (eight cases around one, two around another). The second outbreak, reported by Han et al[40] (rated as low methodological quality), occurred in January 2021 in a complex of 260 flats, in which cases located in three flats along the same drainpipe and ventilation duct could not be explained by close contact or fomite transmission. For both outbreaks, transmission routes were mainly investigated through interviews with cases, and therefore recall bias (no video analysis) was possible. All cases reported wearing face coverings in the communal areas of the buildings.

For all three outbreaks, long distance airborne transmission between flats through vertical air ducts or floor drains was deemed possible for at least some of the secondary cases, although environmental investigation (tracer gas experiment) to support this hypothesis was conducted in only one[38] of the three studies. In two of the three studies,[38 40] the ventilation ducts were found to be malfunctioning, which could have contributed to transmission risk. However, only one of these studies[39] tested all residents and only one conducted whole genome sequencing,[40] which reduces confidence in the results.

Other indoor settings

The other outbreaks identified in this review occurred in a food processing factory,[41] fitness facility,[42] courtroom,[43] office,[44] and department store.[45]

Gunther et al[41] (rated as medium methodological quality) reported on an outbreak in a meat processing plant in Germany in May and June 2020 in which 31 out of the 140 workers on the same shift had tested positive for SARS-CoV-2 and were part of the same genomic cluster. Although close contact or fomite transmission in other areas of the processing plant and outside the factory (some workers shared accommodation and carpools) was possible for some cases, the spatial distribution of the cases suggested that transmission was likely to have occurred on the processing line at distances up to 12 m from the primary case who was asymptomatic. The authors hypothesised that factors such as increased respiratory rates (from physically demanding work), lack of air replacement, and continuous recirculation of cooled unfiltered air might have promoted long distance airborne transmission, but these were not investigated further. Some covid-19 measures were in place, including increased distance between workers and use of single layer face coverings, but adherence was not assessed as part of the study.

Groves et al[42] (rated as low methodological quality) reported on an outbreak involving two fitness instructors at classes taught in three different facilities in June and July 2020, although the investigation suggested that close contact and fomite transmission were likely to have occurred in all classes but one. The class in which long distance airborne transmission might have happened was a one hour static cycling class in which bikes were placed at least 1.8 m apart, with doors and windows closed and three large fans directed towards the class participants. The instructor, who had shouted instructions while facing the participants, was identified as being the primary case (with symptom onset the next day) and all 10 class participants had tested positive for SARS-CoV-2 three to six days after the class. Face coverings had not been used during the class.

In an outbreak in a courtroom in Switzerland reported by Vernez et al[43] (study rated as low methodological quality), five out of the 10 participants at a three hour hearing held on the 30 September 2020 tested positive for SARS-CoV-2. The use of face coverings was mandatory in the building, but not when seated, and social distancing measures were in place, with a minimum of 1.5 m between each seat. Long distance airborne transmission (1.5-3 m) was likely to have happened between a primary case (with symptom onset on that day) and three secondary cases, although close contact or fomite transmission after the hearing or in the bathroom cannot be ruled out. The hypothesis that a lack of air replacement (doors and windows were closed and there was no mechanical ventilation) might have promoted long distance airborne transmission was supported by field measurements and modelling.

Sarti et al[44] (rated as low methodological quality) reported on an outbreak in an office in Italy in which five of six coworkers were identified as cases. One of the five coworkers was identified as the primary case, and transmission happened before symptom onset. The sixth coworker, who was not infected, was not present in the office for the two days before symptom onset of the primary case. This transmission event happened in November and December 2020 when mitigation measures were in place, including social distancing, acrylic panels between desks, hand hygiene, and use of a face covering except when seated at a desk. The office was not well ventilated (no air conditioning and windows were closed), which could have promoted long distance airborne transmission. On the basis of the investigation, however, close contact, fomite transmission, and transmission from outside the event cannot be ruled out, so it is unclear as to whether long distance airborne transmission was the most likely route.

Jiang et al[45] (rated as low methodological quality) reported on an outbreak linked to a department store that occurred in January 2020 in Tianjin, China, involving 24 cases (six staff and 18 customers). Airborne transmission was considered as the most likely route of transmission between a primary case and 12 secondary cases, which might have been promoted by a lack of air replacement (doors were closed) and high density of people in the store. As genomic sequencing of SARS-CoV-2 was not performed, however, transmission from outside this event cannot be ruled out and, based on symptom onset dates, it is possible that several primary cases were present. On the basis of this investigation, it is unclear whether long distance airborne transmission had occurred in the store.

Singing events

In addition to transmission events associated with specific settings, four epidemiological investigations reporting on outbreaks linked to singing events were identified.

Katelaris et al[46] (rated as high methodological quality) reported on an outbreak in Sydney, Australia, linked to a series of four church services held between 15 and 17 July 2020. The probable primary case, a choir member, had sung at each of these one hour services, and 12 secondary cases were identified (2.4% secondary attack rate across the four services), who had sat in the same section of the church, between 1 m and 15 m from the primary case. Viral genomic sequencing of the primary case and 10 secondary cases showed a single genomic cluster, suggesting that transmission had occurred during the church services.

The second epidemiological investigation[47] (rated as medium methodological quality; preprint) reported on five singing events held between September and October 2020 in the Netherlands. At the time, national recommendations were in place to reduce covid-19 transmission, and although singing in groups was allowed, physical distancing (>1.5 m) and ventilation were recommended. Each singing event had between nine and 21 attendees, and attack rates of between 53% and 74% were observed. Fomite transmission was deemed unlikely in all but one event, but close contact transmission was considered possible for some of the secondary cases in three of the five events. However, owing to the high secondary attack rates, it is possible that at least some of the secondary cases had been infected via long distance airborne transmission and, even though ventilation through open doors or windows was reported for all events, air exchange rates were likely to have been low in at least three of the five events.

The two other outbreaks occurred in March 2020—that is, during the early stage of the pandemic when no mitigation measures were in place. One of them (70% attack rate, including probable cases) happened in France during a two hour choral rehearsal in a narrow, indoor, non-ventilated space[48] (study rated as low methodological quality). The second outbreak (87% secondary attack rate, including probable cases) after a 2.5 hour choral rehearsal on 10 March 2020 in Washington (USA) was initially reported by Hamner et al[1] (rated as low methodological quality) and further discussed by Miller et al.[52] For both outbreaks, close contact and fomite transmission were only assessed through interviews and cannot be fully ruled out. The high secondary attack rate, however, suggests that long distance airborne transmission might have occurred for at least some of the cases.

The results from the four studies suggest that long distance airborne transmission was likely to have occurred for at least some of the transmission events, and that singing may have increased the amount of aerosol generated by the primary cases, which is consistent with modelling results reported by some of these authors.[52,53]

Summary and critical analysis of results

Seven of the outbreaks identified[1,34,36-38,45,48] occurred in the early stage of the pandemic (January-March 2020) when knowledge of covid-19 was limited, especially the incubation period and the extent of asymptomatic or presymptomatic transmission. As a result, most of these studies only conducted symptomatic testing and considered potential secondary cases to be participants with symptom onset soon after the potential exposure event, including the next day. In addition, for the studies conducted in January 2020 in China and in March 2020 in Europe or the US, it is possible that community transmission was higher than perceived at the time.

Therefore, in an outbreak such as the one reported by Luo et al[37] where no genomic sequencing was conducted and three of the nine secondary cases developed symptoms or tested positive for SARS-CoV-2 one or two days after exposure, it is plausible that more than one primary case was present and that transmission occurred through means other than long distance airborne transmission. In two of the studies reporting on singing events,[1,48] genomic sequencing and asymptomatic testing were not carried out and some of the secondary cases developed symptoms in the days after exposure but because of the high attack rates reported for these outbreaks, it is possible that long distance airborne transmission had happened for at least some of the transmission events. Long distance airborne transmission was also considered possible for two other early studies as a result of detailed epidemiological investigations.[34,36] However, the plausibility of long distance airborne transmission for the outbreak in the department store was unclear as other transmission routes could not be ruled out.[45]

Among the other studies, four[33,35,41,46] provided convincing evidence for long distance airborne transmission as a result of detailed epidemiological investigations combined with genomic sequencing. Eichler et al[32] also conducted genomic sequencing but their reporting of the epidemiological investigation was not sufficiently exhaustive to exclude other transmission routes (close contact or fomite) for the only secondary cases who could have been infected by long distance airborne transmission. The investigations by Shah et al,[47] Hwang et al,[39] Groves et al,[42] Han et al,[40] and Vernez et al[43] suggested that long distance airborne transmission was possible for at least some of the transmission events (close contact or fomite could not be fully ruled out), but stronger conclusions could not be drawn owing to methodological limitations (including the absence of genomic sequencing and risk of selection bias). Finally, the likelihood of long distance airborne transmission was unclear in the outbreak in the office reported by Sarti et al[44] as, despite the covid-19 measures in place, close contact and fomite transmission could not be completely ruled out on the basis of the investigation.

Eleven of the 18 studies reported on the use of face coverings.[33,35-44] Overall, the information provided was limited, and two of these studies only mentioned that face coverings were compulsory in the settings of interest (quarantine hotel[33] and food processing factory[41]) without reporting on adherence or behaviour (eg, whether workers wore face coverings correctly for the duration of their shift). Based on this limited information, we found no evidence of long distance airborne transmission where participants were known to have worn face coverings for the duration of exposure.

Only one of the outbreaks[33] identified occurred at a time when covid-19 vaccines were available, although in this outbreak the primary and secondary cases were not vaccinated.

Grading of the evidence

Table 3 provides the grading of the evidence for each of the primary outcomes: SARS-CoV-2 infection via airborne transmission at a distance >2 m, insufficient air replacement (modifying factor), directional air flow (modifying factor), and increased aerosol emission when singing, speaking loudly, or doing intense physical work (modifying factor). Assessment of modifying factors was considered not applicable for the two outbreaks where the likelihood of long distance airborne transmission had been judged as unclear.

For all four outcomes, the evidence was judged as having methodological limitations owing to study design and to be at serious risk of imprecision owing to small numbers of participants as well as some risk of bias in exposure or outcome assessment, or both. However, the risks of inconsistency and indirectness were judged as not serious as the results were consistent across studies conducted in a range of settings and with different populations and provide evidence of direct relevance to the public health question of interest. The risk of publication bias was judged to be serious for the outcome of SARS-CoV-2 infection through airborne transmission at a distance >2 m and for the modifying factor of activities associated with increased emission of aerosols, but not serious for the modifying factors of insufficient air replacement and directional air flow. As a result, the certainty of evidence was judged as very low for all outcomes.

Because of high heterogeneity between studies, the additional outcomes of time spent in the transmission setting and distance over which airborne transmission was thought to have occurred could not be summarised or graded using the GRADE framework. Exposure timings ranged from five minutes to three hours, and distances were up to 15 m.

Discussion

Evidence from the outbreak investigations discussed in this review suggests that airborne transmission of SARS-CoV-2 from an infectious individual to others located >2 m away can occur in different indoor non-healthcare settings. The results of this review show that when long distance transmission occurred, one or more factors were thought to have contributed. Modifying factors such as insufficient air replacement and singing are likely to result in an increased concentration of infectious respiratory particles within the indoor space, whereas factors such as directional air flow are likely to allow viable virus to travel further in a certain direction, which could potentially infect someone downstream of a primary case. The results of this review therefore confirm the importance of the role of ventilation to mitigate the risk of long distance aerosol transmission.[54-57]

A total of eight events (from four studies) in which singing may have contributed to long distance airborne transmission were identified.[1 46-48] These results are in line with experimental and modelling studies that have reported on singing and aerosol generation, suggesting that more virus-containing respiratory particles tend to be emitted when singing compared with speaking or breathing.[53 58] More generally, the quantity of respiratory particles emitted increases with loudness of vocalisation,[59 60] which was thought to have contributed to long distance aerosol transmission in a fitness facility.[42]

In 13 out of 18 studies identified,[33-37 41-48] suspected primary cases were asymptomatic, presymptomatic, or near the time of symptom onset when transmission occurred. This finding is consistent with wider evidence that people with asymptomatic or presymptomatic SARS-CoV-2 infection can contribute to the community spread of covid-19,[61-63] including from long distance airborne transmission.

Although the evidence on face coverings was limited, no outbreaks in which participants had been wearing face coverings for the duration of the exposure were identified. Evidence suggests that face coverings can reduce the number of respiratory particles emitted from the nose and mouth.[64] However, it is not possible to deduce from the evidence assessed in this review if wearing a face covering can prevent or reduce the risk of long distance transmission of SARS-CoV-2.

Most of the outbreaks we identified occurred at a time when population immunity was limited, either naturally acquired or vaccine mediated. This limits the applicability of our findings to the current context, although there is evidence that transmission of SARS-CoV-2 after vaccination does occur.[65] While the lack of evidence identified in vaccinated populations may to some extent reflect the successes of vaccine rollout, there may also be a time lag in publication of outbreak reports since vaccine programmes were initiated. There may also be less interest in publishing reports on SARS-CoV-2 associated outbreaks over time.

The evidence from our rapid systematic review was deemed to be of very low certainty based on 18 studies. The relatively small number of studies identified could suggest that outbreaks related to long distance airborne transmission are rare, although also likely to result from difficulties in identifying such events or to under-reporting—for example, in countries without sufficient contact tracing. It can also be partly explained by the level of detail needed to assess transmission routes. Indeed, even outbreak investigations that follow reporting guidelines such as the Outbreak Reports and Intervention studies Of Nosocomial infection (ORION) statement published by the Canada Communicable Disease Report[66] are not necessarily thorough enough to be able to fully rule out other transmission routes. As a result, several outbreaks in which long distance airborne transmission may have happened were excluded on full text, including a few reports on clusters in aeroplanes that did not properly consider transmission routes during boarding and disembarking.[67-70] Finally, the wider challenges of the pandemic should be acknowledged, including the limited resources in public health teams to conduct detailed epidemiological investigations.

The outcomes were rated as being of very low certainty using the GRADE framework, although this reflects the principles of GRADE rather than a lack of quality of the included studies because in traditional evidence hierarchies, outbreak investigations are

Table 3 | Summary of findings using Grading of Recommendations, Assessment, Development, and Evaluation approach

Outcome	Effect	No of studies	Certainty in the evidence
SARS-CoV-2 infection through airborne transmission over a distance >2 m	Sixteen studies suggested that long distance airborne transmission was the main transmission route for at least some of the transmission events in the reported outbreaks. Unclear in two studies	18	Very low owing to methodological limitations of the studies and serious risk of imprecision and publication bias
Modifying factor: insufficient air replacement	Fourteen studies suggested that insufficient air replacement had increased the likelihood of long distance airborne transmission. Unclear in two studies	16	Very low owing to methodological limitations of the studies and serious risk of imprecision
Modifying factor: directional air flow	Eleven studies suggested that directional air flow might have increased the likelihood of long distance airborne transmission. Unclear in one study	12	Very low owing to methodological limitations of the studies and serious risk of imprecision
Modifying factor: activities associated with increased emission of aerosols	Five studies (reporting on nine events) suggested that singing and speaking loudly might have increased the likelihood of long distance airborne transmission. Unclear in one study (intense physical work)	6	Very low owing to methodological limitations of the studies and serious risk of imprecision and publication bias

classed as a low level of evidence. However, some of the included studies were well conducted investigations of covid-19 outbreaks and their contribution to this particular research question should not be underestimated—they provide critical insight where other types of study are just not feasible.[71] The GRADE framework was developed to inform clinical practice where randomised controlled trials are feasible, and linear causal pathways are more often the norm. Public health research does not always fit easily within this framework and the question of what level of public health evidence is sufficient to support decision making for a novel infection warrants further consideration.

Comparison with other studies

These findings are an important addition to the wider body of evidence that supports the biological plausibility of airborne transmission as a potentially important route of transmission in certain scenarios. The wider evidence includes experimental evidence from animal studies[72] as well as experimental studies that have shown that SARS-CoV-2 can remain viable in artificially generated aerosols for up to 16 hours, and that the stability and viability depends on environmental factors such as temperature, humidity, and exposure to sunlight.[22] Similarly, biological monitoring studies have shown that SARS-CoV-2 RNA can be detected in exhaled breath and environmental air samples, but the evidence on viable virus remains limited to a few studies that mostly detected infectious virus in air samples collected at <2 m from the infectious individual.[22-24] These experimental and biological studies provide evidence that SARS-CoV-2 can be viable in aerosols and therefore support the epidemiological evidence from this rapid review, and from others[22 23] that suggest that airborne transmission can happen in some settings.

Strengths and limitations of this review

This rapid systematic review critically assessed the likelihood of long distance airborne transmission of SARS-CoV-2 using only direct real world evidence from observational studies from indoor non-healthcare settings. The application of inclusion criteria that focused the critical appraisal on those studies, which involved comprehensive investigations, is a key strength of our approach: some of these studies not only included epidemiological data, but also genomic analysis, video surveillance, analysis of seating arrangements, and environmental hypothesis testing.

The main limitation of selecting studies of only real world human-to-human transmission events is that scenarios where transmission has not occurred were not included, and likewise where transmission events have not been detected by contact tracing systems, which could be seen as a form of publication bias. All the evidence is from retrospective epidemiological investigations of outbreaks and therefore this review cannot make inferences on the extent to which long distance airborne transmission occurs or the contribution it may have on community rates of transmission: these remain critical questions for policy and practice. In addition, most of the outbreaks occurred before vaccine rollouts and it is unclear how these results apply to populations with a high level of immunity to infection. Finally, and as with all reviews assessing evidence related to covid-19, this rapid review is limited by the fact that the evidence assessed is from an emerging specialty.

Future work and policy implications

Well conducted outbreak investigations continue to be needed to assess the potential for long distance airborne transmission in vaccinated populations, and with more transmissible SARS-CoV-2 variants such as omicron. To assess transmission routes, such outbreak investigations should deploy robust and mixed methods, ranging from genomic analysis to environmental assessment, and they should be conducted as early as possible to reduce recall bias.

The results from this rapid systematic review highlight the need to ensure measures to mitigate SARS-CoV-2 long distance transmission in indoor settings, especially in poorly ventilated spaces. Identification of poorly ventilated public spaces should be undertaken and improvements made. Other factors such as directional air flow or singing that could increase the risk for long distance airborne transmission should also be considered in risk mitigation.

A need also exists to develop a new framework, or to adapt the existing GRADE framework, to support a pragmatic and consistent approach to the collation, interpretation, and synthesis of epidemiological investigations, especially when other types of studies are not feasible. The question of what level of public health evidence is sufficient to support decision making for a novel infection warrants further consideration.

Conclusion

This rapid review found evidence suggesting that long distance (>2 m) airborne transmission of SARS-CoV-2 might happen in indoor non-healthcare settings, and that it can occur from people who are asymptomatic or presymptomatic. All transmission events identified occurred alongside factors believed to have contributed to this type of transmission, including lack of air replacement (absence or little ventilation with fresh air), directional air flow (mainly through air circulation systems), and activities such as singing that increased aerosol emission. In the review, we found no evidence of long distance airborne transmission occurring without one or more of these factors present.

Based on the results from this review, indoor non-healthcare settings that might be at risk of long distance airborne transmission include hospitality settings such as restaurants, public transport, and workplaces with inadequate ventilation, as well as settings where activities resulting in increased aerosol emission, such as singing or speaking loudly are carried out.

These results highlight the importance of assessing ventilation, especially in indoor spaces where people meet others from outside their household. Particular attention should be given to ventilation in settings with activities that might increase the number of respiratory particles, for example, singing. Where ventilation is assessed to be inadequate, improvements should be made.

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Data sharing: Data are from published research and therefore are in the public domain. Extracted data are available in supplementary material 2.

The manuscript's guarantor (RC) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Dissemination to participants and related patient and public communities: This paper will be shared widely within the UK Health Security Agency and used to inform relevant guidance. It will also be shared with relevant stakeholders, policy makers, and other public health agencies within the United Kingdom and internationally. Further dissemination will include our website https://ukhsalibrary.koha-ptfs.co.uk/covid19rapidreviews/ and through colleagues working in covid-19 evidence synthesis.

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Supplementary information: supplementary material 1: search strategy, quality criteria checklist, and list of excluded studies
Supplementary information: supplementary material 2: data extraction of included studies

EXHIBIT J

Indoor Air and COVID-19 Key References and Publications

This page lists some of the technical publications addressing the science related to aerosol transmission of SARS-CoV-2 and related topics. Key publications about actions that can reduce the likelihood of this type of transmission are also listed.
The following links exit the site

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* workshop reports, agency reports, and other sources that do not undergo a standard peer-review

No FEAR Act Data

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EXHIBIT K

Ecosystems supported by Lake Balkhash in Kazakhstan are in jeopardy as desertification increases.

Edited by **Jennifer Sills**

Save Kazakhstan's shrinking Lake Balkhash

Kazakhstan is home to Lake Balkhash, one of the largest inland drainless lakes in the world. Estimated to be more than 35,000 years old (*1*), this lake has cultural, historical, and ecological value. However, since 1970, a substantial decrease in the Ili river runoff has led to a drawdown of water reaching the lake [(*2*), p. 18], leading to a decrease in water depth. Out of the original 16 lake systems around Lake Balkhash, only 5 remain (*1*). Preserving this lake ecosystem is crucial to halting the desertification process, which has already claimed a third of the lake and will have devastating effects on the diverse flora and fauna that depend on it.

Lake Balkhash's varying degrees of water mineralization support a wide variety of species; the western basin is freshwater, whereas the eastern basin is salty (*3*). The lake serves as a habitat for 20 species of fish, 6 of which live only in this lake (*3*), and 60 species of plants that don't grow anywhere else [(*4*), pp. 304–310]. More than 120 bird species rely on the lake [(*2*), pp. 24–26], 12 of which are listed in Kazakhstan's Red Book of endangered species [(*4*), p. 305]. Because the lake is located in a desert area, without runoff and with a dry continental climate and very little precipitation, these species will have nowhere else to go if their water source disappears.

To protect Lake Balkhash, local legislation that regulates industrial exploitation of the lake water area should be updated and enforced. The media should actively promote environmental awareness among the population of Kazakhstan. Designating Lake Balkhash a national treasure would increase the social significance of the lake in Kazakhstan as well as abroad. Kazakhstan should monitor the lake and provide public access to up-to-date data on its parameters (especially the current volume of water). The country should also clearly define areas of responsibility among the states that are responsible for water resources management. Given rising water security risks in Kazakhstan, Lake Balkhash needs an international collaboration to provide urgent and effective protection. It is crucial that local and national policy-makers, law enforcement authorities, scientists, the public sector, socially responsible businesses, and the world community work together to protect this ancient lake.

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Airborne transmission of SARS-CoV-2

There is overwhelming evidence that inhalation of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) represents a major transmission route for coronavirus disease 2019 (COVID-19). There is an urgent need to harmonize discussions about modes of virus transmission across disciplines to ensure the most effective control strategies and provide clear and consistent guidance to the public. To do so, we must clarify the terminology to distinguish between aerosols and droplets using a size threshold of 100 µm, not the historical 5 µm (*1*). This size more effectively separates their aerodynamic behavior, ability to be inhaled, and efficacy of interventions.

Viruses in droplets (larger than 100 µm) typically fall to the ground in seconds within 2 m of the source and can be sprayed like tiny cannonballs onto nearby individuals. Because of their limited travel range, physical distancing reduces exposure to these droplets. Viruses in aerosols (smaller than 100 µm) can remain suspended in the air for many seconds to hours, like smoke, and be inhaled. They are highly concentrated near an infected person, so they can infect people most easily in close proximity. But aerosols containing infectious virus (*2*) can also travel more than 2 m and accumulate in poorly ventilated indoor air, leading to superspreading events (*3*).

Individuals with COVID-19, many of

whom have no symptoms, release thousands of virus-laden aerosols and far fewer droplets when breathing and talking (*4–6*). Thus, one is far more likely to inhale aerosols than be sprayed by a droplet (*7*), and so the balance of attention must be shifted to protecting against airborne transmission. In addition to existing mandates of mask-wearing, social distancing, and hygiene efforts, we urge public health officials to add clear guidance about the importance of moving activities outdoors, improving indoor air using ventilation and filtration, and improving protection for high-risk workers (*8*).

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COMPETING INTERESTS

K.A.P. is Director of the National Science Foundation Center for Aerosol Impacts on Chemistry of the Environment. L.C.M. is a member of the Science Advisory Board and holds stock options for Phylagen and is a paid reviewer for the Alfred P. Sloan Foundation. R.T.S. is a member of the Gilead Sciences Scientific Advisory Board and chairs Data Safety and Monitoring Boards for VIR, Gilead, and Merck. Honoraria for these activities are paid to the Regents of the University of California. R.T.S. has served as a scientific consultant to Pfizer and to AbbVie. M.A.M. is the unpaid Chair of the National Academy of Medicine Committee on Personal Protective Equipment for Workplace Safety and Health.

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Deliberate poisoning of Africa's vultures

Between September 2019 and March 2020, more than 2000 Critically Endangered (*1*) hooded vultures (*Necrosyrtes monachus*) were killed across eastern Guinea-Bissau. Investigations revealed that the vultures were intentionally poisoned to collect their heads for belief-based use. Locals sighted bait placed where vultures died and reported a demand for vulture heads in Senegal (*2*, *3*). Toxicological analysis of carcasses confirmed poisoning with methiocarb (*3*), a carbamate pesticide banned in Europe (*4*) but still used in Guinea-Bissau. If unchecked, these poisonings are likely to continue, leading to further declines in the population of this imperiled species.

Old World vultures are among the most threatened groups of birds worldwide (*5*). In Africa, the illicit trade in vulture parts accounts for 29% of reported vulture deaths (*6*). In West Africa, up to 61 and 70% (inside and outside parks, respectively) of vultures disappeared in just 30 years (*7*). Hundreds of hooded vultures are traded yearly for belief-based use, and their heads are considered good luck charms (*8*). Prices are rising as they become more rare (*8*, *9*). Guinea-Bissau is home to about 22% of the world's 197,000 hooded vultures (*10*, *11*).

Hooded vultures (*Necrosyrtes monachus*) in Guinea-Bissau could be driven to extinction.

This blow to vulture conservation requires urgent action. Local stakeholders need to be made aware of the loss of critical ecosystem functions, such as waste removal and the likely control of disease (*5*, *12*). African governments should raise awareness about existing anti-poisoning legislation among residents, authorities, and police and invest the human and financial resources required to effectively enforce these laws. In addition, the governments should curb cross-border and local trade. International partners must help West African countries develop and implement national action plans to conserve vultures and avoid their looming extinction.

Mohamed Henriques[1]*, Ralph Buij[2,3], Hamilton Monteiro[4,5], Joãozinho Sá[4,6], Francisco Wambar[4], José Pedro Tavares[7], Andre Botha[8], Geoffroy Citegetse[9], Miguel Lecoq[10], Paulo Catry[11], Darcy Ogada[2,12]

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COMPETING INTERESTS

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PHOTO: PEDRO NARRA/MINDEN PICTURES

Airborne transmission of SARS-CoV-2

Jennifer Sills, Kimberly A. Prather, Linsey C. Marr, Robert T. Schooley, Melissa A. McDiarmid, Mary E. Wilson, and Donald K. Milton

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EXHIBIT L

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Indirect Virus Transmission in Cluster of COVID-19 Cases, Wenzhou, China, 2020

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To determine possible modes of virus transmission, we investigated a cluster of coronavirus disease cases associated with a shopping mall in Wenzhou, China. Data indicated that indirect transmission of the causative virus occurred, perhaps resulting from virus contamination of common objects, virus aerosolization in a confined space, or spread from asymptomatic infected persons.

[1]These authors contributed equally to this article.

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the causative agent of coronavirus disease (COVID-19), is presumed to spread primarily via respiratory droplets and close contact. However, these transmission modes do not explain all cases. To determine how the virus may have spread among a cluster of COVID-19 cases associated with a shopping mall in Wenzhou (a city with 8 million residents), China, we monitored and traced close contacts and hypothesized possible transmission modes. We analyzed clinical and laboratory data for cases by using real-time reverse transcription PCR (*1*). The study was approved with written consent from the Ethics Committee of Wenzhou Central Hospital and written informed consent from all case-patients.

On January 20, 2020, a 23-year-old man (patient E) sought care at a hospital after 11 days of fever and headache. On January 21, COVID-19 was confirmed for patient E and his co-worker, patient G. The Wenzhou Center for Disease Control and Prevention traced and tested their contacts, and by January 28, COVID-19 was confirmed for 7 persons (patients A–G) from the same office (on floor 7).

Patient A, a 30-year-old woman, the only case-patient who indicated that she had been in Wuhan, China, returned from Wuhan on December 18, 2019. On January 15–16, 2020, she had a fever, but symptoms resolved without treatment. Despite symptom resolution, on January 30 she was confirmed to have SARS-CoV-2 infection. If patient A is the index patient, infected in Wuhan, her incubation period would have been 28 days, which would be extremely long, according to updated information (W.J. Guan et al., unpub. data, https://www.medrxiv.org/content/10.1101/2020.02.06.20020974v1). Asymptomatic carrier transmission has been reported for SARS-CoV-2 (*2*); hence, patient A could have been screened as a close contact during her incubation period and then hospitalized on the basis of a positive test (PCR) result only. However, her clinical symptoms did not appear until after hospitalization. Because persons with asymptomatic COVID-19 can spread the virus, patient A also could have been an asymptomatic carrier with a persistent infection (*3*).

On January 22, the mall was shut down. During January 19–February 9, COVID-19 was diagnosed for 7 mall staff from floors B1–3 and for 10 mall customers. Close contacts associated with the mall were traced, and COVID-19 was confirmed for 11 persons. Sixteen patients had had direct contact with other patients or had gone shopping in the mall. The average incubation period was 7.3 (range 1–17) days.

The mall has 8 floors above ground and several basement levels; floors B1 to 6 are commercial

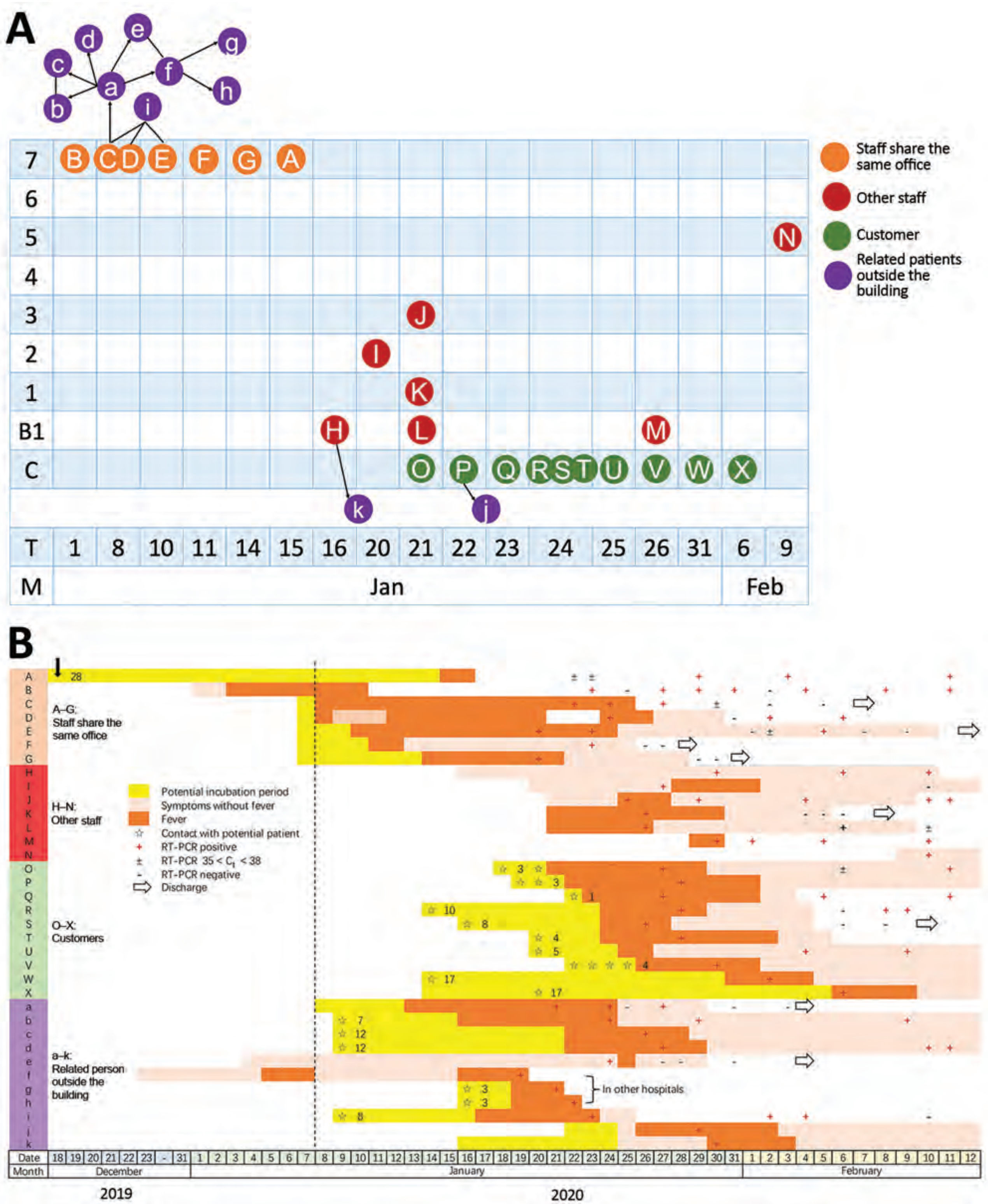

Figure. Cluster of COVID-19 cases associated with a shopping mall in Wenzhou, China. A) Distribution of COVID-19 case-patients by mall floor, time, and internal relationship. B) Dates of symptom onset, confirmed test results, and hospitalization information. Numbers within yellow bars indicate length of incubation period. Black vertical arrow indicates date when patient A returned from Wuhan, China. B1–7, mall floors; C, customer; COVID-19 coronavirus disease; C_t, cycle threshold; T, date of symptom onset; M, month; RT-PCR, reverse transcription PCR.

shopping space, and floor 7 contains shopping and office space. We created an illustration showing the floors where the eventual COVID-19 case-patients worked or shopped, along with dates of symptom onset, potential incubation periods, symptom durations, confirmed times of positive diagnosis, and times of discharge (Figure 1, panel A).

Except for those who had been on floor 7, all other case-patients denied direct close contact with other case-patients. The possibility of customers being infected from other sources cannot be excluded. However, most customers reported early symptom onset in a concentrated time frame (Figure 1, panel B). We found no convincing evidence of definitive transmission pathways in this building. Patients A–G (Figure 1, panel A) worked in the same room on floor 7. Other case-patients who had been on other floors denied any direct contact with confirmed patients from floor 7, but they shared common building facilities (e.g., restrooms, elevators). Also, staff from floor 7 visited shops on other floors daily.

Until now, no evidence has shown that SARS-CoV-2 can survive outside the body for long. However, Middle East respiratory syndrome coronavirus demonstrates high robustness and a strong capability to survive outside the body and can remain infectious for up to 60 minutes after aerosolization (*4*). Hence, the rapid spread of SARS-CoV-2 in our study could have resulted from spread via fomites (e.g., elevator buttons or restroom taps) or virus aerosolization in a confined public space (e.g., restrooms or elevators). All case-patients other than those on floor 7 were female, including a restroom cleaner, so common restroom use could have been the infection source. For case-patients who were customers in the shopping mall but did not report using the restroom, the source of infection could have been the elevators. The Guangzhou Center for Disease Control and Prevention detected the nucleic acid of SARS-CoV-2 on a doorknob at a patient's house (*5*), but Wenzhou Center for Disease Control and Prevention test results for an environmental sample from the surface of a mall elevator wall and button were negative.

We cannot exclude the possibility of unknown infected persons (e.g., asymptomatic carriers) spreading the virus. However, according to screening protocols implemented by the Wenzhou Center for Disease Control and Prevention, we traced all close contacts and included all patients with positive PCR results, including the asymptomatic carrier (patient A), in this study. Our findings appear to indicate that low intensity transmission occurred without prolonged close contact in this mall; that is, the virus spread by indirect transmission.

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About the Author

Dr. Cai is deputy chief physician and deputy director of the comprehensive internal medicine department. Her major research interest focuses on infectious diseases and gastrointestinal diseases.

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EXHIBIT M

U.S. Department of Homeland Security

Estimated Surface Decay of SARS-CoV-2 (virus that causes COVID-19)

on surfaces under a range of temperatures, relative humidity, and UV Index

Use the sliders to select the UV index (select either 0 or a value between 1.5 and 12), temperature and relative humidity of interest. Information on how long SARS-CoV-2 would be expected to remain stable on surfaces will be displayed in the table below. Users can find the environmental conditions for a specific location by accessing general weather resources online.

SARS-CoV-2 Surface Decay Calculator

UV Index:
0 10
UV Index: 2

Temperature:
74 95
Temperature: 68 °F / 23.3°C

Relative Humidity:
20 60
Relative Humidity: 20 %

* Note: Temperature (68°F) and relative humidity (20%) input cannot be changed for UV values greater than 0.

COVID Stability:

% Virus Decay	Hours	Days
50% (half-life):	5.32	0.22
99.99%:	70.71	2.95
99.9999%:	106.07	4.42
99.999999%:	141.42	5.89

Relative humidity, temperature, and sunlight (UV) can be used to provide an estimated half-life for SARS-CoV-2 with this model with some degree of certainty. The predictive power is limited to temperature between 74-95°F and relative humidity between 20-60% for a UV index of 0, and a temperature of 68°F and 20% relative humidity for a UV index between 1.5 and 12. The formula below was developed in °C, but has been modified in the web calculator to use °F.

Examples of Applying Surface Stability Model to Estimate SARS-CoV-2 Stability on Indoor Surfaces

Equation:

$t_{1/2}(T,RH) = 32.43 - 0.62T - 0.15RH$

Examples:

$t_{1/2}(28,30) = 32.43 - 0.62(28) - 0.15(30)$

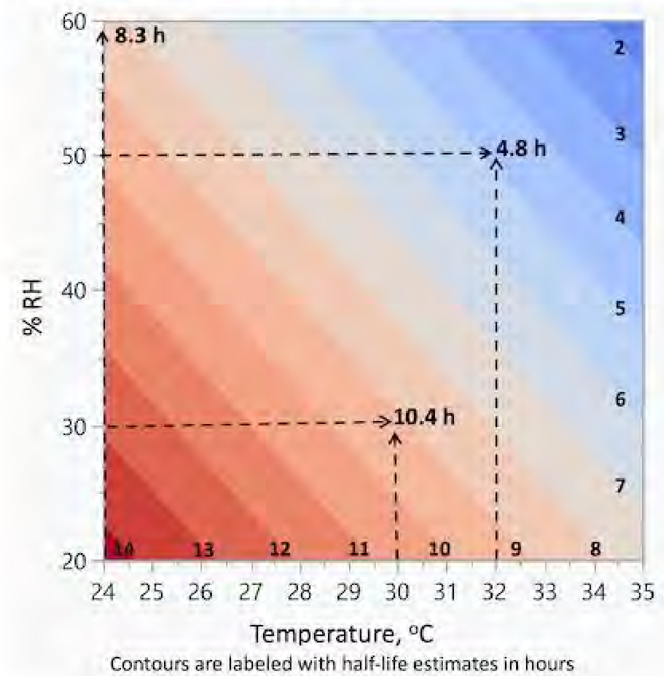
$t_{1/2}(28,30) = 10.4$ h

$t_{1/2}(24,60) = 32.43 - 0.62(24) - 0.15(60)$

$t_{1/2}(24,60) = 8.3$ h

$t_{1/2}(32,50) = 32.43 - 0.62(32) - 0.15(50)$

$t_{1/2}(32,50) = 4.8$ h

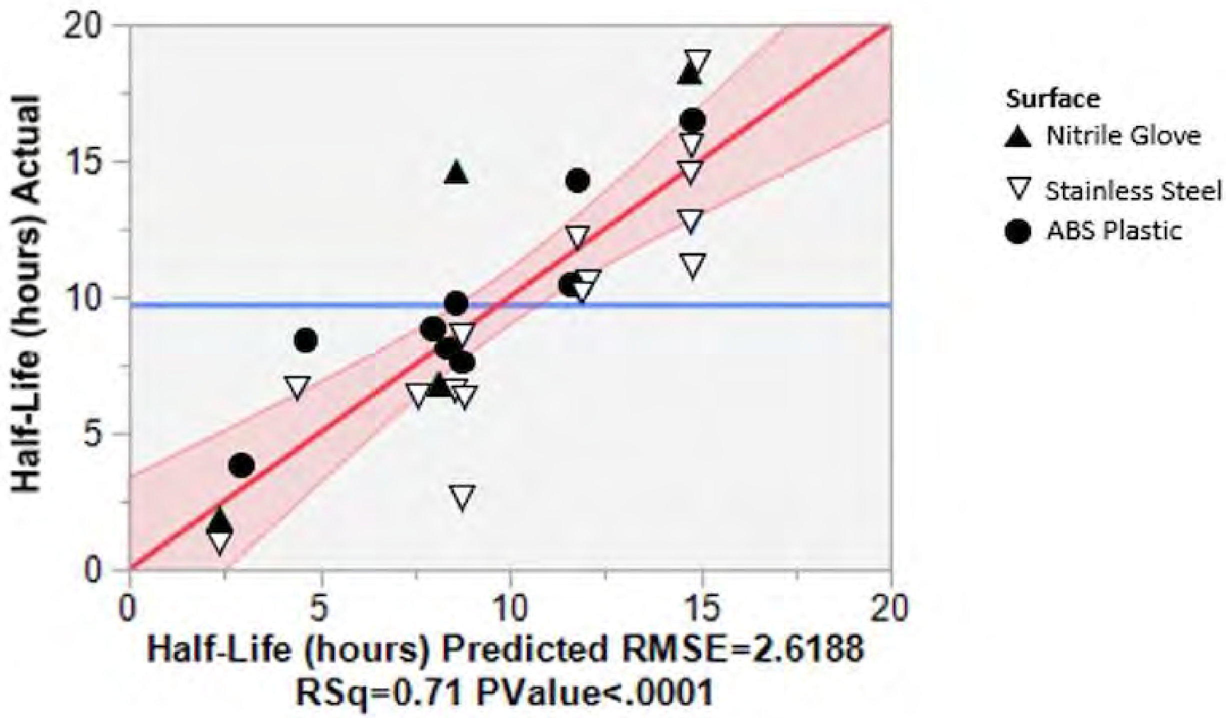


Close all   Open all

Background

- Preventing person-to-person spread of SARS-CoV-2 is the only means to reduce the impact of COVID-19 in the absence of an effective therapeutic.
- Transmission occurs primarily through respiratory droplets produced by talking, coughing and sneezing.
- Contact with contaminated surfaces and objects may also contribute to spread.
- SARS-CoV-2 will survive in saliva and respiratory fluids on surfaces for extended periods of time under certain conditions.
- DHS S&T has studied the stability of SARS-CoV-2 in simulated saliva, using droplets of varying size deposited on a non-porous surface under a range of temperature and RH conditions.
- Viral survival on surfaces is driven by temperature, relative humidity (RH), sunlight (UV), and matrix (e.g., bodily fluids).
- These data have been used to develop a predictive model to estimate virus decay under a limited range of environmental conditions.
- Testing performed on non-porous surfaces, specifically stainless steel, ABS plastic, and nitrile rubber.
- There was no significant difference found in the decay of the virus found between stainless steel ABS plastic, and nitrile rubber.
- For additional information and details on methodology for the research on the impact of temperature and relative humidity on SARS-CoV-2 decay on surfaces, please see the article titled, "Increasing Temperature and Relative Humidity Accelerates Inactivation of SARS-CoV-2 on Surfaces" published in the American Society for Microbiology journal (https://www.dhs.gov/now-leaving?external_url=https%3A%2F%2Fmsphere.asm.org%2Fcontent%2F5%2F4%2Fe00441-20%23%3A~%3Atext%3DThe%20results%20show%20that%20SARS%2Cnot%20significantly%20impact%20decay%20rate.&back_url=https%3A%2F%2Fwww.dhs.gov%2Fsc and-technology%2Fsars-calculator) .
- Research to determine impact of UV exposure on SARS-CoV-2 decay on surfaces was conducted at one temperature/relative humidity parameter. For additional information and details on methodology, please see the article titled, "Simulated Sunlight Rapidly Inactivates SARS-CoV-2 on Surfaces" published in the Journal of Infectious Diseases (https://www.dhs.gov/now-leaving?external_url=https%3A%2F%2Facademic.oup.com%2Fjid%2Farticle%2F222%2F2%2F214%2F5841129&back_url=https%3A%2F%2Fwww.dhs.gov%2Fscience-and-technology%2Fsars-calculator) .

Model Caveats



- Infectious dose is unknown (how much makes a person sick)
- Virus shedding is unknown (how much a sick person puts into the environment)
- Contact Hazard (how much virus comes off from touching surfaces)

This tool is valid for the following ranges of conditions:

- Without exposure to sunlight (UV 0): temperature (74°F to 95°F) and relative humidity from 20-60%.
- With exposure to sunlight (UV 1.5-12): temperature 68°F and relative humidity 20%.

S&T is partnering with CWMD to develop a tool that is easily accessible could be used by Occupational Safety and Health (OSH) professionals to support risk assessment, cleaning and disinfection in accordance with guidance provided by CDC and EPA including Guidance for Cleaning and Disinfecting: Public Spaces, Workplaces, Businesses, Schools, and Homes (https://www.cdc.gov/coronavirus/2019-ncov/community/pdf/reopening_america_guidance.pdf) . *(PDF, 9 pgs., 235 KB)*

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REVIEW

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Stability and transmissibility of SARS-CoV-2 in the environment

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Abstract

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus causing the ongoing global coronavirus disease 2019 (COVID-19) pandemic, is believed to be transmitted primarily through respiratory droplets and aerosols. However, reports are increasing regarding the contamination of environmental surfaces, shared objects, and cold-chain foods with SARS-CoV-2 RNA and the possibility of environmental fomite transmission of the virus raises much concern and debate. This study summarizes the current knowledge regarding potential mechanisms of environmental transmission of SARS-CoV-2, including the prevalence of surface contamination in various settings, the viability and stability of the virus on surfaces or fomites, as well as environmental factors affecting virus viability and survival such as temperature and relative humidity. Instances of fomite transmission, including cold-chain food transmission, and the importance of fomite transmission in epidemics, are discussed. The knowledge gaps regarding fomite transmission of SARS-CoV-2 are also briefly analyzed.

KEYWORDS

cold-chain transmission, environmental stability, fomite transmission, SARS-CoV-2, surface contamination, survivability

1 | INTRODUCTION

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2, family *Coronaviridae*, genus *Betacoronavirus*, species *severe acute respiratory syndrome-related coronavirus*) is the causative agent of coronavirus disease 2019 (COVID-19). SARS-CoV-2 is highly contagious as evidenced by its spread to nearly all countries worldwide within a very short time.[1] However, the viral determinants for the high transmissibility of SARS-CoV-2 are still unclear, and routes by which the virus can effectively spread through the population remain debating.

Respiratory viruses are transmitted between individuals when virus is released from the respiratory tract of infected individuals and is transferred to the environment, leading to infection of the respiratory tract of exposed and susceptible people.[2] It is recognized that respiratory viruses spread via four transmission routes: droplet, aerosol, direct contact, and indirect transmission.[2,3] SARS-CoV-2 was initially recognized to transmit mainly via respiratory droplets from an infected host. Aerosol transmission of SARS-CoV-2 was subsequently proven to be the predominant transmission mode.[4–6] Transmission through droplets and aerosols are both classified as airborne transmission.[3] Droplets and aerosols are conventionally distinguished by size (5 μm), delineating distinct characteristics such as dispersion efficiency, residence time in the air, and deposition patterns along the human respiratory tract.[5] Direct contact transmission refers to direct virus transfer from an infected to a susceptible individual (e.g., via contaminated hands), and indirect transmission occurs via contaminated environmental surfaces or fomites that serve as vectors for virus transmission.[2,3] Direct transmission of SARS-CoV-2 has been confirmed after tracing case clusters. However, the role of indirect SARS-CoV-2 transmission through intermediate surfaces or fomites remains under discussion, with considerable controversy.[7,8]

For contaminated surfaces or fomites to play a role in transmission, a respiratory pathogen must be shed into the environment, possess the capacity to survive on surfaces, be transferred to hands or other objects at a concentration above the minimum infective dose, and be able to initiate infection through contact with the eyes, nose, mouth or by re-inhalation into the respiratory tract.[2,9] In this study, we review current new evidence on these topics, including the shedding of SARS-CoV-2, contamination of environmental surfaces in various settings, stability and viability of SARS-CoV-2 on environmental surfaces and objects including cold foods, and current evidence for and against the importance of fomite transmission. We aim to summarize the findings regarding the transmissibility of environmental SARS-CoV-2 and relative importance of indirect environmental transmission in COVID-19 spread. We also identify ongoing research gaps and opportunities. The information provided herein will help in establishing practical and effective protocols to interrupt indirect environmental transmission of SARS-CoV-2 and mitigate its associated risks.

2 | SHEDDING AND DISSEMINATION OF SARS-CoV-2 FROM INFECTED INDIVIDUALS

Viral shedding is the first step of virus transmission from infected to susceptible individuals. Respiratory virus shedding occurs after airway epithelial cells excrete virions to extracellular fluid in the respiratory tract, especially the upper respiratory tract, through sneezing, breathing, talking, singing, coughing, and other aerosol-generating activities.[2]

Studies show that shedding of SARS-CoV-2 can begin before symptom onset,[10–13] peak in the first week of illness.[12,13] In contrast to SARS and MERS but similar to influenza, COVID-19 exhibits high viral shedding at an early stage of infection, when virus carriers display no or mild symptoms.[14,15] Most studies attempting virus isolation from respiratory samples have also successfully cultured viable virus within the first week of illness whereas live virus is rarely isolated from patients beyond 9 days of symptomatic illness.[15] When SARS-CoV-2 RNA screening was carried out in communities, more than half of the residents with positive test results were asymptomatic at the time of testing.[16–19] The rapid dissemination of COVID-19 may be attributed to the existence of presymptomatic and asymptomatic patients with active virus shedding, as these patients are harder to identify and control. The relative contribution of asymptomatic transmission was much higher in regions where case-based interventions were stringent.[20]

The viral load in infected individuals is an important factor affecting their transmissibility. Studies found that the viral load in patients' nasopharyngeal swabs is positively correlated with viral loads emitted in both droplets and aerosols, and with environmental contamination.[21–23] Multivariate analyses have identified that viral load (viral RNA) larger than 10^7 copies/ml (OR = 14.7) is independently associated with isolation of infectious virus from respiratory tract samples.[13] Numerous studies have demonstrated that higher SARS-CoV-2 viral load in the upper airway of an infected person is associated their increased infectivity.[24–26]

Using quantitative RT-PCR assay, Pan et al. determined viral loads in sputum and throat swab samples of 80 patients. The median viral load was 7.52×10^5 copies/ml and 7.99×10^4 copies/ml; the highest load was 1.34×10^{11} copies/ml and $>10^8$ copies/ml, respectively.[12] Studies have found that SARS-CoV-2 viral load in respiratory samples is similar in symptomatically and asymptomatically infected persons. Yang et al. showed that the distribution of SARS-CoV-2 viral load in 1405 asymptomatic individuals fits under a log-normal distribution centered around the mean of 2.1×10^7 virions/ml, while the highest viral load found in saliva was 6.1×10^{12} copies/ml.[27] Comparing with H1N1 influenza A, the standard deviation of the overall respiratory viral load distribution for COVID-19 was significantly higher, showing that the heterogeneity in viral load was indeed broader for SARS-CoV-2 infected persons.[28] This indicates that some patients shed virions at very high concentrations, for example, the highest viral load found in H1N1 influenza A patients was 1×10^{10}copies/ml, while the highest viral load in SARS-CoV-2 infected individuals can reach 6.1×10^{12} copies/ml.[28] Approximately 2% of individuals with SARS-CoV-2 have a viral load $>10^{10}$ copies/ml.[27] Further analysis found that just these 2% of individuals carry 90% of the virions circulating within communities, serving as viral "supercarriers."[27]

The heterogeneity in transmissibility among infected individuals may be associated with dissimilarity of viral shedding. The supercarriers shed virions at very high concentrations, making them highly infectious and more likely to contaminate the environment. Analyses of such individuals suggest heterogeneity associated with superspreading events as an intrinsic viral factor facilitating greater overdispersion of SARS-CoV-2 during the COVID-19 pandemic than influenza A during the 2009 influenza pandemic.[27,28]

In addition to respiratory tract specimens, viable SARS-CoV-2 has been detected in other biological samples, including stool and urine.[29] The detection of viable SARS-CoV-2 in diverse bodily fluids and secretions indicates various other potential sources of environmental contamination.

3 | ENVIRONMENTAL CONTAMINATION OF SARS-CoV-2

SARS-CoV-2 environmental contamination occurs through the release of nasal mucus, sputum, saliva, and other biological fluids by infected individuals into their surroundings. Infected individuals can contaminate surfaces and objects to create fomites by either shedding onto their hands and then touching a surface or by expelling respiratory particles when coughing, speaking, or even breathing, which then fall onto a surface.[6,30,31] Aerosolized droplets from an infected person can easily settle and persist on immediate surfaces for extended periods, especially in poorly ventilated indoor spaces with a continual affluence of people.[6,32]

3.1 | Presence of SARS-CoV-2 in clinical settings

Studies have found extensive SARS-CoV-2 contamination of surfaces in hospitals dedicated to patients with COVID-19. In airborne infection isolation rooms where COVID-19 patients were hospitalized in Singapore, 56.7% of rooms were found have at least one contaminated environmental surface, and high-touch surface contamination was found in the rooms of 10 (66.7%) of 15 patients during the first week of their illness.[33] In a study at six acute care hospitals in Toronto, 125 (26%, 125/474) surface samples from 42 (57%, 42/74) patient rooms were positive for SARS-CoV-2 RNA.[34] In another study, swabs taken from hospital air exhaust outlets yielded positive test results, suggesting that small virus-laden droplets may be displaced by airflows and deposited on equipment, such as vents.[22]

Some patients with SARS-CoV-2 infection appear to cause more extensive environmental contamination than others. In addition to higher viral load in respiratory samples, multivariable analysis indicates that hypoxia at admission, higher Charlson comorbidity score, and the time from illness onset to the sampling date are significantly associated with the presence of SARS-CoV-2 RNA on surface samples.[23,34]

In outpatient health care facilities, surface contamination has also been found, including on dental chairs, sinks, keyboards, ophthalmoscopes, laboratory equipment, and door handles. Places with greater contact had higher positive rates.[30,33] Toilet bowl and sink samples have tested positive for SARS-CoV-2, suggesting possible viral shedding in stool.[22]

3.2 | Presence of SARS-CoV-2 on surfaces in households

Households have been important sites of transmission throughout the COVID-19 pandemic. SARS-CoV-2 has been detected in the household environment of individuals with COVID-19, notably on surfaces in areas where there is close, prolonged contact with persons who have recently tested positive for SARS-CoV-2.[35,36] SARS-CoV-2 RNA appears to be able to sustain on environmental surfaces for a long time. One study found that a month after symptom subsidence, 46% of surfaces in the home had detectable levels of SARS-CoV-2.[36] Some surfaces found to be SARS-CoV-2 positive, such as home HVAC filters, floors, and the top of televisions, are common reservoirs for dust build-up and might be infrequently touched.[36] In contrast to hospitals and health care settings, there are limited data on environmental contamination with SARS-CoV-2 in households.

3.3 | Prevalence of SARS-CoV-2 on high-touch surfaces in community settings

During the ongoing pandemic, emerging evidence shows that SARS-CoV-2 is present in different community environments. Longitudinal monitoring of SARS-CoV-2 RNA on high-touch surfaces was carried out in Massachusetts, United States during a COVID-19 outbreak. SARS-CoV-2 RNA was found on various surfaces in 10 of 12 locations sampled; the overall positive rate among surface samples was 8.3% (29/348).[37] In a densely populated urban area of Brazil, SARS-CoV-2 RNA was detected in 5.3% (49/933) of swab samples collected from public surfaces, including metal and concrete, and in distinct places, mainly around hospital care units and public squares.[38] The viral RNA concentrations detected on surfaces in both studies ranged between <0.1 and 40 gc/cm^2 (gene copies per cm^2) and 2.5–102 gc/cm^2, respectively.

SARS-CoV-2 viral RNA has also been detected on environmental surfaces in playgrounds,[39] supermarkets,[40] cruise ship surfaces,[41] public transport vehicles,[42] tourist recreational facilities,[43] retail stores, and workplaces.[37] Surfaces in public areas that are exposed to human crowding or that are frequently touched by the hands (e.g., ATMs in public facilities) are frequently found to be positive for SARS-CoV-2 RNA contamination.[30]

3.4 | Presence of SARS-CoV-2 in cold foods

During the pandemic, workers in labor-intensive workplaces such as seafood processing and food manufacturing plants or slaughterhouses, have had high COVID-19 infection rates.[44,45] Processed foods and their packaging can be contaminated by infected workers with mild or no symptoms through falling respiratory droplets or hand contact. SARS-CoV-2 RNA has been detected many times in cold-chain aquatic products imported to China and their packaging materials.[46] In September 2020, the contamination status of imported frozen seafood from a cargo ship in Qingdao was investigated; the positive rate of SARS-CoV-2 RNA in frozen seafood was 11.53% (106/919).[47]

4 | VIABILITY AND STABILITY OF SARS-CoV-2 IN THE ENVIRONMENT

Assessment of the risks posed by SARS-CoV-2 on surfaces requires data on viability and stability of the virus on environmental surfaces as well as how virus viability is affected by environmental variables, such as air temperature and relative humidity.

4.1 | Viability of SARS-CoV-2 isolated from surface samples in natural settings

Many studies have attempted to assess the viability and infectivity of SARS-CoV-2 present on surfaces or objects. Using cell culture

TABLE 1 Viable severe acute respiratory syndrome coronavirus 2 isolated from various surfaces

Settings	Sample source	Culture cell	Virus *Ct* (or concentration) of the swab from surface	References
Patient room	Bathroom door, bed and switch, phone, table and chair, toilet and sink	Vero E6	NA	[34]
Household	Nightstand	Vero CCL-81	26.4	[35]
Quarantine unit	Windowsill	Vero E6	0.65 copies/µl	[48]
Patient room	Windowsill	Vero E6	>102 copies/µl	[48]
Negative-pressure isolation rooms	Endotracheal tube, floor, bed rails, bedsheet, ambu mask/NIV, bedside table, remote controller	Vero E6	30.9-34.3	[49]
Imported food	Frozen cod package	Vero E6	NA	[50]

Abbreviations: Ct, cycle threshold of real-time PCR; NA, not available; NIV, noninvasive ventilation.

systems, viable SARS-CoV-2 virus has been isolated from various environmental settings,[34,35,48,49] as well as frozen food packaging[50] (Table 1). These studies provide direct evidence supporting SARS-CoV-2 survival in fomites for a length of time consistent with the possibility of onward transmission.

4.2 | Stability of SARS-CoV-2 on skin, environmental surfaces, and in cold foods

4.2.1 | Stability of SARS-CoV-2 on the skin

Human hands are considered critical vectors in direct contact and indirect transmission of SARS-CoV-2. To understand how long SARS-CoV-2 can remain viable on the hands and evaluate the importance of hand hygiene, two experimental studies evaluated SARS-CoV-2 stability on the skin. In one study, 50 µl of SARS-CoV-2 virus at a starting titer of 4.5 ± 0.5 log10 PFU (plaque-forming unit) was deposited onto swine skin with the hair removed. The virus remained viable on skin samples for 8 h at 37°C, at least 96 h at 22°C, and for 14 days at 4°C.[51] In another study on human skin, Hirose et al. compared the stability of SARS-CoV-2 and influenza A virus and found that SARS-CoV-2 could survive approximately 9 h on skin, significantly longer than the survival time of influenza A virus (approximately 1.8 h), indicating that the stability of SARS-CoV-2 is markedly higher. However, the survival and half-life times of both SARS-CoV-2 and influenza A virus were significantly shorter on human skin than on other surfaces, indicating that the hands are less suitable for virus survival.[52]

4.2.2 | Stability of SARS-CoV-2 on inanimate surfaces

Several in-vitro studies have evaluated the survivability of SARS-CoV-2 when inoculated onto dry surfaces and shown that SARS-CoV-2 is relatively stable.[53–60] Using large initial viral concentrations and under optimized environmental conditions, SARS-CoV-2 can remain viable on solid surfaces such as plastic, glass, stainless steel, and polymer banknotes for up to 28 days at 20°C (Table 2).

Some researchers have controversed the results because of much higher amount of virus used in these studies than that in actual contamination. Considering that a portion of infected individuals have a viral load >10^{10} copies/ml in saliva,[27] and the most infectious saliva and cough specimens exhibited virus loads approaching 10^6 PFU/ml,[61] the initial viral concentrations used in these studies are plausible. In fact, SARS-CoV-2 shows an exponential decay in virus titer across all experimental conditions, as indicated by a linear decrease in the log10 TCID50/ml (50% tissue-culture infectious dose per ml) on surfaces over time.[53,54] When decimal reduction time (*D* value), the time of a 1-log reduction in viability (or infectivity), was used to gauge the stability of SARS-CoV-2, the virus inactivation rate on environmental surfaces was independent of initial loading.[54] Paton et al.[55] compared the viability of SARS-CoV-2 on stainless steel coupons between two starting titers, and found that the virus could be recovered after 4 days at the lower titer of 4×10^3 PFU/ml and 7 days at the higher titer of 4×10^5 PFU/ml, suggesting that the virus can remain viable on stainless steel for several days even with a lower initial viral load. Sun et al.[62] also reported that at 22°C the virus with a low starting titer of 10^4 TCID50 on stainless steel and plastic bag maintained infectious for 3 days.[62] These findings suggest high stability of SARS-CoV-2 on certain surfaces.

A comparison of SARS-CoV-2 and SARS-CoV-1 showed that these viruses have similar levels of stability on dry surfaces under the same experimental circumstances. However, the survival and half-life of SARS-CoV-2 was significantly longer than that of influenza A virus across different inanimate surface types, suggesting that SARS-CoV-2 is more stable.[53] Therefore, SARS-CoV-2 may pose a higher risk of transmission through fomites than influenza A virus.

4.2.3 | Stability of SARS-CoV-2 in cold foods

Unlike regular surfaces or fomites, cold foods are generally characterized by conditions that promote viral particle survival, such as high protein and moisture levels, temperatures below 4°C, and a lack of exposure to direct sunlight. Numerous studies have found that

TABLE 2 Studies on the survival of severe acute respiratory syndrome coronavirus 2 on dry surfaces

Surface type	Virus titer	Loading volume (μl/cm²)	Medium	Relative humidity (%)	Temperature	Time of virus decay	References
Stainless steel, plastic, cardboard, copper	1.78×10^5 TCID50/ml	50	Cell culture medium	65	21°C–23°C	3 days, 3 days, 1 day, 4 h	[53]
Stainless steel	4×10^3PFU/ml, 4×10^5 PFU/ml		Cell culture medium	45	21.5°C	4 days, 7 days	[54]
Plastic, aluminum, glass	10^6 TCID50/ml	50	None or BSA	45–55	19°C–21°C	4 days	[55]
Plastic, cotton, stainless steel, nitrile gloves	7.58×10^7 TCID50/ml		Organic soil	30–40	20°C	21 days, 0–4 h, 14 days, 7 days	[56]
Stainless steel, plastic, rubber glove	3.38×10^7 TCID50/ml	10	Simulated saliva	50	20°C	28 days	[57]
Cotton cloth						14 days	
Stainless steel, Plastic, glass, Banknote, surgical mask, cloth, wood, tissue paper	6.31×10^6 TCID50/ml	5	Cell culture medium	65	22°C	4 days, 4 days, 2 days, 2 days, 7 days, 1 day, 1 day, 30 mins–3 h	[58]
Salmon	3.16×10^6 TCID50/ml	soaked	Cell culture medium	NA	25°C, 4°C	2 days, 8 days	[59]
Plastic, metal coupons	10^6 PFU/ml		Cell culture medium	50	22°C	3 days, 3 days	[60]

Abbreviations: NA, not available; TCID50, 50% tissue-culture infectious dose; PFU, plaque-forming unit.

in cold foods contaminated with SARS-CoV-2 RNA, the viability and stability of virions within the foods, as a marker for transmission, raises much concern.

A laboratory study demonstrated that SARS-CoV-2 on contaminated fish with a titer of 3.16×10^6 TCID50/ml can survive for 2 days at 25°C and for 8 days at 4°C.[59] In an experiment involving contamination of pork, beef, and salmon meat with low virus concentrations close to the actual concentration in respiratory secretions, SARS-CoV-2 retained viability for 3 days at 4°C and for 7 days at −20°C.[63]

Similar to raw meats and seafood, deli foods that are high in protein, fats, and moisture can maintain infectivity of SARS-CoV-2 for up to 3 weeks when stored at refrigeration temperature (4°C).[64,65] However, processed meat, such as salami, and some fresh produce have exhibited antiviral effects.[65]

Under refrigeration (4°C) and freezing (−10°C to −80°C) conditions, the virus can remain infectious for more than 21 days in some foods.[59,66] Because under globalized logistics networks, imported and exported cold foods are usually transported in a low-temperature (e.g., 0°C to −4°C) environment from one country or region to another within a few days, contaminated food may serve as a vector for international transmission of SARS-CoV-2.

4.3 | Environmental factors affecting the viability of SARS-CoV-2

The survival and persistence of SARS-CoV-2 on surfaces appears to be influenced by many environmental factors, of which the following are particularly important.

(1) Types of surface and medium or metrics

The stability and viability of SARS-CoV-2 on surfaces is highly dependent on surface materials (Table 2). In general, coronaviruses are inactivated more rapidly on porous materials (i.e., containing pores/cavities) than nonporous materials. Longer persistence is observed on less absorbent or hydrophobic porous surfaces, particularly hydrophobic synthetic items, such as surgical masks, compared with hydrophilic natural fibers like cotton. It is hypothesized that dryness accelerates the inactivation of SARS-CoV-2 on paper and other porous solids; conversely, droplets of water remaining on waterproof surfaces protects the virus from dryness.[54,67]

Experimental studies show that the stability of SARS-CoV-2 on surfaces is also affected by its surrounding matrix; the suspending medium used to dry the virus onto surfaces is another important factor influencing survival times.[53,68] Several studies have demonstrated that the addition of a moderate amount of protein, like bovine serum albumin or mucus, to the inoculating suspension when loading onto a surface increases SARS-CoV-2 infectivity, indicating that additional protein provides a protective effect for the virus during and after drying on surfaces.[55–58] These results suggest that a protein-rich medium, like airway secretions, could protect the virus when it is expelled and may enhance its persistence and transmission via contaminated fomites.

(2) Temperature

Temperature is a critical environmental factor that affects SARS-CoV-2 survival. Like other known viruses, the stability of SARS-CoV-2 either in solution or on a dry surface is inversely correlated with temperature.

The half-life of SARS-CoV-2 infectivity is 1.7–2.7 days at 20°C and decreases to a few hours at 40°C on common surfaces.[57] SARS-CoV-2 can persist for 14 days in Dulbecco's modified Eagle medium at 4°C whereas the persistence time is dramatically reduced to 10 min and 1 min when the temperature is increased to 56°C and 70°C, respectively.[58] Because viruses are sensitive to temperature, heating is one method used for virus inactivation, including for SARS-CoV-2.

Using low virus concentrations close to the actual concentration of viral particles in the environment, SARS-CoV-2 has been shown to be more stable and infectious after storage at −20°C than at 4°C.[69] Infectious SARS-CoV-2 can persist for at least 60 days on cold-chain food packaging (kept at less than −18°C).[70] These foods are produced, transported, stored, and sold in a cold chain to keep them fresh, which also helps the virus to retain its viability and infectivity for a longer time.

(3) Humidity and moisture status

In contrast to dry surfaces, moist surfaces are more likely to be positive for SARS-CoV-2 RNA, and the duration of environmental surface contamination is associated with the moisture status of the sampling site.[23,66] Studies have found that water cups are the most frequently contaminated site in the hospital rooms of patients with COVID-19, and SARS-CoV-2 RNA can be detected in the water cup in room-temperature environments for 48 days after the infected patient has left the room, suggesting that water in the cup may play an important role in virus persistence.[23,70]

Relative humidity is associated with viability of airborne respiratory viruses. Biryukov and colleagues[71] found that SARS-CoV-2 on dry surfaces can decay more rapidly with increased humidity. However, contradictory findings have been obtained regarding SARS-CoV-2 viability and relative humidity. One study found that the rate of viral decay was most rapid at 65% relative humidity and slower with either lower (40%) or higher (75%) humidity.[72] Further studies found that there is an interaction effect between temperature and humidity on viral viability on surfaces. When the relative humidity was increased from 20% to 80%, the virus half-life changed from 18.6 to 6.3 h at room temperature (24°C) and from 8.9 to 1.0 h at 35°C.[71] The rate of inactivation increases with increased temperature and shows a U-shaped dependence on relative humidity.[72]

5 | OCCURRENCE OF SARS-CoV-2 INFECTIONS THROUGH INDIRECT TRANSMISSION

Extensive surface contamination of SARS-CoV-2 around asymptomatically and symptomatically infected individuals has been documented, and increasing evidence shows that SARS-CoV-2 can remain viable on surfaces, from several hours to 21 days. Thus, contaminated surfaces and fomites may result in exposing a larger number of susceptible individuals to potential infection.

5.1 | Fomite transmission estimated using mathematical models

Several mathematical model-based epidemiological investigations have evaluated the relative importance of different modes of virus transmission. Modeling of the Diamond Princess Cruise ship outbreak suggested that short-range (droplets), long-range (aerosols), and fomite transmission modes contributed to 35%, 35%, and 30% of infected cases, respectively, across the entire simulation period. The estimated contribution of fomite transmission before the start of quarantine on the cruise ship was higher than that after quarantine began.[73] Higher relative risks associated with SARS-CoV-2 fomite transmission were also reported in studies modeling child daycare centers[74] and hospital and health care settings.[75,76] However, studies of the infection risk via fomites using different mathematical models have had surprisingly divergent outcomes, with extremely low substantial risk estimates being reported.[37,77] This discrepancy could be explained by bias introduced from data on viral exposure and persistence generated in simulated laboratory conditions and those observed in naturally contaminated real-life scenarios.

5.2 | Fomite transmission demonstrated in animal experiments

Direct evidence for fomite transmission is still lacking because of difficulty in distinguishing between cases arising from fomite transmission and those involving droplet and aerosol transmission. A hamster model provided robust evidence to support fomite transmission, although airborne transmission was found to be more efficient. Hamsters were infected after being exposed to 40 µl of 8×10^4 TCID50 viruses in a propylene dish for 24 h.[78] Hamsters exposed to fomite SARS-CoV-2 displayed delayed replication kinetics in the respiratory tract and less severe lung pathology in comparison with hamsters exposed via aerosol inoculation.[78] Other studies using hamster models also demonstrated SARS-CoV-2 transmission via fomites in the absence of direct contact, droplets, and aerosols, in which naive hamsters were placed in cages where infected hamsters had lived and became infected.[79,80]

Rhesus macaques can be infected with SARS-CoV-2 through direct conjunctival inoculation but develop less severe pulmonary disease than macaques inoculated via an intra-tracheal route, implying that an extra-respiratory route of SARS-CoV-2 infection and hand contamination pose an increased risk of virus infection.[81]

5.3 | Occurrence of COVID-19 through fomite and cold-chain transmission

Because conventional epidemiologic studies cannot distinguish between competing transmission pathways (e.g., droplet, aerosol, direct, or fomite) acting simultaneously, reports on COVID-19 related to the transmission of SARS-CoV-2 from contaminated surfaces are rare.[82,83] Even in the few instances that appear to have been caused by surface transmission, aerosol transmission cannot be ruled out, and debate continues regarding the importance of fomite transmission of SARS-CoV-2.[7,8]

However, several outbreaks and sporadic cases in China have been demonstrated to be associated with transmission from imported cold-chain foods (Table 3).[46,50,84–86] The first outbreak speculated to originate from contaminated imported cold-chain foods occurred at Xinfadi Market in Beijing in June 2020. The index case emerged after 56 days with no community transmission in Beijing, and the possibility of contact with overseas personnel was ruled out based on epidemiological investigations. Subsequent field investigations and an on-site simulation experiment suggested that the virus spread from contaminated foods to humans in the market.[84] In September 2020, an outbreak occurred among dock workers in Qingdao, Shandong Province.[50] Apart from epidemiological evidence that the index case had no exposure to any COVID cases, more convincing evidence involved viable SARS-CoV-2 isolated from the outer packaging of frozen cod to which the workers were exposed.[50] Similar connections have been found in re-emerged COVID-19 outbreaks in the Chinese coastal cities of Dalian, Tianjin, and Guangzhou (Table 3). Investigation results documented the possibility that imported cold foods and their packaging can serve as vectors for the reintroduction of SARS-CoV-2 into areas with controlled transmission. The evidence from these outbreaks supports that cold-chain logistics transmission of SARS-CoV-2 is biologically plausible.

However, it has been nearly impossible to identify cases of infection via cold-chain food transmission during the pandemic when infections are primarily attributed to close-proximity transmission. Fomite transmission can be easily identified during the period of epidemic near-eradication, with the absence of explanatory source cases in the community.[87] With the near elimination of SARS-CoV-2 in China during 2020–2021, it became possible to exclude transmission via close contact with a known case and to distinguish unusual transmissions from single cases.

6 | IMPLICATION OF SARS-CoV-2 INFECTIONS VIA INDIRECT TRANSMISSION AND KNOWLEDGE GAP

Although it is estimated that the transmission of SARS-CoV-2 via fomites is rare, the possibility of fomite transmission cannot be ruled out. The debate over fomite transmission has shifted to the implications of this transmission mode.[7]

6.1 | Implication of SARS-CoV-2 infections via indirect transmission

During 2020–2021, although most Western countries were gradually lifting their border controls and quarantine measures, the Western Pacific Region, including in China, retained the elimination strategy aiming for "zero COVID-19." When stringent quarantine measures were implemented for travelers to control the introduction of infectious diseases, several outbreaks occurred in cities where COVID-19 was close to elimination via imported frozen foods or

TABLE 3 COVID-19 outbreak or sporadic infection initiated by cold chain food

Location, China	Starting date	Related cold chain food (COVID-19 RNA positive)	Period since the last infection (consecutive days)	References
Beijing	June, 2020	Imported salmon	59	[84]
Dalian	July, 2020	Frozen seafood products	111	[85]
Qingdao	September, 2020	Frozen cod packages	151	[50]
Tianjin	November, 2020	Frozen pork packages	125	[86]
Dalian	December, 2020	Imported cold food	NA	[46]
Yingkou	May, 2021	Frozen cod	NA	[46]
LiuAn	May, 2021	Frozen cod	NA	[46]

Abbreviation: NA, not available.

packaging.[46,50,84–86] In these cases, fomite transmission constituted a critical problem, by posing the risk of reintroducing the virus into a region that achieved local epidemic elimination.

Fomite transmission can occur over long distances, when contaminated objects are transported from one site to another. The development of e-commerce and express delivery services has made it possible for fomite transmission to cause intercity, interregional, and international virus spread, thereby sustaining the pandemic. Different from other infectious disease pandemics over the past century, the COVID-19 pandemic represents the first time that modern logistics have been emphasized as a possible vector for virus transmission and a serious concern.

Another concern is that some items contaminated with the virus, such as food products, have been stocked in cold storage during the global pandemic. These frozen items will likely be thawed and consumed over the next years, releasing the viable virus and posing the risk of human reinfection.

6.2 | Knowledge gaps in environmental transmission of COVID-19

The debate over the risks and control measures of fomite transmission is expected to continue until the mechanisms involved are fully understood. Among the many knowledge gaps regarding this transmission mode, the following are of greatest concern: (1) the way via which virus deposited on surfaces is re-transferred to humans is unknown. In addition to transferring virus from fomites to the hands and subsequently to mucous membranes of the mouth, nose, or eyes, there may be alternative routes via which the virus is transferred to humans from fomites. A plausible route could be via “aerosolized fomites,” in which live virus on surfaces is taken up into the air and inhaled.[7,88,89] In living and workplace settings, contaminated objects can generate aerosols, such as when transporting and processing frozen foods.[89] (2) The minimum infective dose required to cause an infection via a specific transmission mode is unknown. Recent studies report that respiratory tract samples from COVID-19 with only 14–30 PFU[28] or a minimum infective dose as low as 1 TCID50 caused illness in Syrian hamsters.[90] Nevertheless, it remains a challenge to identify the minimum infective dose of fomite transmission, making it difficult to quantitatively estimate the risks associated with exposure to fomites. (3) Emergence of the SARS-CoV-2 Omicron strain has raised concerns about whether its increased infectivity is owing to altered contamination/persistence on surfaces and/or a gain in airborne transmissibility.[91–93] Currently, viral factors provide inadequate explanation for its high transmissibility. Further molecular epidemiologic data may help to address this question.

7 | CONCLUSION

There is now extensive evidence supporting the contamination of surfaces and objects caused by individuals infected with SARS-CoV-2. SARS-CoV-2 showed high stability and viability in environment, surviving for hours to days depending on the surface, temperature, and humidity as key factors in viral survival. Studies have isolated viable virions from contaminated surfaces, including dry surfaces and frozen fish. Experimental animal models proved that infections can occur via the fomite transmission route. More importantly, several outbreaks and sporadic cases in China have been demonstrated to be associated with transmission from imported cold-chain foods. It is worth noting for international community that indirect transmission of SARS-CoV-2 through fomite may constitute problems by posing the risks of long distance transmission, reintroducing the virus into an area that achieved local epidemic elimination, and extending the duration of the pandemic. Strengthening the inspection and quarantine of cold-chain foods from high-epidemic areas should be an effective measure for COVID-19 prevention. Personal protective measures including washing hands and regular disinfection practices should reduce environmental contamination and the possibilities of environmental transmission of the virus.

AUTHOR CONTRIBUTIONS

Yansheng Geng and Youchun Wang conceived and wrote the manuscript. Youchun Wang contributed to the modification and revision of the manuscript. Both authors approved the submitted versions.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available on request from the authors.

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EXHIBIT O

HEALTH AND SCIENCE

Virus that causes Covid-19 can survive for 28 days on common surfaces, research says

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KEY POINTS

- The findings from Australia's national science agency, the CSIRO, appeared to show that SARS-CoV-2 can survive on surfaces for significantly longer than many had anticipated.

- The study, which was peer reviewed, also found the virus responsible for the Covid-19 disease was "extremely robust" at lower temperatures, remaining infectious for a longer period when compared to higher temperatures.

- The WHO recommends cleaning hands thoroughly and often, and avoiding touching your eyes, mouth and nose.

A worker cleans the seats in a cinema hall as part of preparations for a possible reopening after the government eased the lockdown restrictions previously imposed due to the Covid-19 coronavirus, in Chennai on October 8, 2020.

Australian researchers said Monday, reinforcing the importance of effective cleaning and handwashing to curb the spread of Covid-19.

The findings from Australia's national science agency, CSIRO, appeared to show that SARS-CoV-2 can survive on surfaces for significantly longer than many had anticipated.

The study, which was peer reviewed, also found the virus was "extremely robust" at lower temperatures, remaining infectious for a longer period when compared with higher temperatures.

The researchers tested the survival rates of the virus, dried in an artificial mucous solution, at three temperatures on six common surface areas. All the experiments were carried out in the dark, however, since UV light has already been shown to kill the virus.

VIDEO 04:46

Covid-19 virus we're seeing is not the same one we saw in March: Holy Name Medical Center CEO

The coronavirus is mostly spread from person to person via small droplets from the nose or mouth, which are expelled when an infected person coughs, sneezes or speaks.

However, the World Health Organization has also said it is possible to become infected when these droplets land on objects and surfaces that are touched by people who may then touch their eyes, nose or mouth.

To protect yourself, the United Nations health agency recommends that people keep a distance of at least 1 meter from others, and disinfect frequently touched surfaces. It also recommends cleaning hands thoroughly and often, and avoid touching your eyes, mouth and nose.

More than 37.4 million people worldwide have contracted the coronavirus, killing 1.07 million people, according to data

CSIRO researchers tested SARS-CoV-2 on several surfaces at 20 degrees Celsius, 30 degrees Celsius, and 40 degrees Celsius, with the relative humidity kept at 50%. The surfaces used in the study were stainless steel, glass, vinyl, paper and polymer banknotes, and cotton cloth.

A droplet of fluid containing the virus at concentrations similar to levels observed in infected patients was dried on multiple small test surfaces and left for up to 28 days, the researchers said.

The study, published in Virology Journal, found the virus survived on smooth surfaces, such as stainless steel, glass, vinyl, and paper polymer banknotes, for 28 days when kept at 20 degrees Celsius (68 F), which is roughly room temperature, and in the dark.

The virus stopped being infectious within 24 hours on some surfaces when tested at 40 degrees Celsius (104 F). At 30 degrees Celsius (80 F), the virus' viability fell to three days on cotton and vinyl, and seven days on glass, steel and polymer banknotes.

A worker cleans the classes to prepare the school before face-to-face teaching at certain classes on October 10, at Taybe Schools in Khan Yunis, Gaza on October 04, 2020.
Mustafa Hassona | Anadolu Agency via Getty Images

"These findings demonstrate SARS-CoV-2 can remain infectious for significantly longer time periods than generally considered possible," the study authors said, noting further research on the number of virus particles that can cause infection was still necessary.

The researchers said that whether virus particles on a surface could infect someone was dependent on several conditions and the time it takes for viruses to naturally inactivate was also dependent on many factors.

remains viable. Environmental conditions such as temperature, exposure to sunlight and humidity also play a part," they said.

CSIRO confirmed to CNBC that what was found was a live viable virus, rather than SARS-CoV-2 RNA or virus fragments.

One previous laboratory test published in The Lancet medical journal found that SARS-CoV-2 could survive for three days on banknotes and glass, and up to six days on plastic and stainless steel.

By comparison, the influenza A virus has been found to survive on surfaces for 17 days.

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EXHIBIT P

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Virology Journal

RESEARCH Open Access

The effect of temperature on persistence of SARS-CoV-2 on common surfaces

Shane Riddell*, Sarah Goldie, Andrew Hill, Debbie Eagles and Trevor W. Drew

Abstract

Background: The rate at which COVID-19 has spread throughout the globe has been alarming. While the role of fomite transmission is not yet fully understood, precise data on the environmental stability of SARS-CoV-2 is required to determine the risks of fomite transmission from contaminated surfaces.

Methods: This study measured the survival rates of infectious SARS-CoV-2, suspended in a standard ASTM E2197 matrix, on several common surface types. All experiments were carried out in the dark, to negate any effects of UV light. Inoculated surfaces were incubated at 20 °C, 30 °C and 40 °C and sampled at various time points.

Results: Survival rates of SARS-CoV-2 were determined at different temperatures and D-values, Z-values and half-life were calculated. We obtained half lives of between 1.7 and 2.7 days at 20 °C, reducing to a few hours when temperature was elevated to 40 °C. With initial viral loads broadly equivalent to the highest titres excreted by infectious patients, viable virus was isolated for up to 28 days at 20 °C from common surfaces such as glass, stainless steel and both paper and polymer banknotes. Conversely, infectious virus survived less than 24 h at 40 °C on some surfaces.

Conclusion: These findings demonstrate SARS-CoV-2 can remain infectious for significantly longer time periods than generally considered possible. These results could be used to inform improved risk mitigation procedures to prevent the fomite spread of COVID-19.

Keywords: Environmental stability, SARS-CoV-2, COVID-19, Survivability

Background

The World Health Organization (WHO) declared SARS-CoV-2 a pandemic on 11th March 2020 and as at the 7th August 2020, there have been over 18.8 million confirmed cases with more than 708,000 reported deaths from SARS-CoV-2 [1].

The transmission of SARS-CoV-2 appears to be primarily via aerosols [2–4] and recent studies have shown that SARS-CoV-2 is able to remain infectious in airborne particles for greater than 3 h [5, 6]. The role of fomites in the current pandemic is yet to be fully determined, although they have been suggested as a potential mode of transmission [7] also reflected by the strong focus on hand-washing by WHO and national control schemes. Broadly, viruses have been shown to be readily transferred between contaminated skin and a fomite surface [8], with high contact surfaces such as touchscreens on mobile phones, bank ATMs, airport check-in kiosks and supermarket self-serve kiosks all acting as fomites for the transmission of viruses [9]. Fomite transmission has previously been shown to be a highly efficient procedure, with transmission efficiencies of 33% for both fomite to hand and fingertip to mouth transfer for bacteria and phages [10]. With the high efficiency of fomite transfer, the persistence of SARS-CoV-2 on environmental surfaces is therefore a critical factor when considering the potential for fomite transmission for this virus. Currently, there are conflicting reports on the survivability of SARS-CoV-2, with data ranging from 3 to 14 days at room temperature for a single surface type, stainless steel

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[5, 11]. This study aims to provide environmental stability data for SARS-CoV-2 under controlled temperature and humidity conditions for a range of common surfaces.

Methods

Virus isolate

The SARS-CoV-2 isolate (*Betacoronavirus/Australia/SA01/2020*) used in this study was kindly supplied by the Peter Doherty Institute (Victoria, Australia) on behalf of South Australian Health (South Australia). The virus was passaged four times through Vero E6 cells (ATCC CRL-1586) in Dulbecco's Modified Eagle Medium (DMEM) supplemented with Penicillin, Streptomycin, Fungizone and 10% fetal calf serum and pelleted via ultracentrifugation at 100,000 × *g* for 90 min. The virus was resuspended in phosphate buffered saline (PBS) with 1% bovine serum albumin (BSA) and stored at − 80 °C. The virus stock was titrated on Vero E6 cells and the $TCID_{50}$ was determined to be 4.97×10^7/mL by the Spearman–Karber method [12, 13].

All work with infectious SARS-CoV-2 was conducted in the high containment laboratory (Biosafety level 4) at the Australian Centre for Disease Preparedness.

Surfaces

Australian polymer bank notes, de-monetised paper bank notes and common surfaces including brushed stainless steel, glass, vinyl and cotton cloth were used as substrates in this study. Both polymer and paper banknotes were included in the study to gather information on the possible roles of note based currency in general for the potential for fomite transmission. Stainless steel is used in kitchen areas and public facilities and is the substrate used in some disinfectant testing standards [14, 15]. Glass was chosen due to its prevalence in public areas, including hospital waiting rooms, public transport windows and shopping centres, and high contact surfaces such as mobile phone screens, ATMs and self-serve check-out machines. Vinyl is a common substrate used in social settings, tables, flooring, grab handles on public transport, as well as mobile phone screen protector material. Cotton was chosen as a porous substrate, often found in clothing, bedding and household fabrics.

All surfaces were prepared by cutting into approx. 1–1.5 cm^2 coupons, non-porous surfaces were disinfected prior to use by washing in a mild detergent (Beckman 555), rinsing in distilled water and then immersing in 80% v/v ethanol. Paper bank notes (in very good condition) were heated in a dry oven to 75 °C for 1 h to reduce bacterial/viral contamination. The 100% cotton cloth was steam sterilised prior to use.

Following preparation, all surfaces were placed into a petri dish and allowed to dry in a class II biological safety cabinet (BSCII) at room temperature and humidity prior to inoculation.

Surface inoculation and sampling

Stock virus was diluted in a defined organic matrix, consisting of bovine serum albumin (BSA), mucin and tryptone, following international standard ASTM E2197 [15], designed to mimic the composition of body secretions. Briefly, 360 µL of virus stock was added to 160 µL of a solution consisting of 2.5 mg/mL BSA, 3.5 mg/mL tryptone and 0.8 mg/mL mucin. Ten microlitres of the resulting suspension (final concentration of 3.38×10^5/10 µL) was inoculated onto the centre of the coupon and allowed to dry in a BSCII for 1 h. Once dry, the coupons were placed into a humidified climate chamber (Memmert HPP110) for specified time points. Samples were incubated in the dark to limit any effect light might have on viral decay. A single humidity set point (50% relative humidity) was maintained for each of three separate temperature experiments (20 °C, 30 °C, 40 °C). For the 20 °C and 30 °C temperature experiments, three replicates of each surface type were inoculated and sampled at the following time points; 1 h, 1 day, 3 days, 7 days, 14 days, 21 days and 28 days post inoculation. For the 40 °C experiment, triplicate samples were inoculated for the following time points; 1 h, 1 day, 2 days, 3 days, 4 days, and 7 days.

For non-porous surfaces, for each replicate, virus was eluted in 2 × 115 µL volumes of DMEM with repeated pipetting then titrated individually, in quadruplicate wells on a 96-well plate. For recovery from cotton cloth, inoculated swatches of the cloth were individually submersed in 500 µL DMEM and pipetted repeatedly for at least 1 min before 230 µL of the recovered eluent from each swatch was titrated separately, in quadruplicate. Suspensions of Vero E6 cells (3×10^5/mL) were added to the wells and the plates were incubated for 3 days at 37 °C with 5% CO_2. Wells were scored for the presence of cytopathic effect and titres calculated using the Spearman–Karber method.

Statistical analysis

Data analysis (regression analysis) and graphical representations were performed using GraphPad Prism (version 5). Decimal reduction time (D value—time at which there was a one log/90% reduction in titre) was calculated using

$$D = \frac{t}{\left(\log N_0 - \log N_f\right)}$$

Z-values (temperature change required to achieve a tenfold (i.e. 1 $\log_{10}$) change in the D value) was calculated by plotting log D values against temperature. Calculated using:

$$Z = (t_2 - t_1)/(\log D_1 - \log D_2)$$

The half-life of each surface was calculated using;

$$t_{1/2} = \frac{log_{10}2}{k}$$

Results

At 20 °C, infectious SARS-CoV-2 virus was still detectable after 28 days post inoculation, for all non-porous surfaces tested (glass, polymer note, stainless steel, vinyl and paper notes). The recovery of SARS-CoV-2 on porous material (cotton cloth) was reduced compared with most non-porous surfaces, with no infectious virus recovered past day 14 post inoculation. The majority of virus reduction on cotton occurred very soon after application of virus, suggesting an immediate adsorption effect. The calculated D values for surfaces at 20 °C ranged from 5.5 days for cotton to 9.1 days for paper notes and are shown in Table 1.

At 30 °C, infectious virus was recoverable for 7 days from stainless steel, polymer notes and glass, and 3 days for vinyl and cotton cloth. For paper notes, infectious virus was detected for 21 days, although there was less than 1 log of virus recovered for both 14 day and 21 day time points. The D values for surfaces at 30 °C ranged from 1.4 days for vinyl to 4.9 days for paper notes (Table 1).

At 40 °C, virus recovery was significantly reduced compared to both 20 °C and 30 °C experiments. Infectious SARS-CoV-2 was not recovered past 24 h for cotton cloth and 48 h for all remaining surfaces tested. Greater than 4-log reduction (99.99% reduction from starting titre) was observed in less than 24 h at 40 °C on all surfaces. The D values for surfaces at 40 °C have been converted to hours as they were all less than 1 day, values ranged from 5 h for polymer notes to 10.5 h for vinyl (Table 1).

For each temperature and substrate material, the mean titre from three replicates of recovered virus was plotted against time, with standard deviations included. Linear regression was used to calculate a line of best fit. Plots showing virus survival on each substrate at the three temperatures investigated are shown in Fig. 1. Plots presenting this data grouping all substrates at each of the three temperatures are given in Fig. 2. Calculated D-value, Half Life and Z-value are presented in Table 1.

An additional table containing average titre and standard deviation for all substrates, time points and temperatures is available (See Additional file 1).

Table 1 Calculated D values (time taken to achieve a 90% reduction in titre) and half-life (time taken to achieve a 50% reduction in titre—in parentheses) for all surfaces at 20 °C, 30 °C and 40 °C

	D values (half-life)			Z value
	20 °C—days	30 °C—days	40 °C – hours	(°C)
Stainless steel	5.96 (1.80)	1.74 (12.6 h)	4.86 (1.5 h)	13.62
Polymer note	6.85 (2.06)	2.04 (14.7 h)	4.78 (1.4 h)	13.02
Paper note	9.13 (2.74)	4.32 (32.7 h)	5.39 (1.6 h)	12.43
Glass	6.32 (1.90)	1.45 (10.5 h)	6.55 (2.0 h)	14.65
Cotton	5.57 (1.68)	1.65 (11.0 h)	–	18.91
Vinyl	6.34 (1.91)	1.40 (10.1 h)	9.90 (3.0 h)	16.86

Calculated Z values (temperature shift required to alter D value by 1 log). No infectious virus was recovered for cotton cloth at 40 °C at 24 h, D values were not able to be calculated

Discussion

While the primary spread of SARS-CoV-2 appears to be via aerosols and respiratory droplets, fomites may also be an important contributor in transmission of the virus. Fomite transmission has been demonstrated as an important factor in the spread other coronaviruses such as porcine epidemic diarrhea virus [16], as well as being suspected for Middle East Respiratory Syndrome coronavirus [17], human coronavirus 229E and OC43 [18] and SARS-CoV-2 [7].

This study utilised a virus concentration of 4.97×10^7/mL diluted into a standard solution which mimics body fluid composition (final concentration of 3.38×10^5/10 μL inoculum), which equates to a cycle threshold (CT) value of 14.2, 14.0 and 14.8 for N gene, E gene and RdRp gene real time RT-PCR, respectively (unpublished data). Previous studies have shown some patients with high viral loads have recorded CT values of between 13 and 15 [19–21]. van Doremalen et al. [5] described their test material (10^5 $TCID_{50}$/mL) as having a CT of 20–22, which compared similarly to CTs reported from clinical patients [5, 22]. While the titre of virus utilised in this study is high it represents a plausible amount of virus that may be deposited on a surface.

The present study has demonstrated that in controlled conditions, SARS-CoV-2 at a starting viral load and in a fluid matrix equivalent to that typically excreted by infected patients, remains viable for at least 28 days when dried onto non-porous surfaces at 20 °C and 50% relative humidity. Research on the original SARS virus also showed recovery of infectious virus when dried on plastic for up to 28 days at room temperature and 40–50% RH [23]. Recent data published on SARS-CoV-2 survivability on hospital PPE observed viable virus up to 21 days post inoculation on both plastic and N95 mask material when

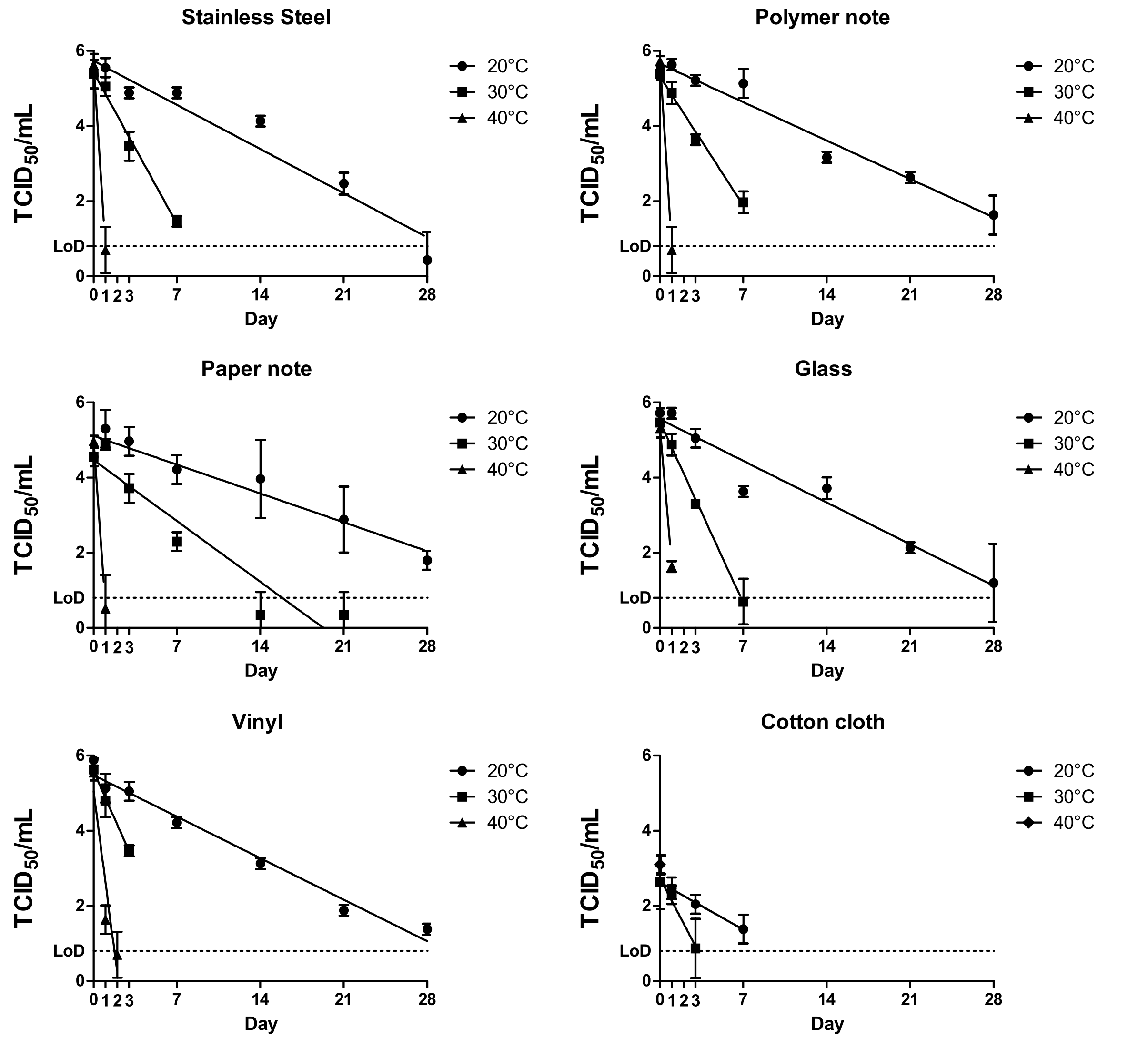

Fig. 1 Recovery of infectious SARS-CoV-2 for all surfaces and temperatures over time, $TCID_{50}$ data is plotted in log_{10} intervals. No infectious virus was recovered at 24 h at 40 °C for cotton cloth. LoD (limit of detection) is recorded as 0.8 Log_{10} $TCID_{50}$

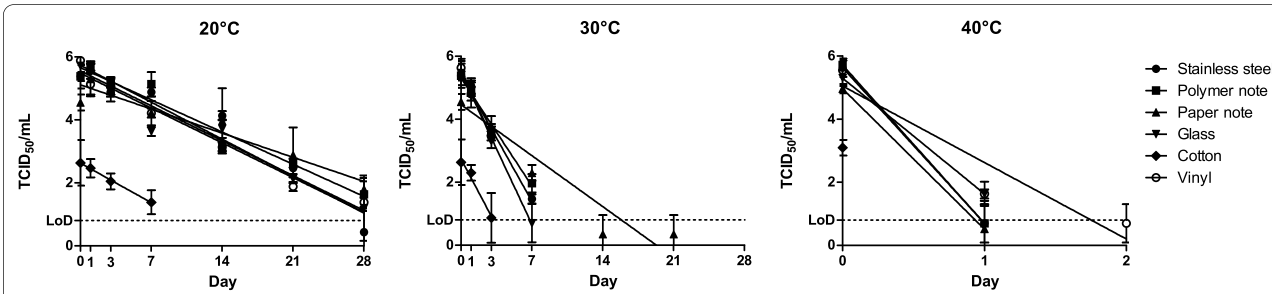

Fig. 2 Grouping of each surface for individual temperatures. Trend lines for 20 °C show similar slopes, including for cotton cloth (although a reduced recovery was observed). A single well of virus was observed for paper banknotes in one out of three replicates for both 14 days and 21 days.

held at room temperature [11], correlating with the data presented in this study. The persistence of SARS-CoV-2 on surfaces presented here and from Kasloff et al. [11] demonstrate significantly longer time points than previously published data for SARS-CoV-2 [5, 24]. These earlier studies reported recovery of infectious SARS-CoV-2 up to 3 days post inoculation and 4 days on non-porous surfaces, respectively. The titre of virus used in this study is at least 2 logs higher than used in the paper by van Doremalen et al. [5], which may account for the longer survivability. Work by Lai et al. has shown that stability of SARS virus was enhanced with higher concentrations [25]. Temperature and humidity are both critical factors in viral survivability with an increase in either being detrimental to virus survival [23, 26, 27]. Survivability on stainless steel coupons for transmissible gastroenteritis virus and murine hepatitis virus (both coronaviruses) was reduced with higher humidity's and temperature [28] and survivability of Middle East Respiratory Syndrome coronavirus also followed a similar pattern [29]. The higher humidity of ~ 65% RH used by Chin et al. [24] may explain the shorter persistence of virus when compared to the data presented here.

SARS-CoV-2 has been shown to be rapidly inactivated under simulated sunlight [30, 31]. To remove any potential decay by light sources, inoculated coupons were held in the dark for the duration of the experiment.

Decimal reduction (D value; the timetaken to reduce the titre by 1 log) for SARS-CoV-2 at 20 °C and 50%RH ranged from 5.57 to 9.13 days (average 6.82) for all surfaces tested. This data is significantly longer than modelling predications performed by Guillier et al. [32]. The data presented here was performed under controlled conditions with fixed temperatures, relative humidity, suspension matrix and in the absence of light, which may explain the enhanced survivability observed in this study. The generation of Z values at different temperatures also allows for extrapolation of D values for each surface at other temperatures. The Z value represents the temperature change required to alter the D value by 1 log. For stainless steel, the D value was determined to be 6.48 days at 20 °C, and the Z value of 13.62 °C, therefore if the temperature was to drop by 13.62 °C from 20 °C (i.e. to 6.38 °C), then the D value would increase from 6.48 days to over 64 days. This data could therefore provide a reasonable explanation for the outbreaks of COVID-19 surrounding meat processing and cold storage facilities. The data also supports the findings of a recent publication on survival of SARS-CoV-2 on fresh and frozen food [33].

Stainless steel is a common surface for study of viral stability, and has been used to study the persistence on a number of viruses such as Ebola virus, hepatitis virus, Influenza A and Coronaviruses [28, 34–37]. This study demonstrates that SARS-CoV-2 is extremely stable on stainless steel surfaces at room temperature (> 28 days at 20 °C/50%RH) however, is less stable at elevated temperatures (7 days at 30 °C and < 48 h at 40 °C). Recovery of infectious virus on stainless steel has been observed for murine hepatitis virus and transmissible gastroenteritis virus for up to 28 days albeit at a lower humidity 20%RH [28]. Interestingly, the same study showed survivability at 20 °C and 50%RH was significantly less (4–5 days), further suggesting the humidity may play a significant role in virus survival.

The persistence of virus on both paper and polymer currency is of particular significance, considering the frequency of circulation and the potential for transfer of viable virus both between individuals and geographic locations. While other studies have shown that paper notes harbour more pathogens than polymer notes [38], this data demonstrates that SARS-CoV-2 persists on both paper notes and polymer notes to at least 28 days at 20 °C, albeit with a faster rate of inactivation on polymer notes. Data presented in this study for banknotes is significantly longer than reported for other respiratory viruses such as Influenza A (H3N2) which demonstrated survival up to 17 days at room temperature [39]. It is also noted that prior to SARS-Cov-2 being declared a pandemic, China had commenced decontamination of its paper based currency, suggesting concerns over transmission via paper banknotes existed at the time [40, 41]. The United States and South Korea have also quarantined bank notes as a result of the pandemic [42, 43]. It is important to note that after 28 days, infectious SARS-CoV-2 was also recovered from stainless steel, vinyl and glass, suggesting survivability on paper or polymer banknotes was not very different from the other non-porous surfaces studied.

The persistence on glass is an important finding, given that touchscreen devices such as mobile phones, bank ATMs, supermarket self-serve checkouts and airport check-in kiosks are high touch surfaces which may not be regularly cleaned and therefore pose a transmission risk of SARS-CoV-2. It has been demonstrated that mobile phones can harbour pathogens responsible for nosocomial transmission [44], and unlike hands, are not regularly cleaned [45]. The data presented in this study correlates well with previously published data for Influenza A (H1N1) which recovered infectious virus up to 22 days at 22 °C and 7 days at 35 °C [37]. The persistence of SARS-COV-2 on glass and vinyl (both common screen and screen protector materials, suggest that touchscreen devices may provide a potential source of transmission, and should regularly be disinfected especially in multi-user environments.

The persistence of both SARS and SARS-CoV-2 on cotton has been demonstrated to be significantly shorter than on non-porous surfaces [11, 25]. The data presented here also shows a significant decrease in titre of recovered virus after just 1 h drying at room temperature (20 °C) the amount of virus recovered from cotton swatches was approximately 99% less than for comparable virus recovery time points for non-porous material. To verify the reduced recovery on cotton, virus was eluted 5 min after depositing on the cotton, as well as 1 h, the titre of recovered virus after 5 min was similar to that of non-porous surfaces (data not shown) suggesting the process of drying down was a significant factor for cotton material but not from the non-porous surfaces. Recovery of virus from porous substrates is also likely to be reduced compared to non-porous substrates due to adherence of the virus to the fabric fibres. When the rate of viral inactivation is considered over time rather than the gross reduction from the initial inoculum there is a more subtle difference from the non-porous surfaces. The D values for cotton at 20 °C, when compared other materials, are not significantly different from other substrates (eg. 5.6 days for cotton vs. 6.3 days for vinyl), and the slopes of the line which suggests the decay rate of virus is similar across substrates. This study also demonstrates significantly longer survival times on cotton (7 days) than previous reported [11, 25]. This difference could be due to differences in the types of cotton material used, the current study used 100% cotton cloth, while previous studies used either a cotton gown or cotton t-shirt.

Conclusions

The data presented in this study demonstrates that infectious SARS-CoV-2 can be recovered from non-porous surfaces for at least 28 days at ambient temperature and humidity (20 °C and 50% RH). Increasing the temperature while maintaining humidity drastically reduced the survivability of the virus to as little as 24 h at 40 °C. The persistence of SARS-CoV-2 demonstrated in this study is pertinent to the public health and transport sectors. This data should be considered in strategies designed to mitigate the risk of fomite transmission during the current pandemic response.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s12985-020-01418-7.

Additional file 1. Table of average titre and standard deviation for recovery of infectious SARS-CoV-2 for all substrates, time points and temperatures.

Abbreviations

ASTM: American Society for Testing and Materials; ATM: Automatic teller machine; BSCII: Biological Safety Cabinet, Class 2; BSA: Bovine serum albumin; CO_2: Carbon dioxide; CT: Cycle threshold; DMEM: Dulbecco's Modified Eagle Medium; E gene: Envelope gene of SARS-CoV-2; N gene: Nucleocapsid gene of SARS-CoV-2; N95: Non-oil 95 mask; PBS: Phosphate buffered saline; RH: Relative humidity; RT-PCR: Reverse transcription polymerase chain reaction; RdRp: Ribonucleic acid dependant ribonucleic acid polymerase; SARS: Severe Acute Respiratory Syndrome; SARS-CoV-2: Severe Acute Respiratory Syndrome Coronavirus 2; $TCID_{50}$: Tissue Culture Infectious Dose—Fifty; U/V: Ultraviolet; WHO: World Health Organisation; V/V: Volume per volume.

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Authors' contributions

SR—Conceptualisation, Data curation, Formal analysis, investigation, methodology, writing—original draft. SG—Conceptualisation, Data curation, Formal analysis, investigation, methodology, writing—review and editing. AH—Conceptualisation, Data curation, Formal analysis, writing—review and editing, supervision. DE—Conceptualisation, writing—review and editing, funding acquisition. TD—Conceptualisation, analysis methodology, writing—review and editing. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analysed during the study is included in the Additional file 1.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Publisher's Note

EXHIBIT Q

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A Nanomechanical Study on Deciphering the Stickiness of SARS-CoV-2 on Inanimate Surfaces

Lei Xie,[†] Fenglin Liu,[†] Jifang Liu,* and Hongbo Zeng*

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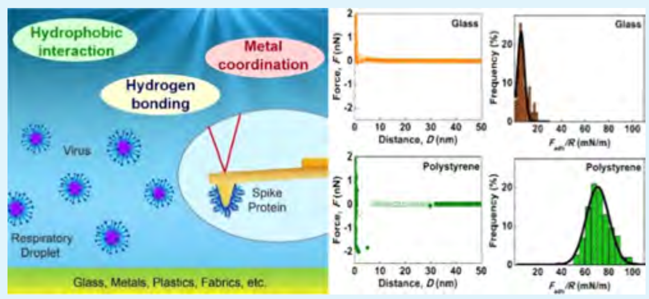
ABSTRACT: The SARS-CoV-2 virus that causes the COVID-19 epidemic can be transmitted via respiratory droplet-contaminated surfaces or fomites, which urgently requires a fundamental understanding of intermolecular interactions of the coronavirus with various surfaces. The corona-like component of the outer surface of the SARS-CoV-2 virion, named spike protein, is a key target for the adsorption and persistence of SARS-CoV-2 on various surfaces. However, a lack of knowledge in intermolecular interactions between spike protein and different substrate surfaces has resulted in ineffective preventive measures and inaccurate information. Herein, we quantified the surface interaction and adhesion energy of SARS-CoV-2 spike protein with a series of inanimate surfaces via atomic force microscopy under a simulated respiratory droplet environment. Among four target surfaces, polystyrene was found to exhibit the strongest adhesion, followed by stainless steel (SS), gold, and glass. The environmental factors (e.g., pH and temperature) played a role in mediating the spike protein binding. According to systematic quantification on a series of inanimate surfaces, the adhesion energy of spike protein was found to be (i) 0−1 mJ/m^2 for hydrophilic inorganics (e.g., silica and glass) due to the lack of hydrogen bonding, (ii) 2−9 mJ/m^2 for metals (e.g., alumina, SS, and copper) due to the variation of their binding capacity, and (iii) 6−11 mJ/m^2 for hydrophobic polymers (e.g., medical masks, safety glass, and nitrile gloves) due to stronger hydrophobic interactions. The quantitative analysis of the nanomechanics of spike proteins will enable a protein−surface model database for SARS-CoV-2 to help generate effective preventive strategies to tackle the epidemic.



KEYWORDS: *spike protein, intermolecular interaction, surface adhesion, COVID-19, surface forces*

1. INTRODUCTION

Since December 2019, the COVID-19 outbreak caused by SARS-CoV-2 has led to over 70 million of confirmed cases and over 1.6 million deaths in 218 countries.[1−5] The main transmission routes of SARS-CoV-2 indicate that this respiratory disease can spread by inhalation and/or direct contact with droplets of infected people as well as indirect contact with contaminated surfaces that carry respiratory droplets from infected persons.[1−5] While social distancing is proved to be an effective approach to inhibit the human−human transmission through direct routes, infections through indirect contact remain challenging to combat, owing to the invisible spreading paths and unclear surface behaviors of the new coronavirus.[5−8] Therefore, identifying the surface interactions of SARS-CoV-2 has become essential for prohibiting virus transmission via surface contaminations. The Munster group evaluated the persistence of SARS-CoV-2 by accessing virus decay rates in aerosols and on several typical substrates,[9] and similar studies were also conducted on other respiratory viruses such as SARS,[9,10] MERS,[11,12] and Ebola,[13] as shown in Table 1. Despite the significant progress achieved, it remains unclear in terms of the intermolecular interactions involved, such as adsorption and binding strengths of the virus on typical substrates, which are critical for evaluating viral loads on those target surfaces. Thus, detailed studies toward the nanomechanics of the virus-contaminated surfaces are urgently needed to determine the interaction mechanisms at the nanoscale, as well as their influences on viral persistence.

Spike protein refers to a class I fusion protein that is located at the surface of a coronavirus virion (illustrated in Figure 1A).[14−16] Consisting of more than 1000 amino acids, the spike protein can assemble into crownlike nanoarchitecture that allows the viral binding and fusion to host cell membranes through molecular recognition.[17−19] With regard to the structure of the new coronavirus, there are two main subunits in the spike protein named S1 and S2, the former of which is

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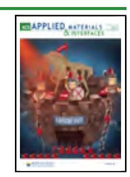

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Table 1. Persistence of Selected Coronaviruses on Typical Inanimate Surfaces

virus type	inanimate surfaces	environment	persistence	references
SARS-CoV-2	copper	21−23 °C; 40% humidity	4 h	9
	cardboard	21−23 °C; 40% humidity	24 h	9
	SS	21−23 °C; 40% humidity	48 h	9
	plastic	21−23 °C; 40% humidity	72 h	9
MERS-CoV	SS	20 °C	48 h	11,12
	plastic	20 °C	48 h	11,12
Ebola-CoV	SS	21−27 °C; 40−80% humidity	11−27 h	13
	plastic	21−27 °C; 40−80% humidity	11−43 h	13
	Tyvek	21−27 °C; 40−80% humidity	15−52 h	13
SARS-CoV	copper	21−23 °C; 40% humidity	8 h	9
	cardboard	21−23 °C; 40% humidity	8 h	9
	SS	21−23 °C; 40% humidity	48 h	9
	plastic	21−23 °C; 40% humidity	72 h	9
	metal	room temperature	5 days	10
	wood	room temperature	4 days	10
	paper	room temperature	24 h	10
	glass	21 °C	4 days	10

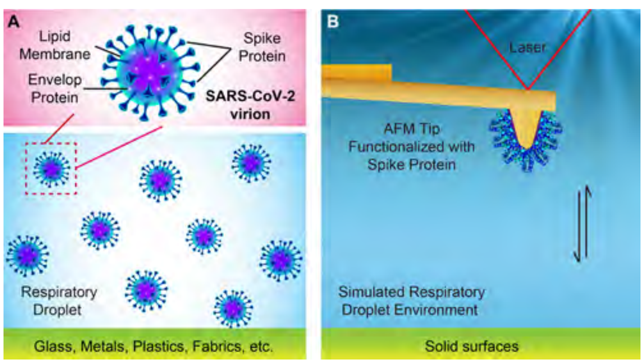

Figure 1. (A) Schematic of SARS-CoV-2 virions in respiratory droplets contaminating solid substrates such as glass, metals, plastics, and fabrics (down), and the zoomed-in structure of the SARS-CoV-2 virion (up). (B) Schematic of the experimental setup for measuring the interaction forces between the spike protein-functionalized AFM tip and various solid surfaces in simulated respiratory droplet environments.

responsible for ACE2 receptor binding using its receptor-binding domain, while the latter is managing the subsequent membrane fusion.[16,17,20] Considering the critical role of the spike protein in viral infection, characterizing the adsorption behavior and adhesion strength of spike protein can shed light on the molecular mechanism how the new coronavirus contaminates the surfaces of inanimate substrates. The active subunit S1 has been recognized as a good candidate to understand the adsorption and adhesion of spike protein at the molecular level owing to its representative structure and function.[17−19] Being the powerful nanomechanical techniques, atomic force microscopy (AFM) and surface force apparatus (SFA) have been widely employed to quantitatively characterize the intermolecular interactions, including adhesion and single-molecule binding, of a variety of biological molecules in vapor or liquid media.[21−32] As compared to SFA that requires molecularly smooth surfaces with at least one surface being transparent, AFM is more versatile to quantify the interaction forces of the materials that cannot be easily accessed by SFA. The unique, flexibility, and accuracy of AFM make it feasible to access the interaction mechanism of spike protein at the nanoscale.

To systematically investigate the adsorption behavior and interaction mechanism of COVID-19 spike protein, herein, a direct and quantitative analysis of surface interactions of spike protein was presented with respect to adsorption, kinetics, and intermolecular forces in the pico/nanonewton range (schematic illustrated in Figure 1B). A series of inanimate surfaces, including glass, plastics, metals, fabrics, and so forth, were applied to systematically evaluate the adsorption behaviors of the spike protein. In particular, we focused on four targeted surfaces (i.e., glass, gold, stainless steel (SS), and polystyrene-(PS)), which represent the most commonly used materials ranging from inorganics and organics to metals and composites/hybrids. We also discussed the key factors affecting the spike protein binding and explored the protein−surface interaction mechanisms under simulated respiratory droplets, as well as proposed feasible strategies to modulate the binding of spike protein with inanimate surfaces. This work will improve the fundamental understanding associated with the adsorption and adhesion mechanisms of spike protein on various solid substrates, thereby providing guidelines for developing preventive/protective equipment and optimizing current public measures against COVID-19 pandemic.

2. RESULTS AND DISCUSSION

2.1. Adsorption of Spike Protein on Various Surfaces. Figure 2 shows the AFM topography images of glass, gold, SS, and PS surfaces before and after the adsorption of spike protein. The bare glass, gold, SS, and PS surfaces exhibit a root-mean-square (RMS) roughness of 0.3−0.7 nm, and such smooth surfaces allow the accurate observation of protein adsorption. It is noted that the uniform grainlike pattern on bare metal (i.e., gold and SS) surfaces is arising from their metal particles. After spike protein adsorption, all the surfaces become rough with the obvious binding of spike protein as indicated by the white dots shown in Figure 2. The spike protein adsorbed on glass is sparsely distributed with a considerable size. In contrast, the size of the spike protein adsorbed on gold and SS is relatively small, and the distribution of the adsorbed spike protein is much denser for SS. However on PS, the size of the adsorbed protein becomes even smaller, and an ultra-dense distribution of protein pattern is observed (2×2 μm^2 image shown in Figure S1). The smaller size and denser distribution of the adsorbed spike protein reveal the preferential binding of spike protein with the surface instead of self-aggregation. Therefore, spike protein most preferentially adsorbs on PS followed by SS and gold. On the other hand, the adsorption of spike protein on glass is relatively weaker, as compared to the other three substrates.

2.2. Quantitative Force Measurements. To unravel the nanomechanics of spike protein interacting with various solid surfaces, the gold-coated AFM probe (including the AFM tip, cantilever, and cantilever base) is self-assembled with 11-mercaptoundecanoic acid, which subsequently covalently

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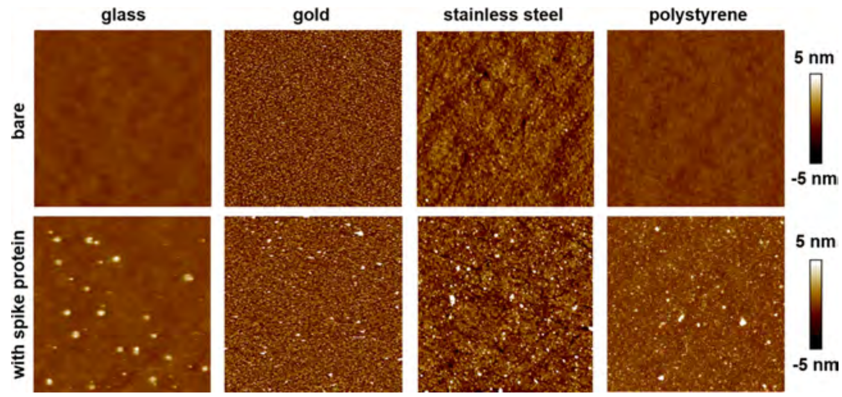

Figure 2. AFM topography images (5×5 μm^2) of glass, gold, SS, and PS before and after the adsorption of spike protein.

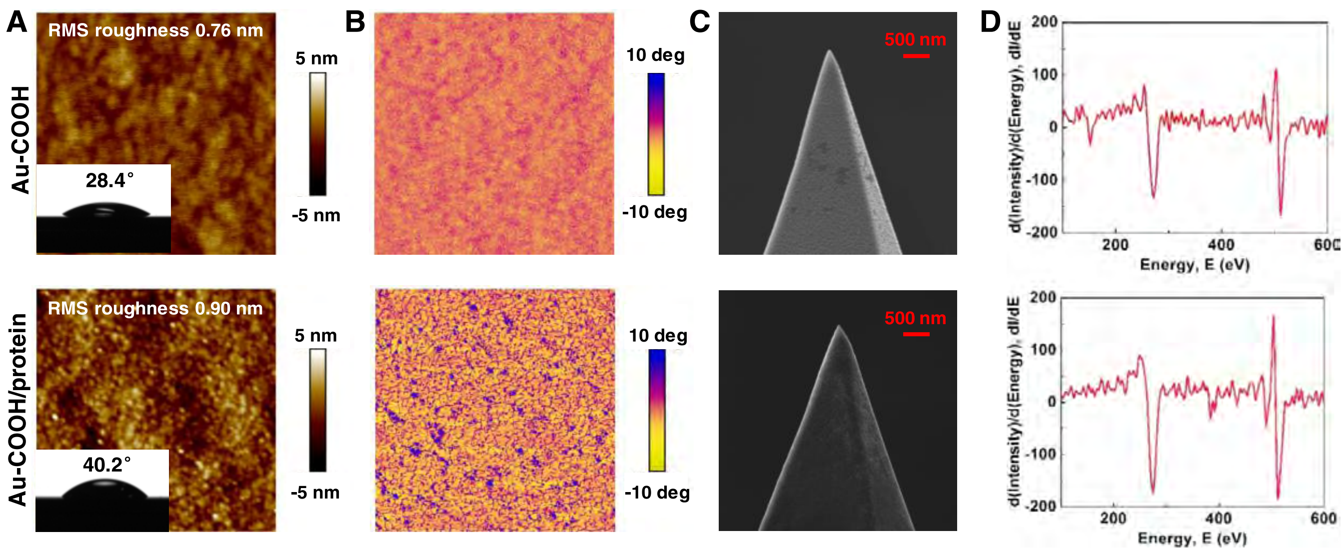

Figure 3. Characterization of the gold-coated AFM probe functionalized with carboxyl groups (up) and spike protein (down): (A) AFM topography image (2×2 μm^2) with the water contact angle (inset) on the cantilever base of the AFM probe, (B) phase image (2×2 μm^2) of the cantilever base of the AFM probe, (C) HIM on the AFM tip, and (D) Auger electron microscopy on the AFM tip.

bonds with spike protein via the carbodiimide crosslinking strategy.[21,33] The prepared AFM probe was characterized by AFM imaging, contact angle measurements, helium ion microscopy (HIM), and Auger electron spectroscopy (AES). As demonstrated in Figure 3A,B, the AFM probe without and with protein coating displays distinct morphologies and phase images, with spike protein closely and uniformly packing on the AFM probe that enhances RMS roughness from 0.76 to 0.90 nm. Meanwhile, the water contact angle increases from 28.4° ± 0.6° for the AFM probe without protein modification to 40.2° ± 0.8° for the protein-functionalized AFM probe (inset of Figure 3A), which suggests that the AFM probe becomes relatively hydrophobic after the protein modification. HIM is a unique surface-sensitive imaging technique that enables the high-resolution imaging of insulating proteins adsorbed at subnanometer resolution.[34] As shown in Figure 3C and Figure S2, the tip of the COOH-functionalized AFM probe displays the grainlike pattern of gold; instead, an evident coverage of nonconductive substances is detected for the tip of the protein-functionalized AFM probe. AFM imaging, water contact angle measurement, and HIM imaging all reveal the successful grafting of spike protein on the AFM probe, which is also further confirmed by the AES analysis where an additional nitrogen Auger peak at ~369 eV appears for the protein-functionalized AFM tip (Figure 3D).

The adsorption and adhesion of the virus outer protein on the surface that occur in droplet environments right after a virus-containing-droplet impacts and attaches to a solid surface are the key to the mechanism how the virus contaminates the surface. The intermolecular forces of spike protein in droplet environments play a central role in the adsorption and adhesion of spike protein on substrate surfaces. To ensure the accuracy of force measurements, force mapping was performed on bare surfaces in an area of 5×5 μm^2 using the protein-functionalized AFM probe to acquire a two-dimensional array of force-separation profiles at 10×10 points (100 consecutive force-separation measurements). Force mapping was performed in at least three different regions of the substrate surface and at least two independently prepared samples of the same batch. The interaction forces measured between the protein-functionalized AFM tip and selected surfaces that are ubiquitous in daily life, including glass, gold, SS, and PS, during the approach−separation cycle under the typical simulated respiratory droplet condition (10 mM NaCl solution at pH 5.6 and 23 °C) are shown in Figure 4 (left). For spike protein interacting with glass, the measured force−distance profile (orange open symbols) shows a purely

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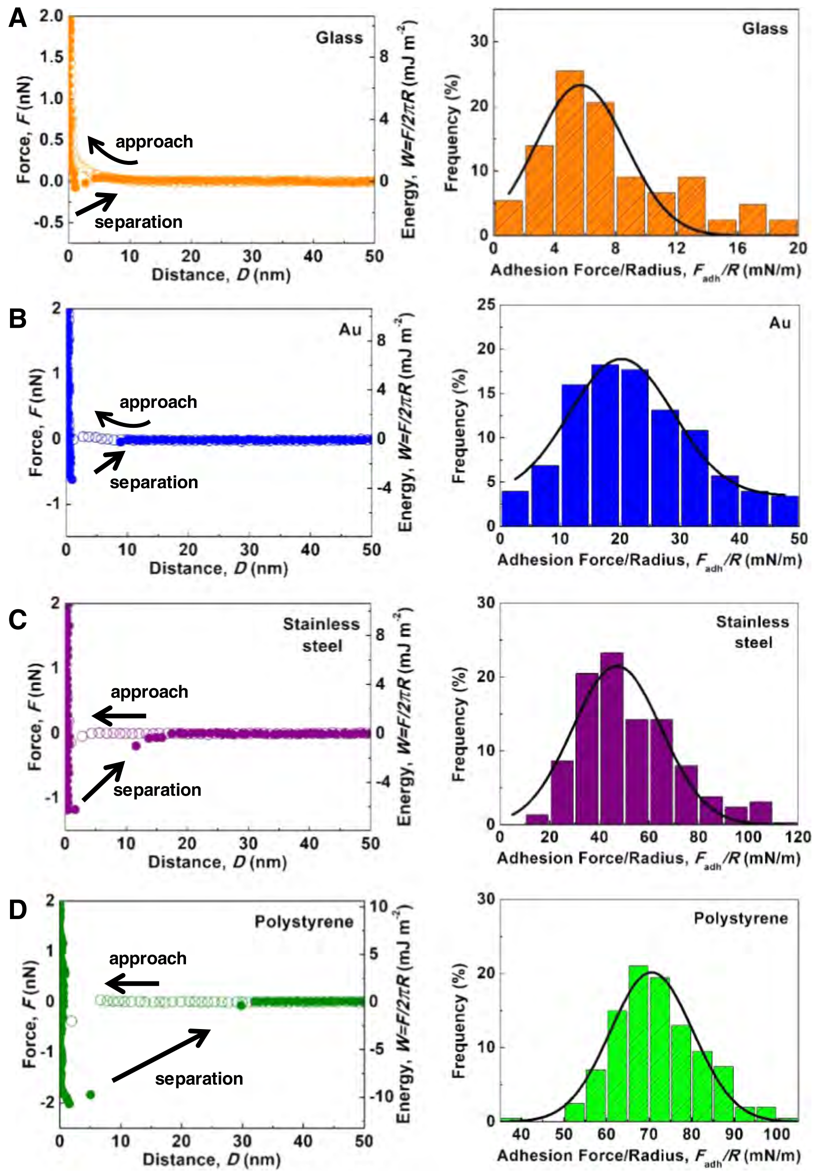

Figure 4. Force−distance profiles between the spike protein-functionalized AFM tip and different solid substrates in 10 mM NaCl solution at pH 5.6 and 23 °C (approach data: open symbols and separation data: solid symbols) and the histogram of normalized adhesion force F_{adh}/R with the fitted Gaussian distribution: (A) glass, (B) gold, (C) SS, and (D) PS.

repulsive force during approach. Zeta potential measurements (Table S1) show that the isoelectric point of spike protein is below pH 5.6, while glass always carries the negative charges under the testing condition;[35] therefore, the measured repulsion is attributed to the repulsive electrical double layer (EDL) force. Upon separation (orange solid symbols), an interfacial adhesion is occasionally detected, probably contributed by the short-range hydrogen bonding between the side chains of amino acids (e.g., lysine, asparagine, and tyrosine) in the spike protein and glass surface. For gold (blue symbols) and SS (purple symbols), in addition to the long-range EDL repulsion, an attractive force starting from a separation distance of 3−4 nm is measured during approach because of the relatively strong van der Waals (VDW) force for metal-involved systems.[36] The adhesion force for gold and SS during separation is mainly induced by the strong coordination interaction between metal atoms and specific sites of spike protein (e.g., carboxyl group and aromatic ring of amino acids),[37] which is evidently stronger than the adhesion force measured for glass. The spike protein−PS interaction (green symbols) exhibits a strong attraction during approach that induces a "jump-in" phenomenon at ∼7 nm. Evidently, the attraction measured is stronger and has a longer range than VDW contribution and considered as the hydrophobic interaction between hydrophobic PS and hydrophobic moieties of spike protein (e.g., hydrophobic side chains of tyrosine). Such strong hydrophobic interaction enables intimate contact between the spike protein and PS, which correspondingly triggers a considerable adhesion during separation.

Based on the adhesion forces measured during separation (300−500 events), the histograms of normalized adhesion force, F_{adh}/R, are established and fitted by the Gaussian distribution (solid curve) as shown in Figure 4 (right). The magnitude of average normalized adhesion force follows the trend: glass (5.71 ± 0.36 mN/m) < gold (20.23 ± 0.66 mN/

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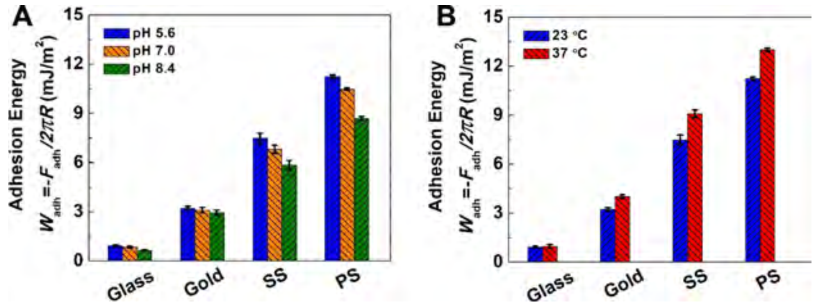

Figure 5. Average adhesion energy $W_{adh} = -F_{adh}/2\pi R$ between the spike protein-functionalized AFM tip and solid surfaces, including glass, gold, SS, and PS, in 10 mM NaCl solution (A) at 23 °C under the effect of pH: 5.6, 7.0, and 8.4 and (B) at pH 5.6 under the effect of temperature: 23 and 37 °C.

m) < SS (47.02 ± 1.89 mN/m) < PS (70.58 ± 0.63 mN/m). Based on the Derjaguin−Muller−Toporov model $W_{adh} = -F_{adh}/2\pi R$ that correlates the normalized adhesion force (F_{adh}/R) of a sphere on a plane with the adhesion energy per unit area (W_{adh}) of two flat surfaces of the same materials,[36,38−40] the average adhesion energy is obtained as ∼0.91 mJ/m^2 for glass, ∼3.22 mJ/m^2 for gold, ∼7.48 mJ/m^2 for SS, and ∼11.23 mJ/m^2 for PS, respectively. The adhesion energy between the spike protein and these substrates could be contributed by surface interactions involving hydrogen bonding, hydrophobic interaction, and coordination interaction.

Glass can form hydrogen bonding with the side chains of amino acids in spike protein. Considering the theoretically simulated hydrogen bond energy for protein in solution (2.09−6.28 kJ/mol)[41] and the measured adhesion energy (0.91 mJ/m^2 for protein−glass), there only exists one effective hydrogen bond between spike protein and glass within an area of over 2.76 nm × 2.76 nm. The possible reason for such a low bonding efficiency is that the entropic (or steric) effect restricts the optimization of spike protein toward the preferential formation of hydrogen bonds.[42] As compared to the spike protein−glass interaction, the adhesion energy mainly arising from hydrophobic interaction of PS with spike protein is even 10 times stronger, revealing the dominant role of hydrophobic interaction in modulating the adhesion of spike protein (or stickiness of new coronavirus), particularly under the nano-confined regime. The hydrophobic interaction energy is expressed as $W_{HB} = 2\gamma\exp(-D/D_0)$ for the symmetric cases (e.g., PS−PS interaction in water), where γ is the interfacial energy, D_0 is the decay length of hydrophobic interaction, and D is the separation distance.[36,43] From the thermodynamic perspective, $W_{HB} \approx 2\gamma = 79$ mJ/m^2 for PS−PS interaction as D approaches zero.[36,43] It is noted that the adhesion energy of ∼11.23 mJ/m^2 for the spike protein−PS interaction is approximately one seventh of the adhesion energy of PS−PS interaction, which indicates that the hydrophobic moiety of spike protein that contributes to the hydrophobic interaction with PS only accounts for a small portion of the entire protein molecule. Metals interacting with spike protein display the adhesion energies that are evidently stronger than those for glass but relatively weaker than those for PS. It is known that metals could form a coordination complex with specific binding sites of protein, and the magnitude of metal−protein binding energy is dependent on the binding capability of the metal and the number of binding sites on the protein. Thus, metals with relatively weaker binding capability (e.g., gold as compared to SS) exhibit smaller adhesion energy, while the relatively weaker adhesion energies for gold and SS, as compared with that for PS, are likely due to the limited metal−protein binding sites.

2.3. Effect of Environmental Factors on Adhesion. The respiratory droplet normally displays a pH value ranging from 5.6 to 8.4, and the environmental temperature is also varied for different seasons and regions, which could affect the intermolecular interactions of spike protein and thus alter its adsorption behavior and the stickiness of the new coronavirus on substrates. To further unravel the impact of environmental conditions on the interaction mechanism of spike protein, the adhesion energy of spike protein with solid surfaces was measured in 10 mM NaCl solution at different pH values (Figure 5A) and temperatures (Figure 5B). As shown in Figure 5A (with the histogram shown in Figure S3), with pH increasing from 5.6 to 7.0 and 8.4, the adhesion energy slightly drops from ∼0.91 mJ/m^2 to ∼0.84 and ∼0.65 mJ/m^2 for glass as well as from ∼3.22 mJ/m^2 to ∼3.09 and ∼2.93 mJ/m^2 for gold. In contrast, the adhesion energy for the SS and PS cases is more pH-dependent. In particular, the adhesion energy for SS is dramatically reduced from ∼7.48 mJ/m^2 at pH 5.6 to ∼6.80 mJ/m^2 at pH 7.0 and ∼5.84 mJ/m^2 at pH 8.4, while the adhesion energy for PS also significantly decreases from ∼11.23 mJ/m^2 at pH 5.6 to ∼10.47 mJ/m^2 at pH 7.0 and ∼8.69 mJ/m^2 at pH 8.4. Because spike protein, glass, gold, SS, and PS all carry negative charges over the pH range investigated,[35,44,45] it is reasonable that the electrostatic repulsion is strengthened with the increase of pH, which ultimately weakens the adhesion energy and triggers the pH-mediated adhesion.

The role of temperature in altering the adhesion energy is shown in Figure 5B (with the histogram shown in Figure S4). As the temperature increases from 23 to 37 °C, the adhesion energy for glass almost remains unchanged (0.91−0.95 mJ/m^2), while the adhesion energy dramatically increases from ∼3.22 to ∼4.01 mJ/m^2 for gold and from ∼7.48 to ∼9.08 mJ/m^2 for SS. It is known that enhanced temperature could improve the binding activity of metal−protein interaction, thereby increasing the adhesion energy. It is known that the entropy-driven hydrophobic interaction is also temperature-dependent.[46] The possible conformational rearrangement in spike protein and PS upon heating results in increased entropy, which is the main reason the adhesion for spike protein−PS interaction increases from ∼11.23 mJ/m^2 at 23 °C to ∼13.00 mJ/m^2 at 37 °C. Although the overall trend of average adhesion energy "glass < gold < SS < PS" remains the same regardless of pH and temperature, the environmental factors to a certain degree could contribute to the alternation of protein adhesion, suggesting that the new coronavirus is more readily to stick to solid materials in an acidic environment and at a high temperature.

2.4. Adhesion of Spike Protein with Different Materials. In addition to glass, gold, SS, and PS, we also select a variety of other inorganic, metallic, and polymeric materials for probing their intermolecular forces with spike protein in droplet environments. Figure 6 summarizes the normalized adhesion force and average adhesion energy between the spike protein-functionalized AFM tip and a variety of solid materials in 10 mM NaCl solution at pH 5.6 and 23 °C (with the histogram shown in Figure S5). The hydrophilic inorganic surfaces, such as glass and silica, exhibit the lowest adhesion energy (0−1 mJ/m^2), revealing the negligible role of hydrogen bonding in the adhesion of spike protein. On the other hand, hydrophobic polymeric materials, including PS, polyethylene plastic, and even low-surface-energy polytetrafluoroethylene (PTFE), can achieve very high adhesion energy (6−11 mJ/m^2), which indicates the significance of hydrophobic interaction in the adhesion of spike protein. Because the proteins binding to the substrate surfaces rely on their hydrophilicity, the adhesion results demonstrate that the spike protein preferentially binds to hydrophobic surfaces as compared to hydrophilic cases. It is noted that the interaction mechanism between the spike protein and hydrophobic surfaces in aqueous solution is different from that in air. The adsorption of particles or droplets onto hydrophobic commercial masks in air could be mainly due to electrostatic attraction, while the major contribution of the interaction mechanism between the spike protein and hydrophobic surfaces in aqueous solution is considered as hydrophobic interaction. Because both the spike protein and hydrophobic surfaces carry the overall negative charges, the overall electrostatic interaction between spike protein and hydrophobic surfaces in aqueous solution is repulsive. However, spike protein could display positively charged sites and negatively charged sites. The contribution of electrostatic attraction between the positively charged sites of spike protein and polymer surfaces could not be ruled out. For the metals, the adhesion energy with spike protein lies in a wide range from 2 to 9 mJ/m^2, which relies on the binding capability of metals with spike protein. In the metallic materials investigated, copper exhibits the strongest adhesion with spike protein followed by SS, gold, and alumina foil.

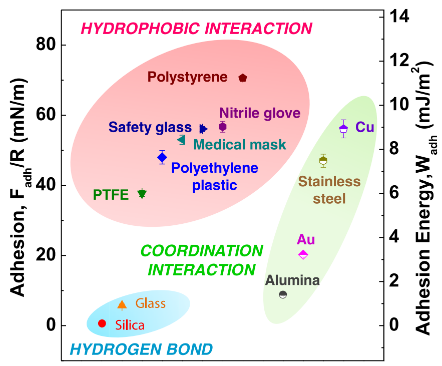

Figure 6. Normalized adhesion force F_{adh}/R and average adhesion energy $W_{adh} = -F_{adh}/2\pi R$ between the spike protein-functionalized AFM tip and a variety of solid materials in 10 mM NaCl solution at pH 5.6 and 23 °C.

It is worth mentioning that the oriented spike protein could be a perfect molecular model for the experimental design; meanwhile, the surrounding temperature, pH, saline concentration, and/or shrinkage because of dehydration could all affect the virion shape and size, as well as the orientation of spike protein on surfaces. In this work, despite the random orientation of the S1 subunits on AFM tips (the exposed subunits of spike protein), over 600 force measurement events have been collected for each S1-surface pair, and the statistical plots can reflect the trend of virion adhesion on various surfaces. It is noted that the real contact region for the force measurements between an AFM tip (a radius of 25−35 nm) and a substrate surface is only at the nanoscopic level, and thus, the influence of surface roughness on the adhesion energy has been dramatically reduced. The uniform distribution of adhesion forces, which can also be reflected from the histogram of adhesion forces (Figures S3−S5), ensures the accuracy of force measurements. It is also noted that the rough alumina foil and copper foil lie in a similar regime of adhesion energy with smooth SS and gold coating (metals), while the rough nitrile glove, safety glass, medical mask (polypropylene), and polyethylene plastic lie in a similar region with smooth PS and PTFE surfaces (hydrophobic polymers).

It is known that the interfacial adhesion of solid materials can be mediated by tuning their surface properties.[47−51] Because the surface hydrophilicity of materials plays an important role in their interactions with the spike protein, it is reasonable to conclude that glass-based materials (e.g., windows, mirrors, glass doors, and glass screens) exhibit relatively low stickiness for the new coronavirus compared to the plastics and fabrics. Nevertheless, the stickiness of the new coronavirus on glass can become strong once the glass is contaminated by organics. It is worth noting that the commonly used personal protective equipment (PPE), including medical masks (polypropylene), safety glass, and nitrile gloves, also displays very high adhesion energy (6−11 mJ/m^2), which could be altered by applying the superhydrophilic or superhydrophobic coatings. In addition, the addition of alcohol (e.g., methanol, ethanol, and isopropyl alcohol) into aqueous media is known to suppress the hydrophobic interaction,[52−54] and thus, the new coronavirus stuck on plastic, fabric, and PPE could be washed off by the alcohol even if the alcohol is insufficiently concentrated to kill the virus. Similarly, the surfactant-containing aqueous solution is also an efficient approach to eliminate the hydrophobic interaction and remove the new coronavirus.

The adhesion of spike protein with solid materials could be an important contributor to the substance-dependent persistence of SARS-CoV-2 virions. There were few reports on the persistence of SARS-CoV-2 on typical substrates under a water-based environment,[9,10] which limit the data availability at this time. The persistence of SARS-CoV-2 was reported to be 4 h for copper, 2 days for SS, and 3 days for plastic.[9] Based on our studies, the adhesion energy of spike protein interacting with copper, SS, and plastic is 8.93, 7.48, and 7.64 mJ/m^2, respectively. It has been reported that the adhesion could lead to the compression of virus, which disrupts the 3D structure of proteins and ultimately inactivates the virus.[55,56] Thus, the higher adhesion for copper could be one contributor to the shorter persistence of coronavirus on copper. Although the adhesion for SS and plastic is similar, other factors such as the complex metal antiviral mechanism could play a critical role in the persistence of coronavirus.

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3. CONCLUSIONS

In this work, we systematically quantified the intermolecular interactions between spike protein (the corona-like component of the SARS-CoV-2 virion) and a series of inanimate surfaces (e.g., glass, plastics, metals, and fabrics) under a simulated respiratory droplet environment at the nanoscale. The environmental factors, including pH and temperature, were observed to affect the spike protein binding. According to the quantitative AFM force measurements, the adhesion of spike protein was (i) very weak on hydrophilic inorganics (e.g., glass) because of the lack of substantial hydrogen bonding formation, (ii) relatively high on metal surfaces because of the strong coordination interaction, and (iii) very strong on hydrophobic polymers (e.g., PS, PTFE, plastics, and PPE), attributed to the hydrophobic interaction. The alternation of surface hydrophilicity of materials or addition of chemical additives could effectively modulate the hydrophobic interaction and even tune the interaction mechanism between hydrogen bonding and hydrophobic interaction, which would be a promising strategy to mediate the adhesion of spike protein and stickiness of new coronavirus. Additionally, the adhesion of spike protein with solid materials could be an important contributor to the substance-dependent persistence of SARS-CoV-2 virions. The developed protein−surface model database for SARS-CoV-2 with respect to their intermolecular and surface interactions will provide scientific guidance for developing effective preventive strategies to prohibit virus transmission via surface contaminations.

4. EXPERIMENTAL METHODS

4.1. Materials. Sodium chloride (NaCl, ACS reagent grade), hydrochloric acid (HCl, ACS reagent grade), and sodium hydroxide (NaOH, ACS reagent grade) were purchased from Fisher Scientific. 11-Mercaptoundecanoic acid ($HS(CH_2)_{10}COOH$, 98%), N-hydroxysuccinimide (NHS, $C_4H_5NO_3$, and 98%), N-(3-Dimethylaminopropyl)-N′-ethylcarbodiimide hydrochloride (EDC, $C_8H_{17}N_3 \cdot HCl$, 98%), and phosphate buffered saline (pH 7.4) were purchased from MilliporeSigma. COVID-19 spike S1 coronavirus active protein (purity >90% by sodium dodecyl sulfate polyacrylamide gel electrophoresis and molecular weight of 120 kDa) was purchased from MyBioSource, Inc. All the chemicals were used as received without further purification, and all aqueous solutions were prepared using Milli-Q water (Millipore deionized, 18.2 MΩ·cm resistivity).

4.2. Preparation of the Spike Protein-Functionalized AFM Probe and Solid Substrates. Spike protein solution was prepared by dissolving 0.1 mg COVID-19 spike S1 coronavirus active protein in 2 mL PbS buffer (pH 7.4), and the prepared spike protein solution was stored at −20 °C. The gold-coated AFM probes were cleaned by UV/ozone treatment for 30 min and then immersed in 10 mM 11-mercaptoundecanoic acid in ethanol overnight. After the self-assembly via the Au−S bonding, the COOH-functionalized AFM probes were washed with ethanol to remove the physisorbed thiol, dried with high-purity nitrogen, and then immersed in an aqueous solution containing 20 mM NHS and 40 mM EDC to activate the COOH functional groups on AFM probes. After 1 h, the NHS/EDC-activated AFM probes were immersed in 0.05 mg/mL spike protein in PbS buffer for 2 h to prepare the protein-functionalized AFM probes. Thereafter, the protein-functionalized AFM probes were washed with Milli-Q water, dried with high-purity nitrogen, and immediately used for characterization and force measurements.

A glass sheet and a silicon wafer (with an oxidation layer) were washed with ethanol and water three times, dried with high-purity nitrogen, and then cleaned by UV/ozone treatment for 10 min. Gold-coated silicon wafers were cleaned with a typical RCA procedure with slight modifications.[57,58] The gold wafer shards were first sonicated in methanol for 5 min, dried with high-purity nitrogen, and immersed in RCA1 solution (Milli-Q water:30% NH_4OH:30% H_2O_2 = 6:1:1 volume ratio) and RCA2 solution (Milli-Q water:37.5% HCl:30% H_2O_2 = 6:1:1 volume ratio) for 5 min at 80 °C. The gold wafer shards were dried and went through argon plasma to further remove residues. Alumina and copper were obtained directly from the aluminum foil and copper foil, which were cleaned with ethanol and water three times. A QSX 304 SS sensor (SS2343, Biolin Scientific) was cleaned by immersing the sensor in 1% Hellmanex II for 30 min, rinsed with Milli-Q water, and dried with high-purity nitrogen. The PS surface was prepared by spin coating PS solution (0.5 wt % in toluene) on silicon wafer at 2000 rpm, and the spin-coated surface was dried under vacuum overnight to completely remove the residual solvent. The plastic bottle of Nestlé pure life natural spring water and a Uline medical mask, which are ubiquitous in daily life and have drawn much attention, were selected as the representative samples of the polyethylene surface and polypropylene surface, respectively. PTFE, polyethylene plastic, medical mask (polypropylene), safety glass, and nitrile glove were cleaned with ethanol and water three times. All the samples were immediately used for the force measurements after the cleaning procedure.

4.3. Characterization. Several selected solid surfaces before and after spike protein adsorption were characterized by AFM topography imaging. The COOH-functionalized and protein-functionalized AFM probes were subjected to AFM imaging, contact angle measurements, HIM, and AES. The imaging of the solid surfaces and the cantilever base of AFM probes was performed using the tapping mode of a Dimension Icon AFM (Bruker, Santa Barbara, CA, USA). Typically, the functionalized gold-coated AFM probe was glued onto the AFM scanning stage by double-sided tape, and then a silicon AFM probe was used to perform the imaging on the cantilever base of the AFM probe. The water contact angle on the cantilever base of AFM probes was measured using the sessile drop method with a contact angle goniometer (ramé-hart instrument Co., NJ, USA). The average water contact angle was reported based on the measurements of few microliter water droplets on at least three independently prepared AFM probes. It is noted that AFM imaging and contact angle measurements were difficult to conduct directly on the AFM cantilever and AFM tip because of their small size, and thus, these two tests were conducted on the AFM cantilever base of the AFM probe with the same material composition as the AFM cantilever and tip. HIM of AFM tips was conducted using a Zeiss Orion NanoFab (Carl Zeiss AG, Oberkochen, Germany) equipped with the He beam, while AES of AFM tips was performed using a JAMP-9500F Field Emission Auger Microprobe (JEOL, MA, USA) equipped with a Shottky field emitter, which produces an electron probe diameter of 3−8 nm.

4.4. Helium Ion Microscopy. HIM was performed using the Zeiss Orion NanoFab (Zeiss Peabody, MA, USA) tool at ProVIS−Centre for Chemical Microscopy at the Helmholtz−Centre for Environmental Research, Leipzig, Germany. For imaging, the landing energy of the ions was set to 25 keV, and a 10 μm aperture was used. By variation of the spot-control parameter (values between 4 and 6), the ion-beam current was adjusted to about 1.0 pA measured at the blanker of the tool. For image acquisition, secondary electrons were detected using an Everhard−Thornley detector. Typically dwell time and line-averaging were set to 0.2 μs and 64, respectively. All micrographs were acquired at a pixel resolution of 2048 × 2048. To achieve a more 3D impression of the images, the stage was tilted by 45°. During imaging, the flood-gun was switched on and used in line-flooding mode such that charging effects could be avoided. Prior to imaging, the resolution of the tool was checked to be better than 3 nm using edge contrast on an empty sample holder.

4.5. AFM Force Measurements. The interaction forces between the protein-functionalized AFM tips and a variety of solid materials were measured under simulated respiratory droplet conditions using an MFP-3D AFM (Asylum Research, Santa Barbara, CA, USA). Typically, the AFM tip was positioned over solid substrates, following which the AFM tip was driven at a loading rate of 0.1 μN/s to approach the substrates until a maximum force load of 5 nN was achieved. After 1 s contact, the AFM tip was retracted from the

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substrates at a loading rate of 0.1 μN/s. The approach−retraction force measurements were conducted for 300−500 cycles on several different samples for the same material and several different locations for the same sample, based on which the distribution of adhesion forces was reported.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsami.0c16800.

AFM topography images (2 × 2 μm^2), high-resolution HIM, histogram of normalized adhesion force, and zeta potential of spike protein subunit S1 (PDF)

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Notes

The authors declare no competing financial interest.

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ACS Appl. Mater. Interfaces 2020, 12, 58360−58368

EXHIBIT R

Indoor Air and Coronavirus (COVID-19)

Spread of COVID-19 occurs via airborne particles and droplets. People who are infected with COVID can release particles and droplets of respiratory fluids that contain the SARS CoV-2 virus into the air when they exhale (e.g., quiet breathing, speaking, singing, exercise, coughing, sneezing). The droplets or aerosol particles vary across a wide range of sizes – from visible to microscopic. Once infectious droplets and particles are exhaled, they move outward from the person (the source). These droplets carry the virus and transmit infection. Indoors, the very fine droplets and particles will continue to spread through the air in the room or space and can accumulate.

Since COVID-19 is transmitted through contact with respiratory fluids carrying the infectious SARS-CoV-2 virus, a person can be exposed by an infected person coughing or speaking near them. They can also be exposed by inhaling aerosol particles that are spreading away from the infected person. Transmission of COVID-19 from inhalation of virus in the air can occur at distances greater than six feet. Particles from an infected person can move throughout an entire room or indoor space. The particles can also linger in the air after a person has left the room – they can remain airborne for hours in some cases. Someone can also be exposed via splashes and sprays of respiratory fluids directly onto their mucous membranes. Spread may also sometimes occur through contact with contaminated surfaces, though this route is now considered less likely. See Science and Technical Resources related to Indoor Air and Coronavirus (COVID-19) <https://epa.gov/coronavirus/science-and-technical-resources-related-indoor-air-and-coronavirus-covid-19> or Indoor Air and COVID-19 Key References and Publications <https://epa.gov/coronavirus/indoor-air-and-covid-19-key-references-and-publications> for technical information.

Frequent Questions

- Read Frequent Questions about Indoor Air and Coronavirus (COVID-19) <https://epa.gov/coronavirus/frequent-questions-about-indoor-air-and-coronavirus-covid-19>.
- Explore all EPA Frequent Questions related to Coronavirus (COVID-19) <https://epa.gov/coronavirus/frequent-questions-related-coronavirus-covid-19>.

Though the risk of infection by breathing in particles carrying the virus generally decreases with distance from infected people and with time, some circumstances increase the risk of infection:

- Being indoors rather than outdoors, particularly in indoor environments where ventilation with outside air is inadequate
- Activities that increase emission of respiratory fluids, such as speaking loudly, singing, or exercising
- Prolonged time of exposure (e.g. longer than a few minutes)
- Crowded spaces, particularly if face coverings are inconsistently or improperly worn

Indoor Air and COVID-19 & Information in Other Languages

- Español <https://espanol.epa.gov/cai/el-aire-en-espacios-cerrados-y-el-coronavirus-covid-19>
- عربى <https://epa.gov/node/258587>
- 中文:简体版 <https://epa.gov/node/258835>

There are straightforward steps that can be taken to reduce the potential for airborne transmission of COVID-19 and the focus of this material is on those measures. The layout and design of a building, as well as occupancy and type of heating, ventilation, and air conditioning (HVAC) system, can all impact potential airborne spread of the virus. Although improvements to ventilation and air cleaning cannot on their own eliminate the risk of airborne transmission of the SARS-CoV-2 virus, EPA recommends increasing ventilation with outdoor air and air filtration as important components of a larger strategy that may include physical distancing, wearing cloth face coverings or masks, surface cleaning <https://epa.gov/coronavirus>, handwashing, and other precautions. Consult guidance from the Centers for Disease Control and Prevention (CDC <https://www.cdc.gov/coronavirus/2019-ncov/communication/guidance.html>) and local authorities on current guidelines on the use of masks.

Best practices recommended by the CDC can be found at:

- How to Protect Yourself and Others <https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/prevention.html>
- Cleaning and Disinfecting Your Home <https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/disinfecting-your-home.html>
- Community, Work and School: Cleaning and Disinfecting <https://www.cdc.gov/coronavirus/2019-ncov/community/clean-disinfect/index.html>
- Masks <https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/masks.html>
- How to decrease levels of virus particles during and after a guest visits a home (Interactive Ventilation Tool) <https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/interactive-ventilation-tool.html>

- 中文:繁體版 <https://epa.gov/node/258855>
- 한국어 <https://epa.gov/node/258719>
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- Português <https://epa.gov/lep/ar-interno-e-coronavirus-covid-19>
- Русский <https://epa.gov/node/258693>
- Tagalog <https://epa.gov/node/258635>
- Tiếng Việt <https://epa.gov/node/258709>

Resources Related to Indoor Air and Coronavirus (COVID-19)

- Healthy Indoor Environments in Schools During the COVID-19 Pandemic and Beyond <https://epa.gov/coronavirus/healthy-indoor-environments-schools-during-covid-19-pandemic-and-beyond>
- Indoor Air in Homes and Coronavirus (COVID-19) <https://epa.gov/node/250623/>
- Ventilation and Coronavirus (COVID-19) <https://epa.gov/node/250615/>
- Air Cleaners, HVAC Filters and Coronavirus (COVID-19) <https://epa.gov/node/250619/>
- Implementing a Layered Approach to Address COVID-19 in Public Indoor Spaces <https://epa.gov/coronavirus/implementing-layered-approach-address-covid-19-public-indoor-spaces>
- COVID-19, Wildfires, and Indoor Air Quality <https://epa.gov/coronavirus/covid-19-wildfires-and-indoor-air-quality>
- Science and Technical Resources related to Indoor Air and Coronavirus (COVID-19) <https://epa.gov/coronavirus/science-and-technical-resources-related-indoor-air-and-coronavirus-covid-19>
    - Indoor Air and COVID-19 Key References and Publications <https://epa.gov/coronavirus/indoor-air-and-covid-19-key-references-and-publications>

Please supplement this information with the latest advice from state, local, Tribal and federal agencies.

Reduce Exposure to COVID-19 Using the Interactive Ventilation Tool

Explore which ventilation practices could help reduce airborne virus particles when guests visit your home with the Centers for Disease Control and Prevention's Interactive Ventilation Tool <https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/interactive-ventilation-tool.html>.

To explore more detailed scenarios, see the National Institute of Standards and Technology expanded model: ViPER - Virus Particle Exposure in Residences <https://www.nist.gov/services-resources/software/viper-virus-particle-exposure-residences>.

- Coronavirus Home <https://epa.gov/coronavirus>
- Disinfectants <https://epa.gov/coronavirus/disinfectant-use-and-coronavirus-covid-19>
- **Indoor Air**
- Drinking Water and Wastewater <https://epa.gov/coronavirus/coronavirus-and-drinking-water-and-wastewater>
- Frequent Questions <https://epa.gov/coronavirus/frequent-questions-related-coronavirus-covid-19>

Contact Us <https://epa.gov/coronavirus/forms/contact-us-about-coronavirus-covid-19> to ask a question, provide feedback, or report a problem.

LAST UPDATED ON JANUARY 27, 2023

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EXHIBIT S

Air Cleaners, HVAC Filters, and Coronavirus (COVID-19)

When used properly, air cleaners and HVAC filters can help reduce airborne contaminants including viruses in a building or small space. By itself, air cleaning or filtration is not enough to protect people from COVID-19. When used along with other best practices recommended by CDC and other public health agencies, including social distancing and mask wearing, filtration can be part of a plan to reduce the potential for airborne transmission of COVID-19 indoors.

Air cleaners and HVAC filters are designed to filter pollutants or contaminants out of the air that passes thru them. Air cleaning and filtration can help reduce airborne contaminants, including particles containing viruses.

In order for an air cleaner to be effective in removing viruses from the air, it must be able to remove small airborne particles (in the size range of 0.1-1 um). Manufacturers report this capability in several ways. In some cases, they may indicate particle removal efficiency for specific particle sizes (e.g. "removes 99.9% of particles as small as 0.3 um"). Many manufacturers use the Clean Air Delivery Rate (CADR) rating system to rate air cleaner performance. Others indicate they use High Efficiency Particulate Air (HEPA) filters. In order to select an air cleaner that effectively filters viruses from the air, choose: 1) a unit that is the right size for the space you will be using it in (this is typically indicated by the manufacturer in square feet), 2) a unit that has a high CADR for smoke (vs. pollen or dust), is designated a HEPA unit, or specifically indicates that it filters particles in the 0.1-1 um size range.

Air Cleaners

Portable air cleaners (also known as air purifiers) may be particularly helpful when additional ventilation with outdoor air is not possible without compromising indoor comfort (temperature or humidity), or when outdoor air pollution is high.

Caution: The use of air cleaners alone cannot ensure adequate indoor air quality, particularly where significant pollutant sources are present and ventilation is insufficient. Read EPA's "Guide to air cleaners in the home" (PDF). <https://epa.gov/sites/production/files/2018-07/documents/guide_to_air_cleaners_in_the_home_2nd_edition.pdf>

Air cleaners and HVAC filters in Homes

Where to place a portable air cleaner in your home

Choosing where in your home to place a portable air cleaner to help protect from airborne infections depends on the situation. Put the air cleaner in the room where most people spend most of their time (e.g., a living room or bedroom) unless:

How to select a portable air cleaner for a residence that can effectively remove

1. Someone in a household is especially vulnerable to the risks from infection, then, place the air cleaner where they spend most of their time or
2. If someone is isolating because of an active infection, then, place the air cleaner where they are isolating. See CDC guidance for creating isolation spaces - COVID-19 Quarantine and Isolation <https://www.cdc.gov/coronavirus/2019-ncov/your-health/quarantine-isolation.html>.

- Read EPA's "Guide to air cleaners in the home" for more information on HVAC filters and placing and operating a portable air cleaner. <https://epa.gov/indoor-air-quality-iaq/air-cleaners-and-air-filters-home>
- Learn how to decrease levels of virus particles during and after a guest visits a home. (Centers for Disease Control and Prevention's Interactive Ventilation Tool) <https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/interactive-ventilation-tool.html>

viruses

Choose a portable air cleaner that is intended for the room size in which it will be used and be sure it meets at least one of the following criteria:

1. it is designated as High-Efficiency Particulate Air (HEPA),
2. it is CADR rated for smoke, or
3. the manufacturer states that the device will remove most particles in the size range below 1 um.

Most manufacturers provide this information on the air cleaner packaging, label or website description.

Do not use air cleaners that intentionally generate ozone in occupied spaces or that do not meet state regulations or industry standards for ozone generation.

Air cleaners and HVAC filters in Offices, Schools, and Commercial Buildings

The HVAC systems of large buildings typically filter air before it is distributed throughout a building, so consider upgrading HVAC filters as appropriate for your specific building and HVAC system (consult an HVAC professional). The variety and complexity of HVAC systems in large buildings requires professional interpretation of technical guidelines, such as those provided by ASHRAE <https://www.ashrae.org/technical-resources/resources> and CDC <https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html>. EPA, ASHRAE and CDC recommend upgrading air filters to the highest efficiency possible that is compatible with the system and checking the filter fit to minimize filter air bypass.

Consider using portable air cleaners to supplement increased HVAC system ventilation and filtration, especially in areas where adequate ventilation is difficult to achieve. Directing the airflow so that it does not blow directly from one person to another reduces the potential spread of droplets that may contain infectious viruses.

Air cleaning may be useful when used along with source control and ventilation, but it is not a substitute for either method. Source control involves removing or decreasing pollutants such as smoke, formaldehyde, or particles with viruses. The use of air cleaners alone cannot ensure adequate air quality, particularly where significant pollutant sources are present and ventilation is insufficient. See ASHRAE and CDC for more information on air cleaning and filtration and other important engineering controls.

- See CDC's Interactive School Ventilation Tool <https://www.cdc.gov/coronavirus/2019-ncov/community/schools-childcare/interactive-ventilation-tool.html> to learn how to improve ventilation.

Air Cleaning Devices that use Bipolar Ionization, including Portable Air Cleaners and In-duct Air Cleaners used in HVAC Systems

Bipolar ionization (also called needlepoint bipolar ionization) is a technology that can be used in HVAC systems or portable air cleaners to generate positively and negatively charged particles. Provided manufacturers have data to demonstrate efficacy, manufacturers of these types of devices may market this technology to help remove viruses, including SARS-2-CoV, the virus that causes COVID-19, from the air, or to facilitate surface disinfection of surfaces within a treated area. This is an emerging technology, and little research is available that evaluates it outside of lab conditions. As typical of newer technologies, the evidence for safety and effectiveness is less documented than for more established ones, such as filtration. Bipolar ionization has the potential to generate ozone and other potentially harmful by-products indoors, unless specific precautions are taken in the product design and maintenance. If you decide to use a device that incorporates bipolar ionization technology, EPA recommends using a device that meets UL 2998 standard certification (Environmental Claim Validation Procedure (ECVP) for Zero Ozone Emissions from Air Cleaners).

Please note that there are many air cleaning devices that do not use bipolar ionization – the device packaging or marketing materials will typically indicate if bipolar ionization technology is being used.

Do not use ozone generators in occupied spaces.

Some products sold as air cleaners intentionally generate ozone. These products are not safe to use when people are present because ozone can irritate the airways. **Do not use ozone generators in occupied spaces**. When used at concentrations that do not exceed public health standards, ozone applied to indoor air does not effectively remove viruses, bacteria, mold, or other biological pollutants.

DIY Air Cleaners

Do-it-yourself (DIY) air cleaners are indoor air cleaners that can be assembled from box fans and square HVAC (or furnace) filters. They are sometimes used during wildfire events when air quality is poor and other filtration options are unavailable. There have been questions about whether DIY air filters can be effective in reducing virus particles in indoor environments. DIY air cleaners may provide some benefits for reducing concentrations of viruses and other indoor air pollutants, but research is limited and there are several important considerations explained below.

EPA does not recommend the routine use of DIY air cleaners as a permanent alternative to products of known performance (such as commercially available portable air cleaners). The performance of different DIY air cleaners will vary and cannot be reliably assessed without specialized instruments. Commercial devices have been tested for performance and can be chosen to match the size of a room.

EPA and Underwriter Laboratories evaluated the use of DIY air cleaners and the risk of fire. Fans that were built since 2012 and met UL standard 507 did not pose a fire hazard under the conditions tested in the study. (See Research on DIY Air Cleaners to Reduce Wildfire Smoke Indoors <https://epa.gov/air-research/research-diy-air-cleaners-reduce-wildfire-smoke-indoors> for more information.)

Tips - If You Choose to Use a DIY Air Cleaner

- **Use government, state, tribal, university or other expert instructions for building the device.** There is limited evidence on the effectiveness of DIY air cleaners. There are many possible DIY designs and variations of those designs, and few tests have been done to see how well they work.

- **Cost and Design Considerations:**
  - Initial costs for single filter designs can be lower than designs that use multiple filters.
  - Designs that use more than one filter can be harder to put together, bulkier, and more difficult to move than single filter designs.
  - Designs with more than one filter may also be harder to disassemble in order to replace the filters.
- Some example designs are:
  - How to build a low-cost air filter (pdf) (from the University of Washington, School of Public Health) <https://deohs.washington.edu/sites/default/files/airfilterinfographic_final.pdf>
    - Spanish version (pdf) <https://deohs.washington.edu/sites/default/files/airfilterinfographic_bj_lh_spanish_tb.pdf>
  - One filter flat against the fan (from the Washington Dept of Ecology)
  - Two filters taped with cardboard to form a triangle against the fan (from the Confederated Tribes of the Colville Reservation)
  - Four filters used to create an air filtration box, also known as the Corsi-Rosenthal box (pdf) (from the University of California, San Diego) <https://blink.ucsd.edu/_files/safety-tab/covid-filter-system-poster.pdf>
- **Use a newer box fan (made since 2012) with a UL (Underwriters Laboratory) or ETL (Intertek) logo because they have verified safety features** to reduce the risk of the fan overheating. EPA does not recommend using DIY air cleaners built with older model box fans (built before 2012), but if they are used, they should not be used unattended or while sleeping.
- **Consider running DIY air cleaners the entire time a space is occupied.** The longer they run, the more particles they will likely remove.
- **When assembling a DIY air cleaner, choose a high-efficiency filter, rated MERV 13 or higher, for better filtration.** Align the arrows on the filter to be in the same direction of the air flow through the fan. Create a good seal between the fan and the filter.
- **Change the filters periodically.** Longer run times, higher fans speeds, and higher levels of air pollution will mean that the filter will be removing more particles from the air, but the filter will also get dirty more quickly. Change the filter when it appears dirty.
- **When changing the filter(s), wear gloves, an N-95 respirator or similar, and goggles (without holes) for personal protection.** Remove the filters gently - outdoors if possible. Avoid shaking or banging the filters to minimize the release of accumulated dust. Dispose of the filters in garbage bags.

Features that can improve DIY air cleaner performance:

- **Cover the outside corners of the front of the box fan**, so that air flows only through the center part of the fan where the blades are visible. You can use cardboard, duct tape, or wood to make the cover – some DIY fan designers call these “shrouds”.
- **Use a thick HVAC filter** that is 2” or 4” thick instead of a 1” filter. Generally, thicker filters are more expensive than thinner filters, but need to be changed less often.
- **Increase the number of filters** in the design. Some designs can have 2, 3, 4 or 5 filters.
- **Improve the seal** where the filters are attached to the fan or each other. Seal the edges using duct tape, for example, instead of ties or clamps.

Additional Information

- See EPA Air Cleaners and Air Filters in the Home for more information. <https://epa.gov/indoor-air-quality-iaq/air-cleaners-and-air-filters-home>

- Read ASHRAE guidance <https://www.ashrae.org/technical-resources/resources>.
  - Schools and universities (pdf) <https://www.ashrae.org/file%20library/technical%20resources/covid-19/ashrae-reopening-schools-and-universities-c19-guidance.pdf> (1.93 MB)
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  - Core Recommendations for Reducing Airborne Infectious Aerosol Exposure (pdf) <https://www.ashrae.org/file%20library/technical%20resources/covid-19/core-recommendations-for-reducing-airborne-infectious-aerosol-exposure.pdf> (152.72 KB)
- CDC websites for more information:
  - Improving Ventilation in Your Home <https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/improving-ventilation-home.html>
  - CDC Interactive Ventilation Tool (for Homes) <https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/interactive-ventilation-tool.html>

Return to Indoor Air and Coronavirus (COVID-19). <https://epa.gov/node/250495>

Coronavirus Home <https://epa.gov/coronavirus>

Disinfectants <https://epa.gov/coronavirus/disinfectant-use-and-coronavirus-covid-19>

Indoor Air <https://epa.gov/coronavirus/indoor-air-and-coronavirus-covid-19>

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EXHIBIT T

Centers for Disease Control and Prevention

COVID-19

Safety Precautions When Using Electrostatic Sprayers, Foggers, Misters, or Vaporizers for Surface Disinfection During the COVID-19 Pandemic

Updated Feb. 27, 2023

Carefully select cleaners and disinfectants and application methods for use in facilities, businesses, and public indoor spaces to ensure that you can clean and disinfect safely and effectively.

In most situations, cleaning surfaces (using soap or detergent) is enough to reduce SAR-CoV-2, the virus that causes COVID-19. Clean surfaces before disinfecting.

Disinfection (using a product or process designed to inactivate SARS-CoV-2) is recommended in indoor community settings where there has been a suspected or confirmed case of COVID-19 within the last 24 hours; when the presence of infectious virus is more likely. When disinfecting, choose the safest method that is also effective. For most situations, using traditional disinfectant methods, such as liquids, wipes, or disinfectant spray bottles, is sufficient to reduce virus exposure. Be sure to use products safely and according to label instructions, and use products that are on EPA's List N: Disinfectants for Coronavirus (COVID-19) .

> **Electrostatic sprayer:** A device that works by applying a small electrical charge to aerosols when passing through the nozzle. These charged droplets adhere easier and stick to environmental surfaces.
>
> **Fogger (also known as mister):** A device that uses a fan and a liquid solution to create a fog (aerosol with small droplets) or mist.
>
> **Vaporizer:** A device used with hydrogen peroxide disinfectant solutions. Doors and ventilation systems must be sealed while in use. Should be used only in healthcare or laboratory settings.

Choosing to use an electrostatic sprayer, fogger, mister, or vaporizer:

If trained professionals are available to apply them, people may decide to use newer technologies that either spray disinfectant electrostatically, or disperse it through fog, mist, or vapor. Cases where these technologies could be more practical include situations where there might be a confirmed case of COVID-19, use of the space is needed quickly, and some surfaces could be very hard to reach to disinfect by hand. These are sometimes used in healthcare settings after a patient is no longer using a room.

These devices aerosolize chemicals, or suspend them in the air, and they can stay in the air for long periods of time, especially if the area is not well ventilated. Aerosolizing any disinfectant can irritate the skin, eyes, or airways and can cause other health issues for people who breathe it in.

CDC does not either recommend, or not recommend, use of these devices for disinfecting community spaces for COVID-19. If they are used, they should be used with extreme caution. A disinfectant product's safety and effectiveness might change based on how you use it. If electrostatic sprayers or foggers are used, they should be used:

- Only by trained professionals
- With disinfectants approved for this method of application
- According to manufacturer instructions for safety, use, and contact time
- With appropriate personal protective equipment (PPE) and other safety measures to ensure safety for the operator, others nearby, and for people who might use the room afterward
- When rooms are not occupied

- With extreme caution if using around food preparation or areas where children play

For information about the application of Environmental Protection Agency (EPA) List N disinfectants with electrostatic sprayers and foggers, refer to the EPA's "Can I use fogging, fumigation, or electrostatic spraying or drones to help control COVID-19?" website . If the product's label does not include disinfection directions for use with fogging, fumigation, wide-area or electrostatic spraying, EPA has not reviewed any data on whether the product is safe and effective when used by those methods.

Understand the risks

Note: Directions for specific devices and chemicals may vary. Always follow safety directions on product labels. If the label is hard to read or missing, do not use the product.

Exposures to chemicals in aerosolized disinfectants can cause skin, eye, or respiratory irritation.

- If you use an electrostatic sprayer or fogger, only the person applying it, wearing appropriate PPE, should be in the room. The person applying should leave the room following application. Stay out of the area for the time indicated in the product label and specified by the application device. Open windows and doors after use, if possible, to air out the space.
- Remove chemical residue, which can pose health risks, before others enter the room. Follow product label directions for wiping or rinsing residue after the appropriate contact time has been achieved.
- Some people, such as children or people with asthma, are more vulnerable to certain chemicals. Follow CDC guidance for People with Moderate to Severe Asthma as any disinfectant can trigger an asthma attack.

In dining and food preparation areas or areas where children spend time, safety risks are greater.

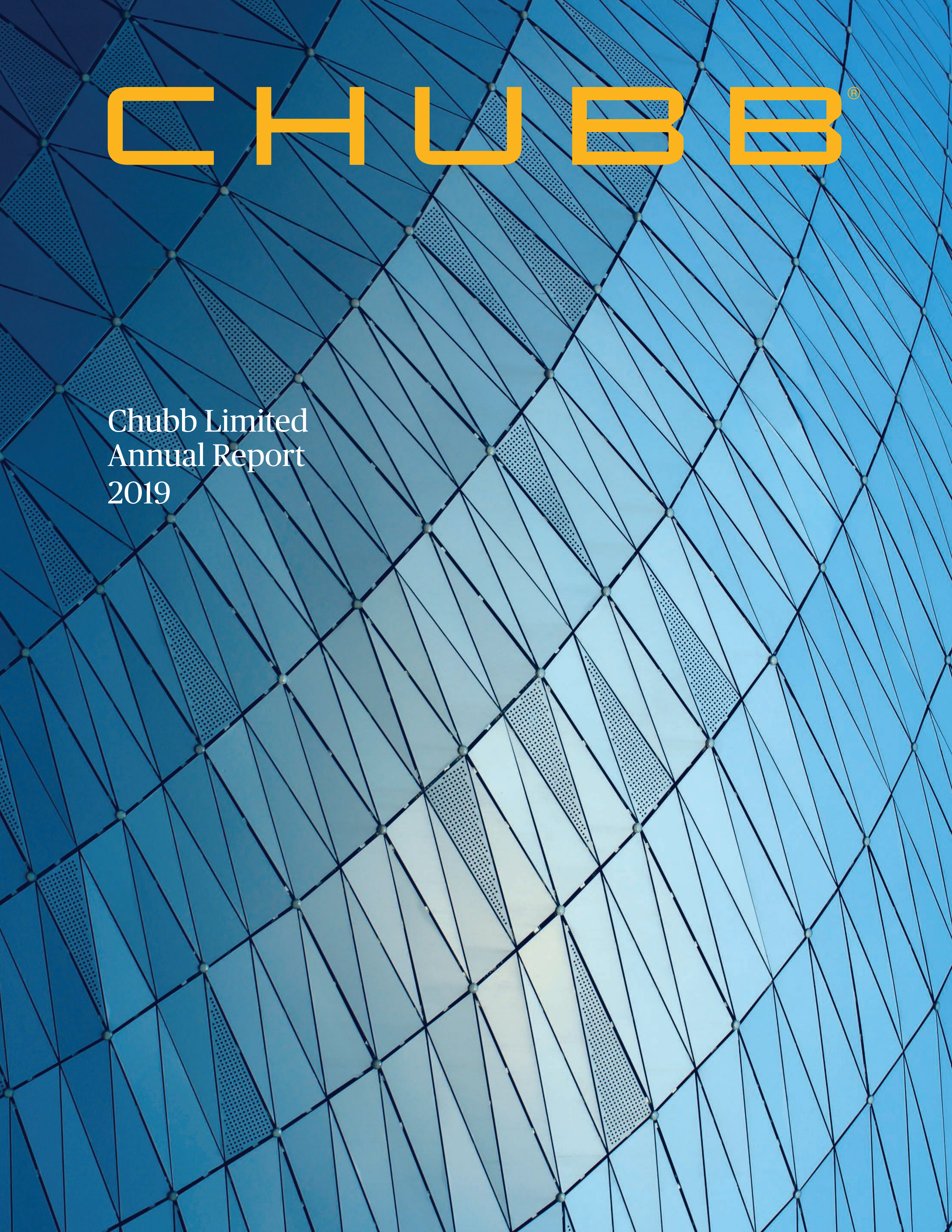
- Use extreme caution if you choose to use an electrostatic sprayer or fogger in dining and food preparation areas. The aerosolized disinfectant could land in areas where the chemical may contaminate food preparation surfaces (e.g., countertops, dishware) or food, or areas where children might touch things (e.g., toys, desktops). Using a liquid, spray bottle, or wiped disinfectant gives you more control over where the disinfectant goes.
- Use only products approved for food contact surfaces in food areas.
- Follow recommendations about how to safely disinfect daycares and schools and restaurants and bars.

Disinfectants have different safety precautions and hazard risks. Anyone handling or using disinfectants with electrostatic sprayers or foggers should understand how to choose the appropriate disinfectant for the device, how to use Safety Data Sheets , and how to protect workers and others.

- Train cleaning and janitorial staff on how to apply disinfectant safely (e.g., use of PPE; how to respond to chemical exposure) and effectively (e.g., application method, concentration, contact time).
- Disinfectant products are approved for certain devices or equipment and are not interchangeable with different products.
- Follow manufacturer's label for application instructions. Beware of new technologies and devices or equipment not specified on manufacturer's label.
- Wash your hands with soap and water after handling disinfectants. Be sure to wash your hands immediately after removing gloves.

Last Updated Feb. 27, 2023

EXHIBIT U



CHUBB®

Chubb Limited Annual Report 2019

Financial Summary

In millions of U.S. dollars
except per share data and ratios

	Year Ended Dec. 31, 2019	Year Ended Dec. 31, 2018	Percentage Change	Percentage Change Constant Dollars
Gross premiums written	$40,124	$37,968	5.7%	7.0%
Net premiums written	32,275	30,579	5.5%	7.0%
Net premiums earned	31,290	30,064	4.1%	5.5%
P&C combined ratio	90.6%	90.6%	NM	
Current accident year P&C combined ratio excluding catastrophe losses	89.2%	88.0%	NM	
Net income	4,454	3,962	12.4%	
Core operating income	4,641	4,407	5.3%	6.8%
Diluted earnings per share – net income	9.71	8.49	14.4%	
Diluted earnings per share – core operating income	10.11	9.44	7.1%	8.6%
Total investments	109,234	100,968	8.2%	
Total assets	176,943	167,771	5.5%	
Shareholders' equity	55,331	50,312	10.0%	
Book value per share	122.42	109.56	11.7%	
Tangible book value per share	78.14	65.89	18.6%	
Return on equity	8.4%	7.8%	NM	
Core operating return on equity	9.0%	8.7%	NM	
Core operating return on tangible equity	14.6%	14.6%	NM	

This document contains non-GAAP financial measures. Refer to pages 50-52 for reconciliations to the most directly comparable GAAP measures.

NM—not meaningful

Evan G. Greenberg
Chairman and Chief Executive Officer
Chubb Group

To My Fellow Shareholders

As this letter goes to press, the U.S. and many other nations of the world are shutting down much of their social and economic activity in response to the spread and threat of the coronavirus. We simply don't know at this time how fast or far it will spread, or how effective we will be in slowing the spread, treating victims and dealing with the consequences. For Chubb, we are clear about our priorities and resolute in our response: To the extent possible, we will take care of our people and keep them safe; we will remain consistent in how we take care of our customers and business partners, doing everything in our power to serve their needs with minimal disruption; and we will be a responsible citizen in our community, heeding the advice of government and health authorities, and as a solid contributor to recovery.

Chubb had a very good year in 2019. We produced strong financial results, including per share growth in earnings, book value and tangible book value. We capitalized on opportunity, benefiting from improved commercial property and casualty (P&C) pricing and underwriting conditions globally and generating our best organic premium revenue growth in over five years. We achieved another year of excellent underwriting profitability – a direct result of our time-tested discipline in underwriting and managing risk. Driven by growth in our invested assets, we generated record investment income despite low interest rates.

Throughout the year, Chubb professionals distinguished themselves through their actions serving customers and business partners, contributing to our admired brand and reputation for quality service. We made progress in our efforts to advance our many longer-term strategies that will position us for future growth, including our presence in China with an increased ownership stake in Huatai Insurance Group. We demonstrated leadership in environmental sustainability by announcing a progressive policy curtailing our underwriting and investments in coal. We concluded the year in excellent financial, operational and competitive shape and have real momentum going into '20 for future growth and profitability.

In my judgment, all successful companies have a clearly articulated view of who they are and why they exist, so let me begin by describing in a few words our unique and distinctive company. Chubb is the largest publicly traded P&C insurer and the fifth largest insurer in the world as measured by market capitalization. (Fifteen years ago, we were #5 and #26, respectively – we are patient and persistent.) We are a truly global commercial and consumer insurer – one of only a few in the world. With substantial local operations in 54 countries and territories, we compete for local business while serving the needs of multinationals. We have an enviable long-term track record of financial performance including growth in earnings, book and tangible book value and market capitalization, underpinned by distinguished underwriting performance.

In the United States, which represents about 30% of the global insurance market, we are a top-two commercial P&C insurer that serves all sizes of companies – from global to middle market to small businesses – with hundreds of traditional and specialty coverages, including a leading position in the wholesale market for excess and surplus (E&S) or difficult to place risks, and we are the #1 crop insurer. On the consumer side, Chubb is by far the leading personal lines insurer protecting America's affluent individuals and families. Our Combined Insurance affiliate serves middle-income households with a variety of personal accident and supplemental health insurance products.

About 40% of our business originates outside the United States and it's growing faster than our U.S. business. Our extensive local operations throughout Europe and the United Kingdom, which represent about half of our international portfolio, in 2019 had their best growth in a decade. The balance is equally split between the developed and developing markets of Asia and Latin America, both of which are growing at high-single or double-digit rates. Our international insurance businesses are essentially split 50/50 in terms of their commercial and consumer focus. In addition to our retail commercial P&C businesses present in just about every major market around the globe, we also have significant E&S wholesale market operations in London and Bermuda. We serve consumers in international markets through our large global accident and health (A&H) business, which writes personal accident and supplemental health insurance, and our international personal lines business, which underwrites everything from cell phones to autos to homes and their contents.

As the first company to convert a domestic Chinese financial services holding company to a foreign-invested joint venture, we are on a path, subject to regulatory and shareholder approvals, to achieve majority ownership of China's Huatai Insurance Group, the holding company of P&C, life and asset management subsidiaries with over 600 offices. We also have a growing Asia-based life insurance business that is becoming a more important contributor to earnings.

Taken together, Chubb has a thoughtfully constructed and managed global portfolio of simply outstanding businesses. Most are top-performing multibillion-dollar businesses, with substantial scale and scope for growth, and the envy of the industry. We have a well-balanced mix of business – 66% commercial lines, 34% consumer lines – and our product breadth and balance are a real strength. We sell our products globally through an extensive range of distribution channels: over 50,000 brokers and independent agents, more than 85,000 exclusive life and health agents, and hundreds of direct-to-consumer partnerships that give us access to tens of millions of potential customers through digital, phone and face-to-face marketing tools and techniques – another strength. At the same time, in aggregate, we are not overly dependent on any one channel.

For the year, total gross premiums written for the company were $40.1 billion while net premiums written, which are the premiums we retain on our balance sheet, were $32.3 billion, both up 7% before the impact of foreign exchange. Our balance sheet is exceptionally strong, with $70 billion in total capital and over $55 billion in equity at December 31, and our company is rated AA by S&P and A++ by AM Best. With a good balance of underwriting and investment income, last year we produced core operating income of $4.6 billion, or $10.11 per share, up 7.1% on a per share basis from 2018.

The macro environment in 2019

I would have characterized the external operating environment in '19 and as we began to move into '20 as marked by great opportunity, risk and complexity. That is until the coronavirus outbreak, which began in China and subsequently spread to the rest of the world. Now, with the specter of a true pandemic upon us, and the substantial damage to be inflicted on society, economies and commerce alike, markets are severely stressed and signaling global recession. As of this writing, to what degree and how long it will last is simply unknowable – it depends on the rate and severity of infection. We lack visibility. However, the coronavirus has already had a real impact on China economically and politically, as well as the global economy, including the U.S.

Beneath the shadow of the coronavirus, U.S. economic performance has remained the strongest in the world among large economies, while the global economy has slowed from trade-related headwinds, poor government policy in many countries, and geopolitical events. Business thrives in an environment of certainty, and business confidence has suffered, and that has impacted business investment.

2019 concluded on a more encouraging note with the signing of the USMCA trade agreement and a phase one U.S.-China trade pact, both a net positive given where we were, as well as increased political certainty surrounding Brexit. By themselves, these developments may provide moderately improved business confidence and, in turn, increased investment, although we still face considerable uncertainty:

• Tariffs with China remain in place, as do tariffs with others at year-end. Manufacturing globally is in recession. The phase one agreement, while a good start, doesn't address many of the fundamental trade issues with China – in that regard, it kicks the can down the road.

• More broadly, protectionist sentiments persist. The rules-based trading system is under attack from the world's two largest economies with the U.S. unilateral approach using tariffs and a strong-arm approach (and by the way the EU is on deck later this year) and China, with its predatory behavior, gaming the global system to its advantage. We are evolving from a unipolar to a multipolar world – China is emerging and the U.S. is more unilateral and inward-looking, both sources of increased tension.

• U.S.-China relations are headed in the wrong direction, marked by lack of trust and cooperation, and increasing confrontation.

• We have numerous geopolitical hot spots including North Korea and Iran.

Industry conditions last year: improving commercial P&C pricing

The insurance industry is experiencing improved commercial P&C underwriting conditions in the U.S. and a number of major international locations. After years of slower growth and shrinking some of our important businesses as we maintained discipline around inadequate terms, market conditions have improved and are spreading to more classes of risk and more countries, which means a time for growth. We built our company to capitalize on conditions such as these and have patiently waited. Today we are achieving rate above loss cost trend in many lines and territories, particularly in those classes where margins have been under pressure. Given the current environment and our longer-term secular growth strategies, this bodes well for future growth in revenue and earnings. I expect the positive market conditions to continue throughout '20 and beyond, and Chubb will benefit.

For perspective, prices in a number of important classes continue to remain below what is adequate to earn a reasonable return for the risk taken. Prices in others have achieved sufficiency, and in those cases we are growing. P&C insurance is a cyclical business. Generally speaking, with few exceptions, loss costs rise every year, and when rates don't keep pace, margins naturally decline, disappear or worse. Companies that in the past pursued market share at inadequate pricing and terms are suffering and will experience margin and potentially reserve pressure. Many in the industry are not earning their cost of capital. On top of that, there is volatility in the loss environment in certain casualty- and property-related classes. It's no surprise, therefore, that we have seen a pull-back and retrenchment by those insurers that took on too much underpriced and poorly underwritten exposures. That's what creates cycles.

The industry's insured natural catastrophe (CAT) losses last year are estimated at $50 billion to $55 billion, down substantially from the previous two years. We continued to observe a rise in weather-related volatility, including increased frequency of large events ($1 billion or greater in losses); more extreme conditions linked to temperature and moisture producing bigger tornadoes, larger floods, wildfires and hurricanes with more moisture; and changing seasonality. This volatility, which is driven by climate change and urbanization resulting in a greater concentration of exposures in coastal and inland locations, we expect to continue. For Chubb, pre-tax net CAT losses were $1.2 billion, down from $1.6 billion in 2018 – an improvement but about $220 million more than we planned for when calculating our "expected" CATs for the year.

Given its concentration of risk exposed to temperature and moisture, crop insurance is a business with CAT-like features. There is a fair degree of volatility and season-to-season variability to growing conditions and commodity prices. Adverse weather in parts of the United States last year impacted growing conditions. After three exceptional years from '16 to '18, last year was below-average. Even so, we recorded a calendar year combined ratio of 95.1%. Crop insurance has been a very good business for Chubb. We are the national leader with the most experienced people and deepest knowledge based on decades of data on over 3 million farm fields, which improves risk selection. Notably, both the CAT and crop losses in 2019 were

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comfortably within our risk tolerance. We purposely take these risks and have no regrets as long as our underwriting is good and we are properly paid.

Craftsmanship: the art and science of underwriting

Chubb is an underwriting company – everything starts with underwriting and assuming risk is at the heart of our business. Our company is led by underwriters and our culture is centered on the art and science of taking risk. We practice our craft better than any company of size and we have an enduring track record of outperformance to prove it. Over the past 15 years, Chubb's P&C combined ratio has outperformed our peers by an average of seven percentage points over any time period. Last year we produced $2.7 billion of pre-tax P&C underwriting income, an increase of nearly 7% in constant dollars, and a 2019 calendar year P&C combined ratio of 90.6%, which was flat with prior year. Our underwriting performance for the results of the current in-force business is measured by the current accident year combined ratio excluding catastrophe losses, a preferred industry measure, which was 89.2% compared with 88.0% prior year, and including anticipated or expected CAT losses, which I believe is a better measure, it was 92.6% compared with 91.4%.

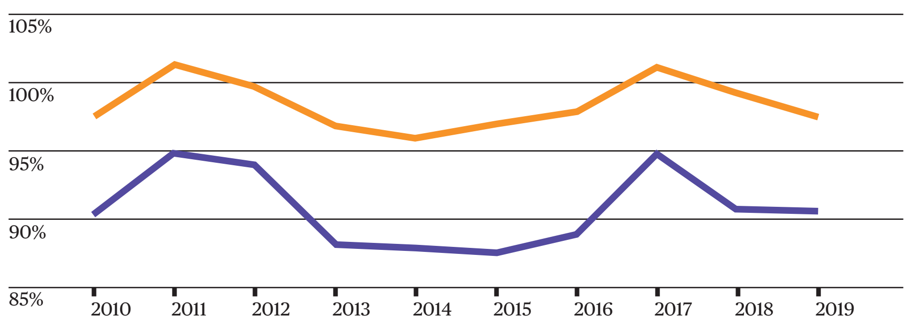
At Chubb, accountability for underwriting discipline starts at the top – management owns it and is deeply engaged at every level and in all parts of the organization around the world. We have operationalized our underwriting culture with a balance between local capability and autonomy and global command and control, which enables us to move nimbly between offense and defense, conditions depending. When we see market opportunity, we strive to quickly seize it. On the other hand, our willingness to trade market share for underwriting profitability, along with relentless expense management and efficiency, contributes to our competitive profile. By the way, expense discipline doesn't mean failing to invest in our people and technology – these are investments.

As I have observed to you previously, generally speaking, loss costs rise every year. For our company, loss costs in aggregate across all P&C lines of business rose 4.5% last year. If pricing doesn't rise at the same rate, all things being equal, loss ratios rise. In our industry, rates have not kept pace with rising loss costs for a number of years now. Separately, the loss trend for certain casualty and property-related lines has worsened due to a changing loss environment, both weather and man-made related. This has stressed insurers' margins and created greater volatility and uncertainty that together have impacted their confidence in taking risk.

In the U.S. and a few international locations, severity and frequency in "first-dollar" layers for casualty classes of business have been relatively steady. However, in the excess layers of certain classes, overall frequency and frequency of severity of large individual claims have been increasing and putting pressure on results for a number of reasons. The most benign reason is casualty attachment points (the level of loss where coverage

P&C Combined Ratio versus Peers

The company's underwriting results have outperformed the average of its peers over the last 10 years.



Averages:	1 year	3 year	5 year	10 year
Peers[1]	97.4%	99.3%	98.5%	98.3%
Chubb	90.6%	92.0%	90.4%	90.7%

[1] Includes AIG, Allianz, AXA, CNA, HIG, QBE, RSA, TRV, XL, Zurich. XL's 2018 and 2019 results are for the AXA-XL division of AXA.

Source: SNL and company disclosures

begins) have not moved for years – a $1 million attachment point for casualty excess 10 years ago is worth a fraction of the amount today.

Contributing to frequency and frequency of severity is so-called social inflation, resulting in increased litigation activity and size of awards primarily driven by (a) increased litigation financing – a new asset class; (b) populist sentiment, including growing distrust of large corporations, expressed in jury attitudes; (c) growing jury insensitivities to large dollar verdicts; (d) erosion of previous tort reform remedies; (e) changing definition or interpretation of corporate responsibility (if something went wrong, someone is strictly liable); and (f) changing social norms in terms of tolerance and definition of gender bias and sexual abuse. This increased litigation is apparent in class actions from securities and anti-trust related cases to science-based: chemical, pharma and physical trauma-related. One-off casualty CAT-type events reflecting society's increasing abhorrence and zero-tolerance with sexual abuse and harassment are leading to legislative actions such as reviver statutes, where it's simply too early to know the ultimate financial impact.

One class of business where costs continue to rise is coverage for directors and officers, or D&O, as the frequency and severity of litigation from securities class actions and M&A objections have worsened. Last year was no exception. Securities class action filings remained at an all-time high – the third consecutive year with more than 400 cases filed and 9% of U.S. publicly traded companies the target of a class action. Meanwhile, severity, as measured by the median settlement value, climbed to the highest recorded level since 2012 and was 25% higher than the median for the previous three years.

Litigation is a necessary process to decide disputes that cannot otherwise be resolved, and the legal profession is a profit-making industry like any other. But our inefficient system benefits lawyers at the expense of shareholders. Excessive litigation is a tax on society and business, enriching the trial bar with little benefit in most cases going to the supposed aggrieved. According to a NERA Economic Consulting study, more than two-thirds of the cases in 2019 resolved in favor of the defendant with no payment made to plaintiffs but plenty to their lawyers. Nearly 90% of M&A objection suits are dismissed. Based on our data, in the last seven years, about half of the money paid in securities claims, including legal expenses and settlements, has gone to the lawyers, both plaintiff and defense, and in the case of M&A objections, it's over 70%. Federal and state legislation will be required to remedy abuses. Reforms should include requiring fees paid to plaintiffs' attorneys be proportional, barring fees for frivolous disclosure suits, and requiring disclosure of all relationships between plaintiffs and their lawyers and third-party funders.

Litigation funding is a new investment asset class in which investors who have suffered no harm pay litigation costs for the sole purpose of sharing in the proceeds of a favorable judgment or settlement. This is a growing problem in the U.S. and a number of other countries, including the U.K. and Australia. It is linked to approximately 75% of all class actions and, in the U.S., more than $7 billion of funding

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is waiting to be invested in lawsuits. Enriching a few, litigation funding is an investment activity that in the main hardly benefits society. Working with the U.S. Chamber of Commerce's Institute for Legal Reform and other organizations, we are educating regulators and members of the judiciary in the U.S. and abroad about the consequences of unrestricted financial speculation in our civil justice system and the need for adequate disclosure and other reasonable regulation. We continue to seek like-minded allies who want to join our coalition.

Growth in invested assets supports growth in investment income

The other source of our earnings is investment income, and in 2019 we generated pre-tax adjusted net investment income of $3.6 billion, up only 1%. During the year, in response to a slowing global economy and trade-related headwinds, the U.S. Federal Reserve reversed course and lowered interest rates again to historically low levels. Our strong operating cash flow of $6.3 billion helped to mitigate the impact and will continue to support investment income as we grow our invested assets, which stood at $109 billion at December 31. Nevertheless, growth in investment income will remain relatively low as long as interest rates remain so. We will continue to maintain a conservative approach to the management of our invested assets by seeking adequate risk-adjusted returns and not reaching for yield. For the year, the portfolio generated an average book yield of 3.5% versus average new money rates of about 3%.

We expect the current low interest rate environment will continue for the foreseeable future, especially

Long-Term Operational & Financial Outperformance (10 Years)

Chubb has delivered on its financial goals and outperformed its peers across most metrics

	Premium & Earnings Growth		Underwriting Profit	Book Value Growth		Average Return on Equity & Return on Tangible Equity		Valuation	Outperformance Since Merger: 3 Years Post Merger	
	Net Premiums Written ('09-'19)	Operating Earnings ('09-'19)[1]	P&C Combined Ratio ('10-'19 Avg.)	Book Value per Share (12/09-12/19)[2]	Tangible Book Value per Share (12/09-12/19)[2]	Average Return on Equity ('10-'19)	Average Return on Tangible Equity ('10-'19)	Market Cap Growth (12/09-12/19)[3]	Tangible Book Value per Share (12/16-12/19)	Average Return on Tangible Equity ('17-'19)
Chubb	143%	68%	90.7%	109%	67%	10.6%	14.6%	315%	29%	14.2%
Avg. Peers[4]	1%	40%	98.9%	42%	53%	8.9%	11.3%	77%	6%	11.7%

[1] AIG excluded due to negative earnings in 2009
[2] AIG adjusted for U.S. Treasury Equity Investment in 2009
[3] AIG excluded due to impact from government intervention
[4] Peers include AIG, Allianz, AXA, CNA, Hartford, Travelers, Zurich
Annual metrics through full year 2019 actuals: Net premiums written, Operating earnings, P&C combined ratio, Average return on equity and Average return on tangible equity. Point-in-time metrics (Book value per share, Tangible book value per share and Market Cap) through December 2019 actuals

given the potential consequences of the coronavirus. The combination of generally sluggish global growth and low inflation encourages exceptionally accommodative central bank monetary policies. These have become a poor substitute for better government economic and fiscal policies. Approximately $15 trillion globally is now invested at negative yields and some political leaders think that's acceptable. However, in my judgment, these conditions won't last. Overreliance on monetary policy is misguided – it hurts savers of all kinds, including pension funds and insurers, and encourages overly aggressive investment behavior that inflates asset values while failing to materially stimulate growth. Many investors are chasing absolute yield instead of risk-adjusted returns, and that never ends well. Given inflated balance sheets and exceptionally low interest rates, central banks have limited room to move in the next economic downturn.

Book and tangible book value growth

Chubb is a growth company. We define that as growth in book and tangible book value over time. Our priority is to grow shareholder value by first growing our company, both revenue and earnings, while deploying capital efficiently. As the chart nearby illustrates, we grew our company faster than the average of our peers over the past 10 years. Premiums increased 143% and core operating income grew 68%. Book value growth of 181% followed, with per share book value up 109%. As a result of our performance, our market capitalization is up over 300%. The second-highest of our peers rose 145% during that period, and most were below 100%. The scale we have today is a strategic advantage for future value creation.

For investor clarity, let me share my thoughts regarding two important metrics – return on equity (ROE) and return on tangible equity (ROTE). ROE is an accounting concept and an inexact measure of returns. If all of the capital we used to acquire The Chubb Corporation in 2016 was used instead to repurchase shares, the denominator of the ROE equation would be reduced, resulting in a higher ROE. But would that have increased the franchise value of our company, and would the returns on deployed capital be higher and more sustainable than they are for Chubb today? Hardly – and what would our future value creation look like if we had done so?

Our core operating ROE currently stands at 9%, well in excess of our cost of equity of approximately 7%. The ROE is impacted by goodwill, which we incurred as a result of acquiring several excellent businesses, Chubb in particular. In my judgment, goodwill is an income producer and an appreciating – not depreciating – asset over time. Look at what that goodwill has created: It has helped transform our company into the franchise that we are today – a leading brand with substantial scale, a portfolio of market-leading businesses and earning power and, critically important, optionality for future growth globally. Our ROE will increase over time as we continue to grow the company and further leverage the scale and capabilities we have built. The goodwill has opened a path for us that we could not have pursued without it.

We are in the risk business. We are a balance sheet business. The most important value-creating measures, in my judgment, are growth in tangible book value and core operating return on tangible equity, or ROTE, which was 14.6% last year. Tangible equity is the most constraining measure to value creation. It is the most fundamental measure that governs our ability to take

"We are in the risk business. We are a balance sheet business. The most important value-creating measures, in my judgment, are growth in tangible book value and core operating return on tangible equity, or ROTE, which was 14.6% last year."

risk and to grow the company, and it shows how our underlying business intrinsically performs. Everything we do is measured against it: We can only pay claims from tangible; premium growth is governed by tangible because exposure is leveraged against tangible; and M&A and debt leverage are dependent on tangible equity.

Our average ROTE over the 10-year period is 14.6%, with growth in tangible book value of 124%. Both are quite strong, but ROTE was impacted by the 2016 Chubb acquisition. We paid a price to build this franchise, and that dilution impacted both tangible book value per share and average ROTE. It took us approximately 3.5 years to recover the dilution, which speaks to the franchise earning power. By the way, when measured over the three-year period following the Chubb acquisition, our average ROTE is over 14%, which is top class, and our tangible book value per share growth leads all peers at 29%.

Our stock price increased 21% last year and produced a total return of 23%, a decent performance but not superior to the S&P 500's 32% or our peers, some of which benefited from a steeper rise from lower price-to-book valuations. The Chubb share price remains a bargain in my judgment. Insurance is a long-term business and attractive long-term shareholder returns are simply a derivative of doing our job well. In that regard, our 10-year total return is 288% and compares well to the S&P 500 (257%) and the S&P 500/Financials (218%) and is equal to the S&P 500/P&C Insurance (289%).

Beyond what we need for risk and growth including M&A, we return surplus capital to shareholders. We have a 25+ year track record of annual dividend increases – earning us membership in the rare "dividend aristocrats" club – and a target payout ratio of approximately 30%. In 2019, we returned to shareholders about $1.4 billion in dividends and over $1.5 billion in share repurchases. We repurchased our shares at an average price of $147, which equals a price-to-book of 1.2 – cheap.

Strategic growth priorities: cyclical and secular

We are builders at Chubb, executing on multi-year plans that take advantage of both cyclical and longer-term secular growth trends taking place around the world. Earlier I said capitalizing on the current commercial P&C market conditions is a major strategic priority right now for a growing number of our businesses. About 45% of our portfolio, representing many short- and long-tail classes, is now benefiting from the improved market conditions – and I expect that percentage to increase.

Beyond the cyclical, our company is focused on important long-term secular trends. There is so much opportunity in so many places, not least in the U.S., which remains a major growth market given its vibrant economy and its wellspring of entrepreneurial spirit, risk-taking and innovation. Here are four others:

• The growth of small and mid-sized businesses in many parts of the globe, particularly Asia and Latin America. As nations in these regions develop, economic growth comes predominantly from small and mid-sized business creation. We have an extensive range of commercial insurance offerings and distribution channels to serve them.

• The rising middle class in many of the developing economies of Asia and Latin America. We have significant future growth opportunity serving these consumers, who need the basic savings and protection products our company provides.

• China looms large as a potential long-term growth opportunity, and our presence there is expanding.

• Digitization is sweeping through society globally, including the business of insurance, offering ways to improve or transform so much of what we do.

Let me take a little time and describe these cyclical and secular growth opportunities in the context of our businesses and tell you how they performed last year and how they are positioned for future growth.

Chubb's North America Commercial P&C Insurance operation, excluding agriculture, produced good growth in 2019 with net premiums written overall increasing over 7%. Momentum built steadily as the year progressed with first half growth of 5.6%, second half growth of 8.6%, and fourth quarter accelerating to 9.4%. Our $8 billion Major Accounts division serves the insurance needs of large domestic and multinational corporations, and Chubb is the leader not only in terms of size but capability, presence and know-how. Even though 90% of the Fortune 1000 are clients, there's still billions of dollars of opportunity available by writing more coverage for each customer. For instance, out of a universe of approximately 5,000 of the largest companies in the U.S., there are about 2,000 accounts where we write fewer than three lines of coverage. This business is benefiting from favorable underwriting conditions and a flight to quality, and it grew over 5% last year and is currently growing even faster.

Our North America middle-market and small business commercial P&C franchise, at $6 billion, is next in size. This business addresses an incredibly large segment of the U.S. economy. With an extensive field organization and the broadest array of traditional and specialty products, we provide coverage and service to businesses ranging from multinational publicly traded mid-sized organizations to single-location private companies. Our two dozen industry practices advise and provide coverage to industries ranging from life sciences and healthcare to CleanTech and advanced manufacturing. Our fast-growing small business division offers a highly automated digital experience – nearly 85% of the more than 50,000 submissions we receive each quarter are not touched by human hands after they leave the agent's office. We have 4,500 agencies in the U.S. using our Chubb Marketplace platform to digitally quote and issue policies and service their clients. Our middle-market and small commercial division benefited from more favorable underwriting conditions as the year progressed, growing 5.5% in the first half and 6.6% in the second. We expect the positive growth trend to continue in '20.

Westchester is our E&S wholesale business in the United States and writes about $2.8 billion in gross premiums. E&S insurers specialize in hard-to-place or unusual risks that require tailored coverages standard companies cannot or won't write. We have a broad product line-up – from specialty property and liability offerings to product recall and railroad liability, as examples. After years of shrinking due to soft underwriting conditions, Westchester took advantage of a rapidly improving marketplace in 2019 and grew over 9%. Chubb Bermuda, our original insurance company founded in 1985, is our other E&S business in North America and specializes in high excess, low frequency coverage for casualty, property, financial lines and political risks. This business experienced some of the fastest price and terms improvement as the year progressed, leading to growth of over 30%. For both Westchester and Chubb Bermuda, good growth should continue in '20 as more E&S risks move toward adequate pricing.

Chubb Personal Risk Services serves the personal lines insurance needs of affluent individuals and families in the U.S. and Canada. We lead this sector with an estimated market share of nearly 60%. In 2019, we more tightly focused the portfolio of this $5.5 billion business on clients who value the richness of Chubb's coverage and service and are willing to pay the price for it. We are constantly adding new coverages and services to respond to the risk management needs of these discerning customers. We continue to refine our risk selection and pricing capabilities through improved analytics and our wealth of data. In this business, customer experience is truly the product and we continued to distinguish ourselves with the industry's most admired claims service while enhancing our clients' digital experience with us. Our clients truly love Chubb – we retain 90% of our customers and 97% of the premium annually – and so it's no wonder that this business is a wellhead of our brand in America. As for growth, net premiums written were up about 2.5% for the year, but 4.6% in the fourth quarter on an adjusted basis.

Chubb Overseas General is our $11.3 billion international P&C business. We have operations in 51 countries and territories outside North America including significant presence and

"We are builders at Chubb, executing on multi-year plans that take advantage of both cyclical and longer-term secular growth trends taking place around the world."

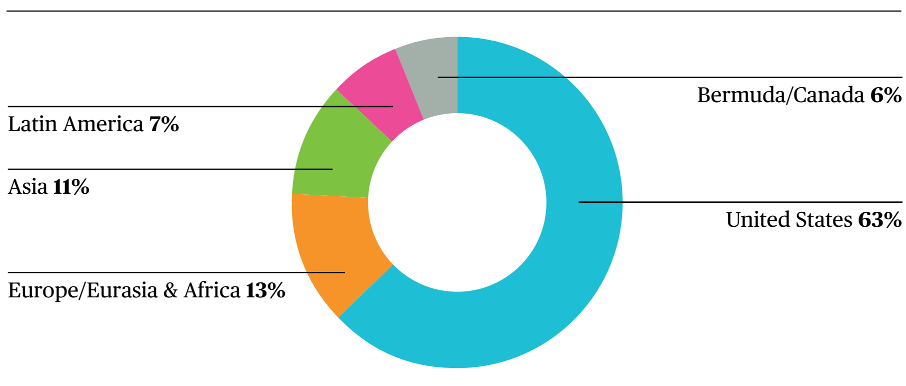
capabilities in Europe, Asia Pacific and Latin America. This division serves large corporates, middle-market and small commercial companies, or SMEs, and individual consumers with a wide range of products and services. We experienced some of our best growth last year, with net premiums up more than 8.5% in constant dollars. Over the years we have built extraordinary local capabilities around the globe to take advantage of local opportunity, including cyclical market conditions wherever they happen. For example, after years of shrinking our Lloyd's London-based wholesale division by almost half when the pricing for risk was inadequate, we experienced four consecutive quarters of serious double-digit growth ranging from 15% to 29%. In Australia, after years of relatively low growth due to overly competitive conditions, our quarterly premium revenue growth hasn't dipped below 16% for the last two years.

A key driver of future growth for Chubb in both the U.S. and internationally is our consumer lines operations, which consists of two large businesses: our global accident and health division and our international personal lines division. Together, this $7 billion operation grew about 5.5% in 2019 in constant dollars and employs multiple distribution methods including telemarketing, agency, broker and digital partners. For example, in North America, Chubb Workplace Benefits, which we built from scratch in our Combined Insurance affiliate, provides voluntary employee benefits for mid-to-large companies in North America. The business leverages our nationwide P&C broker and agent relationships and sales were up 40% last year. In Europe, our cell phone replacement insurance product is offered by 23 mobile network operators in 13 countries. In Mexico, where we now insure almost 2 million consumers, our auto and residential products business grew 22% last year.

Distribution partnerships enable us to reach tens of millions of potential new customers, both individual consumers and businesses. We have more than 150 of these partnerships with banks, retailers, airlines and mobile network operators. In Mexico, for example, after our first year of an exclusive long-term relationship with Citibanamex, we are selling more than 30,000 new policies per month to their 12 million customers through branches, telesales and digital platforms. In Chile, we are selling nearly 50,000 policies each month with Banco de Chile, which generated about $400 million in insurance revenue in 2018 with other insurers before becoming our exclusive distribution partner. On the other side of the world, through our partnership with DBS, the largest and most respected bank in Southeast Asia, we are selling a variety of products – from travel insurance online to

Geographic Sources of Premium

2019 gross premiums written



Premium Growth by Geography

Percentage change in gross premiums written in 2019 versus 2018 in constant dollars

- United States **5.6%**
- Latin America **10.1%**
- Europe/Eurasia & Africa **7.3%**
- Bermuda/Canada **13.5%**
- Asia **9.2%**

home contents coverage to business insurance for SMEs – to more than 11 million of their customers in five countries and revenue is growing briskly.

China: on the path to increased ownership of Huatai Group

Early in 2019, we received support from the Chinese government to increase our ownership in Huatai Insurance Group, which has life, P&C and asset management subsidiaries, and more than 600 branches and 11 million customers. We were granted permission to convert Huatai from a domestic Chinese financial services holding company to a Sino-foreign joint venture – an historic first. The change of status created a path to increased ownership. Later in the year, we announced agreements to make significant additional purchases which, if approved, will take our ownership position to over 50%.

Our investment in Huatai, which we have worked on over the course of 20 years, is another great example of Chubb as a long-term builder. China is currently the world's second-largest economy and is on its way to becoming the largest. Its financial services industry, including insurance, remains underdeveloped. China represents a significant opportunity for Chubb to build an important Chinese insurance and asset management company that will meet the growing savings and protection needs of its consumers and businesses. The country's continued growth and influence will also impact the growth of Asia and enhance other opportunities for Chubb across the region. Over the coming decade or so, I can imagine Huatai becoming a major contributor to Chubb's revenue and earnings, but it's not without risk. Nothing is guaranteed.

Our Asia-focused life insurance business, which has 49,000 captive agents in six countries, now generates $2.4 billion in premium and deposits. International life revenue grew 13% last year in constant dollars and we earned over $150 million of income, up from about $25 million three years ago. These numbers exclude Huatai Life, which we do not consolidate. We expect Huatai Life, which has 35,000 agents, to become over time the centerpiece of our life operation. Life insurance is today a relatively modest business for Chubb, but it has a lot of long-term potential.

Digital begins with the customer experience

Chubb must be vital and compelling in a digital age if we want to remain relevant. This is central to both our short- and long-term strategies, and we are making good progress. Digital begins with the customer experience and cuts across our distribution channels with both our traditional and non-traditional partners. At the same time, we are redefining or modernizing what insurance does and how it does it. Through the use of data and analytics, robotics and machine learning, digital is improving our risk selection and pricing, our underwriting and ability to service and pay claims, our customer experience and our efficiency. It represents a sea change for our business.

Our digital strategy from a customer perspective is focused primarily but not exclusively on consumers and small businesses. The strategy is global in scale, with particular emphasis on the U.S., Asia and Latin America. We

"Distribution partnerships enable us to reach tens of millions of potential new customers, both individual consumers and businesses. We have more than 150 of these partnerships with banks, retailers, airlines and mobile network operators."

are creating new products, enhancing service response and experience, and forming new distribution partnerships with digitally native platforms and financial institutions. We are now generating revenue that wouldn't have been possible without our growing digital capability.

New technologies are beginning to help us engineer the risk environment in a real way so clients can manage their exposures. Deploying Internet of Things technologies helps us to predict and prevent losses for both commercial and consumer insureds. For example, we are monitoring temperature, water/humidity and vibration in environments that are vulnerable to loss – from helping hospitals keep safe their high-value medical equipment and supplies to ensuring the proper storage of a family wine collection.

Digital offers us significant potential to reduce our cost structure. Straight-through processing, robotics and machine learning are eliminating low-value activities to reduce expense and enhance efficiencies. We're digitizing and improving the effectiveness and efficiency of our traditional agent and broker distribution channels to help our business partners remain relevant in a digital age.

Climate change and sustainability: reality and responsibility

We and our industry have an opportunity and responsibility to do our part to support society in managing a risk environment that is both volatile and changing due to global climate change. Our response is guided by our core business competencies and values, and our perspective begins with the obvious: We are an insurance company and our job as underwriters is to assess and manage risk using analysis that is data-driven and apolitical. Applying this approach to the perils of climate change, we recognize a growing global risk that requires action from government, the private sector and, in fact, society at large to manage and mitigate the growing threat.

As an insurer, our first responsibility is to use our expertise in risk management to provide products and services that protect individuals, businesses and communities against the effects of climate change. We manage risk – that's our business. We employ sophisticated modeling and have considerable data that identify the physical and economic impact of climate-related risk on individuals, businesses and communities, and this is reflected in the prices we charge for insurance protection. We essentially serve as a market signal of the rising costs of climate change – as the risk increases, insurance prices increase, or availability becomes more limited.

Importantly, climate change is a long-dated risk but for insurers, such as Chubb, it's generally a short-dated liability. Our insurance contracts are typically limited to a single year, and we can quickly respond to changes we see in the risk environment by adjusting our pricing or by restricting our exposure (e.g., limiting our property risk exposure in coastal regions). As modeling and data around specific perils, i.e., flood and wildfire, get better, we have the ability to take more risk, particularly for clients that adapt to changing conditions by mitigating their risk. Lastly, as we do with all other risks, we can only assume climate-related risk to the extent of our balance sheet wherewithal.

Chubb is a leading provider of insurance for renewable energy project construction and operation, and clean tech companies that are creating new technology to reduce CO_2 emissions.

Complementing our insurance coverage, Chubb risk engineers work with our commercial and consumer clients to moderate the risks from climate change perils and make them more resilient. We bring deep technical knowledge to this work, from providing guidance on construction standards, wildfire land management and coastal protection to the development of lithium battery storage systems.

On the investment side, we apply the same risk management rigor to our broadly diversified fixed income portfolio. For example, asset concentrations are carefully managed in hurricane- and flood-exposed areas. The impact of climate risk on underlying credits will naturally be an increased factor in our investment decision-making over time given the future impact on certain long-dated asset classes, such as mortgages and municipal bonds. Our portfolio is relatively short-dated with an average duration of less than four years.

We are realistic about what a single company can achieve in limiting the effects of global warming and advancing sustainability goals. At the same time, it is hard to be optimistic about the likelihood of timely and effective government action. Most governments are focused on the short-term, both political and economic. Despite a plethora of multilateral organizations, we live in a nation-state world generally incapable of addressing a global problem due to the nature of nation-state self-interest. Yet, only government can raise the cost of carbon use by putting a price on carbon, through tax, cap and trade or other measures. Measures should recognize the cost to the planet of carbon and provide economic incentives to move to less carbon-intensive fuels as well as carbon-free alternative sources of energy. Last year, Chubb implemented a new policy restricting our underwriting of thermal coal businesses and precluding our investment in companies that generate more than 30% of their revenues from coal-related mining or energy production.

Finally, as part of good corporate citizenship, we have a responsibility to take actions to reduce Chubb's environmental footprint and, through our philanthropy and public advocacy, to support efforts that strengthen the resilience of communities and protect biodiversity against the effects of climate change. Most recently, we made a commitment in 2019 to reduce our GHG emissions on an absolute basis by another 20% in five years – a goal we already achieved by year-end – and 40% by 2035. These science-based goals are aligned with the two-degree Celsius limit outlined in the Paris Climate Agreement.

While we can't push back sea level rise, we are engaged in projects such as with The Nature Conservancy to support a resilience project in Miami to increase flood protection and serve as a model for replication in other threatened coastal cities. And while we can't stop storm surge, we supported the expansion of a reef restoration project on Mexico's Yucatan Peninsula that included transplanting 10,000 new coral colonies as a natural barrier to help protect the critical tourist economy – a great example of the sustainable economy. We have supported for many years the Conservation Fund's efforts to enhance and protect biodiversity through the preservation of more than 8 million acres of threatened land and water habitats, as well as extensive forest restoration projects across the U.S. and Canada.

As our work and philanthropy demonstrate, we are serious about understanding and responding to climate change. We are committed to undertaking responsible actions to do our part to provide insurance protection for people, businesses and society from the impact of global temperature increases, develop effective mitigation strategies and support the collective action necessary to address this existential threat.

The case for America and the democratization of capitalism

In America today, the media and many in the political establishment dwell endlessly on what's wrong with our country. For sure, as a nation, we have many challenges:

• A civil society where behavior is now more tribal, less inclusive and no longer so civil;

• A deeply polarized political system incapable of solving tough problems, particularly at the federal level, including insufficient education and skills training, issues of healthcare access and affordability for many, and aging or obsolete infrastructure;

• Senior political leadership that fails to lead with the values and principles that have defined American exceptionalism;

• Rising populism, born in part from the financial crisis, fueled by inequality of wealth and opportunity;

• Growing distrust in our basic institutions including big business and government, with an increasing number of younger people questioning the efficacy of democracy and capitalism; and

"Our open society and values make America a magnet for talented individuals all over the world. But to secure our future and maintain our leadership position, we must recognize and lead with our advantages and strengths while correcting things that hold us back. We need to run a better race."

• Insecurity and anger from the feeling that our way of life, our communities and our well-being are somehow threatened by “foreigners,” particularly those south of the border.

Our failure to address problems makes them begin to appear intractable, and because we focus predominantly on what’s wrong, we lose perspective and that causes us to lose confidence in our country and what has made us great.

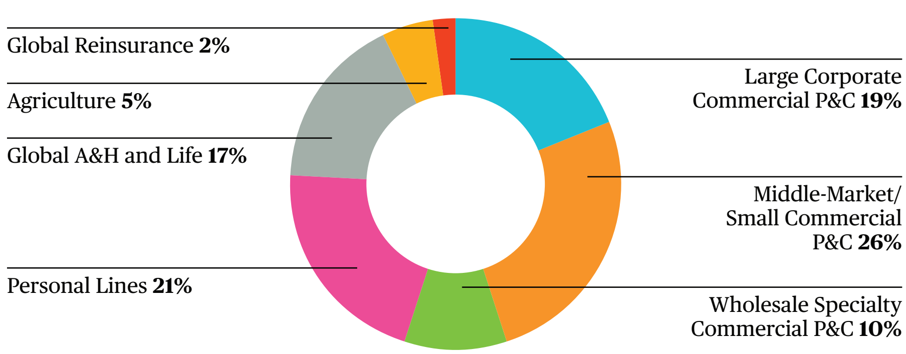
As Americans, we have many reasons to be optimistic. Just look at everything we have: basic natural resource security such as food, energy and water; physical security from two oceans and two neighbors bordering us that are our allies; a society built on values that protect the sanctity of the individual and private property; a democracy supported by an active civil society, the rule of law and independent institutions to safeguard and administer them; an economic and political system with the flexibility and tolerance to embrace creative destruction, a basis for the fostering of innovation and economic dynamism; finally, the English language is the global lingua franca of business, science and diplomacy around the world. Our open society and values make America a magnet for talented individuals all over the world. I have confidence in America. But to secure our future and maintain our leadership position, we must recognize and lead with our advantages and strengths while correcting things that hold us back. We need to run a better race.

Our global system of alliances is a force multiplier. Size matters on the world stage. Just add the number of citizens and economic output of our long-term allies to our own influence and strength and you have over a billion people and tens of trillions in GDP aligned around common value and goals. All alliances require trade-offs and are bound by national self-interest – you give to get. Our brand of America First nationalism, however, fails to account for this trade-off. We should be working together with our allies to defend and improve the rules-based, market-oriented trading system that has contributed enormously to our mutual prosperity. America has been and should remain the model for other nations to follow. After all, the liberal world order that we constructed and have supported for over 70 years was built around this. In this regard, we were the motivating force behind globalization. Through our alliances, we should share the burden of global security. With a clearer sense of our own national security interests and priorities, while recognizing the limits of our own resources, we should strengthen our security alliances, leading efforts in some cases and supporting in others. For example, our government is giving increasing priority to developments in Asia Pacific. After nearly 20 years of war in the Middle East, and supported by our own energy self-sufficiency, we can now concentrate our national focus on other priorities.

We should double down on capitalism. No other system on the planet is more efficient at allocating resources than an open market-oriented system. Governments cannot solve all of our problems and they create distortions. No other system has improved the quality of life for the largest and broadest number of people in history than capitalism. However, it is not perfect. We should do a better job spreading its benefits to all by further democratizing capitalism and creating greater equality of opportunity and access to capital. Our frontier nation was created by bold and driven explorers and entrepreneurs willing

Premium Distribution by Product

2019 net premiums written



to take risks to build something out of nothing. We need to focus on creating the conditions for more builders to flourish in our country while, at the same time, care for the millions who are marginalized or displaced by technological advancements or by globalization. Closing the opportunity gap will require massive investment in people. For this, the private and the public sectors must develop partnerships at scale for skills-based training. We must work together to reform our education system to be able to prepare and accompany individuals from early childhood to career or late career. The business community needs to do a better job of telling leaders of our community colleges and universities what skills we will need and what jobs will be available in the future. Colleges and universities will adapt their educational programs if they receive stronger and clearer market signals from the business world.

We need immigration at scale. In order to remain competitive, we need to increase the size of our population. If we want to grow the size of our economy, and grow much faster, we need many millions more of young people working and paying taxes. For this, we need a pragmatic immigration policy that satisfies America's economic needs while, at the same time, recognizes and preserves the fundamental values of our society and secures our borders. We need to attract the best and brightest by the millions from all over the world. And we welcome those who want to improve their lives and can contribute in productive ways at all levels of our society. In the process they strengthen our culture and values of personal opportunity, responsibility and hard work.

We should borrow to invest in our future. Our public debt exceeds 18 trillion dollars and represents 80% of our GDP. Moreover, nearly 70% of government spending is committed to debt service and entitlements. This level of indebtedness and the health of our public finances put us at risk. The rest of the world will not endlessly lend to us at current low rates. And, we need to reform our entitlement programs, especially Social Security and Medicare. More young migrants will lower the average population age and will translate into a bigger workforce. That will improve worker-retiree ratios and reduce the pressure of entitlements on our government finances. As a nation, we should basically borrow to invest in our future prosperity – to improve our competitiveness – and in our security. Otherwise, we are mortgaging the future of our kids. With more fiscal discipline and more revenue, the government will be able to invest in people, infrastructure, security and R&D. It will also be able to support and nurture key industries that will be crucial to sustain our economic and military preeminence in the 21st century.

In sum, America is the most productive, creative and innovative nation on the planet, and we should be more optimistic but more disciplined about our future. If we run a better race and have more confidence in ourselves, we will have more strategic patience in imagining and guiding the geopolitical future, including our relationship with a rising China.

The U.S.-China relationship

Without a doubt, the U.S.-China relationship is the most important bilateral relationship in the world. However, over the last decade, we have seen it deteriorate. Our relationship is marked by increasing tension and

"We strive to be an inclusive meritocracy, where all employees regardless of gender or background can thrive, and we develop citizens of our culture with our values, work ethic and discipline."

a growing distrust. We have a clash of national interests, values and political systems. We are in strategic drift, failing to define a strategic vision that recognizes each of our priorities and current realities. We need a framework for cooperation in key areas, and rules or understandings for competition and rivalry in others. Today, constituents in both countries see each other as a threat or even as an enemy. Many advocate for disengagement or economic and technological decoupling, and this may form an element of our strategy to defend, but it's hardly the entire answer. In the absence of strategic purpose and sustained diplomatic engagement, we will continue to move in the wrong direction and increase the risk of conflict.

The relationship is broad with many issues of mutual interest and concern. These include, but are not limited to, global warming, terrorism, nuclear proliferation and protection of the commons. We should work together in areas where our interests are aligned and create a framework for dialogue and hopefully clear rules of engagement in the areas where we compete or are at odds. Technology and cybersecurity come to mind.

China is an old civilization with highly talented people, an admirable work ethic and an ambition to be number one in the world. New technologies are seen as their opportunity to reach economic and military primacy. While it is true they have the advantage of size and scale (which is important when it comes to economic and political influence), they are not a juggernaut – and we should not view them as such.

China, too, has many weaknesses and vulnerabilities. First of all, and as opposed to America, they are not resource self-sufficient. They depend on other countries to supply the natural resources they need to survive and grow. They do not have enough food, raw materials or energy, and they are surrounded by distrustful or hostile neighbors, a number of which are nuclear-armed. Their political system is a one-party-controlled techno-authoritarian state that values social stability above all else – a system less conducive to innovation. China's centrally directed economy allocates capital inefficiently, led by Chinese state-owned enterprises (SOEs) whose return on capital is in the low single digits. China substantially lacks the rule of law and the independent institutions to administer it, and this creates uncertainty. Private entrepreneurs are slowing investment as the uncertainty about the future of China's market economy rises. And the Chinese language and a more-closed society are less conducive to attracting outside talent and ideas.

The trade agreement announced at the end of 2019, although modest, created a temporary floor under our trade relationship. The American business community does not support tariffs as a strategy. However, we advocate for fair rules-based competition and a level playing field. We need agreements that address China's predatory policies and practices intended to dominate markets and technologies. We need the same level of access to their markets and opportunities as they find abroad. China is a huge beneficiary of the global trading system, yet their markets remain closed and protected in important ways.

Make no mistake, China is and will be a formidable rival and, in the future, we will share global leadership and influence. We should recognize this fact. If we run our own race well, and have confidence in who we are and our ability, we will sustain our leadership advantages.

Attracting, developing and retaining top talent

Foundational to Chubb's long-term success is our disciplined approach to attracting, developing and retaining the next generation of insurance professionals and leaders. We strive to be an inclusive meritocracy, where all employees regardless of gender or background can thrive, and we develop citizens of our culture with our values, work ethic and discipline. We recognize and reward responsibility, ambition and results with opportunity for individuals to achieve their full potential and advance through our organization. We offer colleagues opportunities to continuously learn, gain valuable new experiences and prove themselves – to grow as individuals. We strive to get to know our people, and we are constantly on the lookout for top performers and those who have the aspiration and commitment to succeed.

We begin by attracting and nurturing early career talent. Hundreds of college grads join us every year on a two-year development journey primarily in the basic core competencies of underwriting and claims, IT and other functional areas. We have been doing this for years now and our success rate has been quite good, with high levels of engagement and rates of promotion. Our talent development efforts are for all employee levels, including mid-career and senior managers. Our Craftsmanship curriculum includes on-the-job and formal training, and opportunities to continuously broaden skills, achieve technical proficiency and hone leadership effectiveness. We give talented employees opportunity to experience a new country and culture, and to bring their skills and knowledge from one market to another, which is so important for a global company. For more seasoned employees, we provide education on new technologies and new areas of insurance. All employees have access to a mix of traditional and virtual classes and team-based projects, which we encourage in their individual development plans.

The development of our leadership and talent pipelines is a focus of senior management, starting with me. We spend several days each year on succession plans including development priorities, talent gaps and ways to further strengthen our bench. In 2019, we promoted from within to fill 100% of all senior executive roles that became open due to retirement or resignations. This resulted in seamless transitions and continuity of service that benefited both Chubb and our customers and business partners. Just as we measure results in other areas of our business, we set clear goals for ourselves concerning our people and we track our progress. Our retention of employees at all levels is at or above external benchmarks and we are achieving improved representation of employees as measured by gender, nationality and experience, including at middle and senior levels of management. We can continue to improve our ability to attract, develop, recognize and retain our employees as we strive to create a company where all who choose to achieve their full potential can do so. As the company grows bigger and we compete for talent, it's mission critical.

A decade of growth and accomplishment

I have many to thank for a gratifying 2019 and a decade of tremendous growth and accomplishment for our company, beginning with my fellow employees and senior management team. I'm surrounded by dedicated, engaged and supportive professionals – amazing people who care so much about our company and their customers. We are a company of builders, and builders want to win. Without their personal and collective sacrifice, our achievements, and the mission we are on to create greatness, simply would not have been possible.

I also want to thank Chubb's active and supportive board of directors, whose commitment and counsel have been essential to our company's success. This year marks the retirement of our lead director, Robert Hernandez. Bob was here at the beginning – he joined the board of ACE when the company was founded in 1985, and for over three and a half decades he actively supported and helped govern the company. As lead director he helped to lead the board in independent governance and deliberation. Bob has been a partner to me for over 15 years. Always supportive yet independent, he exemplifies model governance and represented the interests of shareholders while counseling management – a clear example why rigid term limits are an unnecessary crutch. Bob is a model of wisdom, duty of care and loyalty, and I will miss him. Bob's successor as lead director will be Michael Connors, who has been on our board since 2011. I and my fellow directors look forward to working with Mike and benefiting from his years of experience and counsel in this critical role. Lastly, I want to thank Kimberly Ross, who served as a director from 2014 to 2019, for her contributions and service.

Chubb is a compelling long-term shareholder value creation story. We have a unique, highly competitive global franchise featuring a well-diversified portfolio of market-leading businesses with substantial capabilities, including presence and scale, backed by a world-class service quality reputation and a sterling brand. We have clarity of strategy, purpose and opportunity. Our product and distribution capabilities are well integrated with a disciplined, well-tested execution-oriented culture. Add to that our balance sheet strength and long-term revenue growth and earning power. As we close out one decade and enter an exciting new one with great anticipation, we are confident that our best days are in front of us, and that we will outperform and deliver exceptional value to you, our shareholders, long into the future.

On behalf of the entire organization, thank you for your investment and trust in us.

Sincerely,

Evan G. Greenberg
Chairman and Chief Executive Officer

Consumer and commercial customers have long recognized Chubb for its finely crafted coverage and superior service. We also aspire to create a truly differentiated customer experience. This begins with empathy, is fueled by inspiration and innovation, and brought to life through commitment and resources. We're focused on meeting the insurance needs of customers in ways that provide greater value, ease, speed, convenience and peace of mind. Elevating the customer experience means being there during the moments that matter with relevant capabilities and products that match each customer's lifestyle and life stage.

Using digital technology to enhance the customer experience

In Mexico, where Chubb is the third-largest auto insurer, the company uses technology to get customers back on the road faster after an accident. To expedite the claims process and accelerate car repairs, Chubb insureds use an app to take photos of their damaged auto and digitally select a body shop while a remote adjuster evaluates the claim instantly. When a field adjuster is needed, in-app technology uses a geospatial algorithm to locate the closest adjusters and automatically dispatches one of them for assistance. In most cases – more than 75% of the time in 2019 – a Chubb adjuster arrives at the scene of an accident within 15 minutes of notification, drastically reducing the customer's on-site wait time after an accident.

In the U.S., Chubb Personal Risk Services customers can use Chubb at the Wheel, a new mobile app for family members such as teen drivers and their parents who choose to improve driving safety through monitoring and education. When a teen logs into the app, it records their driving habits, including acceleration and braking, and distracting behaviors, such as texting or calling. The app compiles data to provide a driving score at the end of each ride. New and inexperienced drivers can use app feedback to hone their driving skills. Parents and teens both feel safer knowing that roadside assistance and vehicle location are easily accessible, providing a sense of security in the event of an accident.

Moving from "repair and replace" to "predict and prevent"

For policyholders, the experience that matters most is what happens when they have a claim. But what is the value of an insurer – armed with risk engineering expertise, technology, data and analytics – that can prevent a claim from happening in the first place?

Chubb is helping to answer that question by installing sensors that alert consumer and commercial customers to risks from water, failing equipment and other exposures that can damage property and displace people from their home or workplace for weeks or even months.

For homeowners, sensors installed in wine cellars track temperature and humidity data to diagnose issues before they can cause spoilage of a valuable collection. Chubb-installed sensors can help ensure a stable cellar environment, allowing customers to know their collection is safe.

For commercial customers, Chubb is installing sensors that monitor water, temperature and humidity changes in hospitals and other large, complex properties. Chubb has the expertise to know where large interior water loss damage is likely to occur, and places sensors in the right locations. Avoiding a loss provides real value beyond just the claim payment. It's about avoiding the disruption to the customer that comes with getting damaged assets repaired or replaced.

When the experience is the product

Insurance companies often talk about the coverages they offer as "products." As digital capabilities advance, and opportunities to create tailored and frictionless experiences for customers increase, the experience itself – fast, customized, simple and mobile – can be the product. That vision stands behind a growing number of innovations at Chubb featuring a digital service and experience.

Through its exclusive distribution partnership with Grab, the leading ride-hailing and mobile payments company in Southeast Asia, Chubb offers Singapore-based customers an affordable daily travel product, called Travel Cover. Using the Grab app, customers get an instant quote to purchase travel insurance right up to the time of departure. Available for travel to any destination globally, the per day cost begins at less than $2. Customers can also save their travel profiles on the Grab app, making future purchases easy and convenient.

Beginning in 2019, travel insurance customers in Singapore benefited from a completely automated experience for certain frequent travel-related claims, including overseas medical expense reimbursement, and baggage and travel inconvenience claims. Using their smart phone, computer or tablet, customers complete the claims process in minutes and without the need to download an app or create an account.

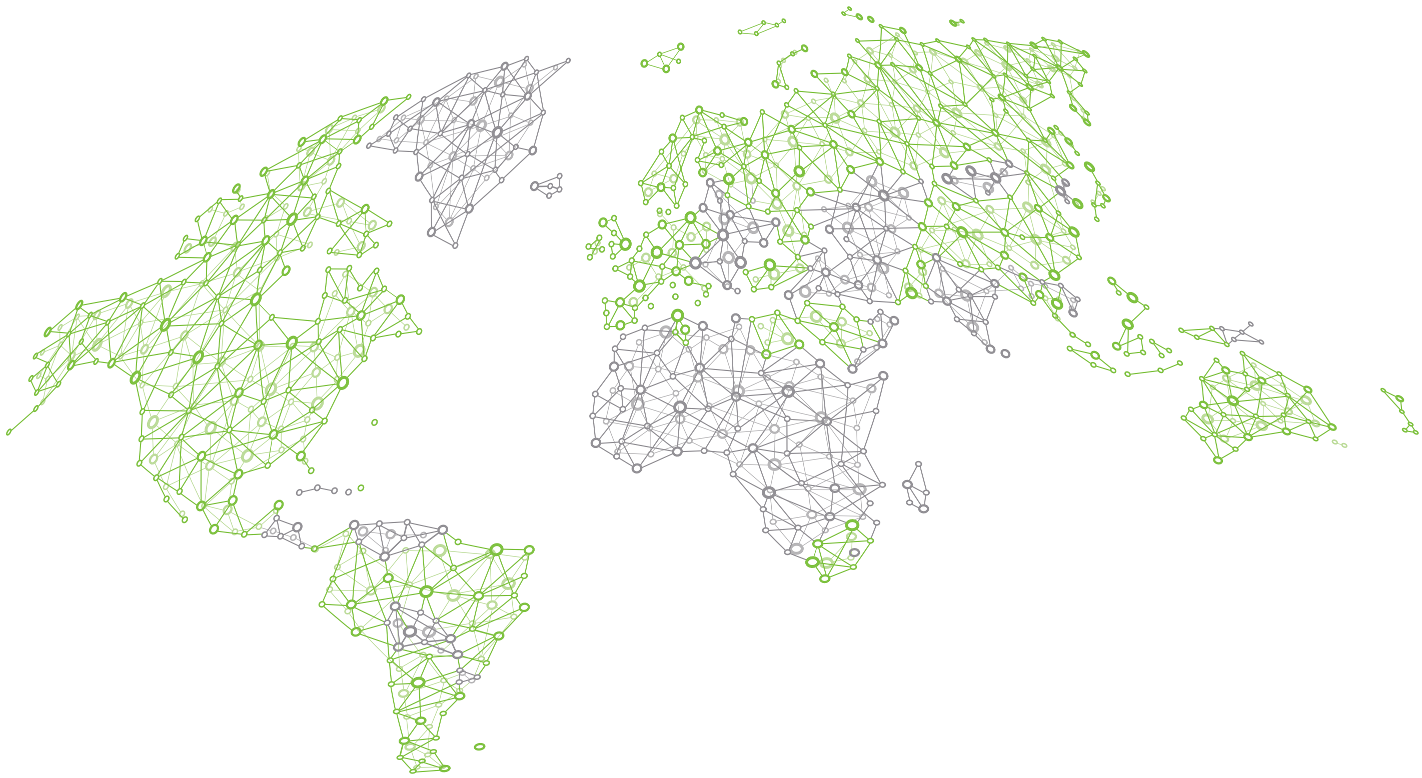
Making it easier to do business with Chubb

A decade ago, Chubb introduced Worldview®, an award-winning web-based application that provides real-time access to Chubb's systems and expertise in one application. Worldview® transformed program management for the complex insurance needs of multinational clients and their brokers, and it remains the most powerful, effective and transparent tool of its kind in the industry. Today, more than 10,000 Chubb clients and brokers utilize the system.

The application has been expanded to include additional product lines and capabilities, including a seamless user experience bolstered by an interactive dashboard. With Worldview®, clients and brokers can also request and upload translations of policies from a local language to English. Adoption and use of Worldview continues to grow, with the number of active users increasing 14% in 2019.

A growing number of small business owners in the U.S. and globally are using the Chubb Commercial Client Center, an intuitive self-service platform that allows insureds to view their billing history and recent statements, pay bills, submit claims, access policy documents and request an endorsement or a certificate of insurance (COI). In addition to bringing greater convenience to customers, Client Center reduces administrative overhead for independent agents. Chubb's investments in the Client Center customer experience are paying off: since its launch, an average of 1,000 new users per month have been added.

A Global Leader in Property and Casualty Insurance



Argentina	Chile	France	Japan	Pakistan	Saudi Arabia	Tunisia
Australia	China	Germany	Korea	Panama	Singapore	Turkey
Austria	Colombia	Gibraltar	Macau SAR	Peru	South Africa	United Arab Emirates
Belgium	Czech Republic	Hong Kong SAR	Malaysia	Philippines	Spain	United Kingdom
Bermuda	Denmark	Hungary	Mexico	Poland	Sweden	United States
Brazil	Ecuador	Indonesia	Myanmar	Portugal	Switzerland	Vietnam
Canada	Egypt	Ireland	Netherlands	Puerto Rico	Taiwan	
	Finland	Italy	New Zealand	Russia	Thailand	
			Norway			

A local presence in 54 countries and territories around the world

Chubb has operations in the countries and territories listed here and can help clients manage their risks anywhere in the world.

Chubb Senior Operating Leaders

John Lupica

Vice Chairman,
Chubb Group;
President, North America
Major Accounts and
Specialty Insurance

John Keogh

Executive Vice Chairman,
Chubb Group;
Chief Operating Officer

Paul J. Krump

Executive Vice President,
Chubb Group;
President, North America
Commercial and
Personal Insurance

Juan Luis Ortega

Executive Vice President,
Chubb Group;
President, Overseas
General Insurance

Chubb's senior operating leadership includes the company's Chief Operating Officer and the leaders of North America and Overseas General insurance operations.

Key Financial Results

Dollars in millions

Total North America P&C Insurance

2019	
Gross premiums written	$25,480
Net premiums written	$19,972
Combined ratio	87.8%
P&C current accident year combined ratio excluding catastrophe losses	87.1%

North America Commercial P&C Insurance

2019	
Gross premiums written	$17,604
Net premiums written	$13,375
Combined ratio	85.6%
P&C current accident year combined ratio excluding catastrophe losses	87.4%
Segment income	$3,942

North America Personal P&C Insurance

2019	
Gross premiums written	$5,461
Net premiums written	$4,787
Combined ratio	91.1%
P&C current accident year combined ratio excluding catastrophe losses	81.4%
Segment income	$660

North America Agricultural Insurance

2019	
Gross premiums written	$2,415
Net premiums written	$1,810
Combined ratio	95.1%
P&C current accident year combined ratio excluding catastrophe losses	99.1%
Segment income	$90

Chubb's insurance businesses in North America serve clients ranging from the largest multinationals, middle-market companies and small businesses to successful individuals and families, and the agriculture community.

For commercial property and casualty insurers in North America, the major theme of 2019 was the improving operating environment. For Chubb, a market with firming pricing and conditions created an opportunity to bring the company's signature capabilities to more clients in more lines of business at risk-adjusted rates in line with rising loss costs.

"The quality of Chubb stood out in 2019," said John Keogh, Executive Vice Chairman, Chubb Group and Chief Operating Officer. "In a market that was sometimes chaotic, Chubb demonstrated that we are professional, stable, consistent and a reliable partner. As a result, we further burnished the Chubb brand and reinforced our industry leadership."

Three North American businesses – **Major Accounts, Westchester** and **Chubb Bermuda** – were best positioned to benefit as headwinds were replaced by tailwinds. The operating environment for Chubb's **Commercial Insurance** retail P&C business serving middle-market companies began to turn bullish mid-year and accelerated in the second half. Chubb core strengths, along with its investments in people and digital technology, have also positioned the company's other North American businesses for secular growth opportunities, including the Commercial Insurance segment serving small businesses, **Chubb Personal Risk Services** and the company's agricultural insurance business.

Total net premiums written for the company's North America P&C insurance businesses were $20.0 billion, up 6.6% from 2018. Chubb reported a world-class combined ratio of 87.8% for its North American P&C insurance operations. Excluding catastrophe losses, the current accident year combined ratio was 87.1%.

"Our combination of products, claims and risk engineering services, expertise and underwriting excellence is a powerful differentiator for Chubb, particularly in a firming P&C market cycle," said Paul Krump, Executive Vice President, Chubb Group and President, North America Commercial and Personal Insurance. "When others are reducing capacity and appetite, Chubb's consistency and quality make us a go-to source for agents and brokers to serve their customers."

John Lupica, Vice Chairman of Chubb Group and President, North America Major Accounts & Specialty Insurance, pointed to another Chubb strength: the North American field operation with 49 branches across the U.S. and Canada. "The field plays a critical role in managing the flow of business, cross-sell opportunities and the

Chubb's North America Insurance Business Units

Major Accounts	Commercial P&C insurance products for the large corporate market sold by retail brokers
Commercial Insurance	Commercial P&C insurance products for middle market and small businesses sold by independent agents and retail brokers
Personal Risk Services	Personal lines coverage, including home, auto, valuables, umbrella and recreational marine insurance, for successful individuals and families sold by independent agents and brokers
Westchester	Commercial P&C excess and surplus lines sold through wholesale brokers
Chubb Bermuda	Liability, property, political risk coverage and captive programs sold by large international brokers
Agriculture	Crop insurance from Rain and Hail and farm and other P&C coverages sold by agents and brokers

introduction of new products," he said. "The market environment in 2019 really put a spotlight on the strength and value of our field operation. With our local presence, agents know we're there for them and, at the same time, we can educate clients on the need for adequate pricing."

North America Commercial P&C Insurance

Chubb is one of the largest commercial P&C insurers in the U.S., offering a full range of traditional and specialty products for businesses of all sizes. Net premiums written for North America Commercial P&C Insurance increased 7.1% from 2018. The combined ratio for the segment was 85.6%. Underwriting income was $1.9 billion, and segment income was $3.9 billion.

Major Accounts, Chubb's P&C business unit that serves large companies, is recognized for the breadth and depth of its product and service offerings, technical underwriting experience, superior client service, and a global platform built to service complex, bespoke insurance programs in many countries around the world. It's a high-touch business where Chubb, with its strong client- and broker-centric culture, has developed long-term, enduring relationships. Chubb serves more than 90% of the Fortune 1000.

"In a market that was sometimes chaotic, Chubb demonstrated that we are professional, stable, consistent and a reliable partner. As a result, we further burnished the Chubb brand and reinforced our industry leadership."

– John Keogh

"Over the past two decades we've built a franchise that is second to none and very difficult to replicate," said Mr. Lupica. "With our proven reputation as a thoughtful underwriter and a partner known for service excellence, we were able to benefit from the 'flight to quality' in 2019. We knew it was important to lead the market by communicating with clients and brokers, expressing the need for rate adequacy in lines where premiums have not kept up with loss costs. A healthier market, where insurers are able to be paid more appropriately for the risk they assume, is good for Chubb because clients value our consistency, services and the relationships we have built over time."

In 2019, the retention rate for Major Accounts was more than 95%, a record. Cross-selling services to existing customers accounted for more than 81% of new business.

Among Major Accounts' distinguishing capabilities are its industry practices, including transportation, private equity, real estate and construction. Multiline clients also have access to a Global Client Executive, who knows the insured and serves as a single point of contact to navigate the Chubb network across the globe. For claims handling, customers also have access to a Claims Client Executive. Worldview®, Chubb's award-winning proprietary portal, enables client risk managers and brokers to manage and track all aspects of their insurance program in real time. More than 10,000 clients and brokers utilize the system.

For the year, Major Accounts and the excess and surplus (E&S) wholesale businesses generated 7.9% growth in net written premiums.

In the E&S lines market, **Westchester** specializes in hard-to-place casualty, property catastrophe and specialty lines for large corporate, middle-market and small businesses. Wholesale brokers distribute these products, including specialty classes such as financial lines, product recall and cyber. Traditional brokerage accounts for about 60% of Westchester's premiums, with the balance from its binding and programs divisions.

In recent years, Chubb has pointed to Westchester as a proof point for the underwriting discipline that defines the entire company: We will trade market share for profitability. From 2015 to 2018, Westchester's net premiums written shrunk an average of 2.6% per year. Yet over the past 13 years, the business produced an average combined ratio of 92.8%. In the current environment, Westchester demonstrates Chubb's ability to react quickly to market changes, and outperform the broader market, which began to turn in late 2018 and accelerated throughout 2019. For the year, the business grew 9.1%.

Westchester's ability to seize opportunities in a changing market is due to investments made to broaden the product set, retain experienced talent, develop the next generation of underwriters, reward experienced underwriters for remaining disciplined, and deploy technology that enables the business to scale efficiently. Investments in digital capabilities, for example, allowed Westchester to make a record number of API connections with E&S agents in the binding division.

North American Business Unit Leaders

(From left)

Scott Arnold
Vice President,
Chubb Group;
Division President,
Chubb Agriculture;
President,
Rain and Hail

Judy Gonsalves
Vice President,
Chubb Group;
Division President,
Chubb Bermuda

Christopher A. Maleno
Senior Vice President,
Chubb Group;
Division President,
North America
Field Operations

Bruce L. Kessler
Senior Vice President,
Chubb Group;
Division President,
Westchester

Chubb Bermuda provides excess coverage in three product areas: casualty, property and financial lines. It also houses the company's political risk group. Operating with a high severity/low frequency business model and offering broad coverage and sizable capacity to clients and brokers around the world, the business produced strong results across all products in 2019.

"Our property business produced record results for the year. Because brokers have been trading with our property team for years – or even decades – they knew where to find access to quality capacity at the right price," said Mr. Lupica.

Commercial Insurance is Chubb's division that provides P&C coverages to middle-market companies with revenues up to $1 billion and small businesses. In the middle-market segment, Chubb is distinguished by its more than 25 industry practices, each handled by teams of experienced underwriting, claims and risk engineering professionals who understand the particular exposures of that industry. The business's core package product is complemented by the industry's largest offering of standard and specialty coverages, including auto, workers compensation, marine, cyber, environmental, multinational, directors and officers (D&O) and errors and omissions (E&O) coverages.

Chubb's commercial P&C offering for small businesses includes a core package product as well as an expanding range of specialty products. This segment is growing rapidly, drawing strength from the company's middle-market expertise as well as capabilities from Marketplace, Chubb's fully automated digital platform that makes it easy for agents to quote, issue and service all of their small business accounts. In 2019, net premiums written in Chubb's middle market and small business division grew 6.1%.

Together, the addressable market for Commercial Insurance includes businesses from sole proprietorships, "A healthier market, where insurers are able to be paid more appropriately for the risk they assume, is good for Chubb because clients value our consistency, services and the relationships we have built over time."

– John Lupica

family businesses and single-location private companies to publicly traded entities with a multinational footprint. Chubb's commercial P&C business has the expertise and appetite to address about 85% of this important growth sector of the economy.

"In the middle market we were able to capitalize on the market shift and seek more opportunities," said Mr. Krump. "This was a direct result of our continued focus on underwriting discipline, delivering exceptional service to our customers and producers, and writing new business in the industries where we have distinct expertise and appetite."

Chubb's North American middle-market and small commercial businesses are at the nexus of several important company initiatives. They serve as the model for Chubb to export and expand its ability to serve these market segments in other regions of the world. The growing technical capabilities of the Marketplace platform, which originally focused on small businesses, are increasingly relevant to companies at the lower end of the middle market. The branch network is also a key channel to distribute Chubb's specialty insurance products to middle-market customers.

Cross-selling is an important part of the Chubb middle-market story. In 2019, nearly 50% of new business written was sold to existing clients. "For mid-market companies, we are an account solution. Our account retention is high – 92% in 2019 – and our average time on a risk is 15 years," said Mr. Krump. "We grow with clients, and work with them to manage through market cycles."

In 2019, Chubb's middle-market business continued to deepen its product offering, developing and launching 15 enhancements to its package coverage, including expanded flood and earthquake coverage.

Chubb has invested in the success of its agents, including developing online resource centers and providing research and marketing and prospecting resources to help them fuel their own business growth. In 2019, Chubb introduced The Cyber COPE Insurance Certification℠ program, an eight-month program for Chubb brokers and agents to learn best practices in cybersecurity risk management, governance and operations.

Chubb also sponsors the National Center for the Middle Market (NCMM) at The Ohio State University. Along with NCMM, Chubb is publishing the Middle Market Indicator, a quarterly survey of 1,000 C-suite middle market company executives across all industries.

For Chubb's small business segment, which had its beginnings just four years ago, 2019 was a year of strong growth and progress. Net written premiums were up 35%, with new business growth approaching 35%. Transactions on Marketplace were up 55% from 2018. The business unit ended 2019 with an annual run rate of $400 million of gross written premium.

North American Business Unit Leaders

(From left)

Matthew Merna
Senior Vice President, Chubb Group; Division President, North America Major Accounts

Frances D. O'Brien
Senior Vice President, Chubb Group; Division President, North America Personal Risk Services

Benjamin Rockwell
Vice President, Chubb Group; Division President, North America Middle Market

James Williamson
Vice President, Chubb Group; Division President, North America Small Business

Adoption of Marketplace continued to grow. By year-end 2019, the platform was deployed to more than 40,000 users at more than 4,500 agencies. Each day, an average of 1,000 agents log in to the platform to transact business. Nearly 85% of submissions for the core package product are processed on a "straight-through" basis, where the agent receives a fast answer from the system without having to interact with an underwriter.

In this high-volume, low-touch segment, the ability to offer a digital experience for agents is paramount. Marketplace was built to scale, and Chubb regularly adds new products, industry segments and services to better serve small businesses as they grow and move into the lower middle market. In 2020, Marketplace is on track to begin offering personal accident and supplemental health products from Chubb's North American A&H business.

Chubb is making other investments to make it easier for customers and agents to do business with the company while driving superior risk selection across the portfolio. By harnessing data and analytics, Chubb is on a path to reduce average quote times for less complex risks to less than three minutes, predict risk classification for the majority of submissions and, ultimately, reduce the number of underwriting questions that must be asked to just two.

Digital investments are also strengthening the company's ability to serve affinity group partners. For example, in 2019 Chubb announced a partnership with the National Association of Women Business Owners (NAWBO), an organization representing nearly 12 million women-owned businesses. NAWBO members now have access to an industry-leading resource for small business insurance needs and education along with access to insurance products and services generally reserved for the larger corporations, including Chubb's cyber enterprise risk management policy.

"We're positioned in a way to bring more product to more types of insurance through our agents than anybody else. It's happening now," said Mr. Krump.

"Our combination of products, claims and risk engineering services, expertise and underwriting excellence is a powerful differentiator for Chubb, particularly in a firming P&C market cycle."

– Paul Krump

North America Agricultural Insurance

Chubb's Rain and Hail subsidiary is the leading crop insurance managing general agency in North America. The business serves approximately 125,000 farmers, insuring more than 100 different crops on 80 million acres. With distribution through 5,600 independent agents, Rain and Hail has the largest agency footprint in this sector. In addition, Chubb's North America agriculture segment includes farm, ranch and P&C commercial agriculture coverages.

Crop insurance is a public-private partnership that operates with a proven model. While the results of the business are not typically correlated with the P&C insurance market cycle, crop insurance is a business with CAT-like risks. In 2019, poor growing conditions in agricultural regions in the U.S. led to crop yield shortfalls and elevated prevented planting claims. For the year, the segment produced a combined ratio of 95.1%. Segment income was $90 million on net written premiums of $1.8 billion.

In a challenging year for farmers, Chubb distinguished itself by delivering superior service and getting claims payments into the hands of farmers quickly.

"Chubb is committed to the crop insurance business, and it's in times of stress that Rain and Hail's service and claims-handling capabilities make a real difference," said Mr. Lupica. "We saw it in 2012, a year of record drought. We saw it again in 2019, when the peril was excessive rain. We responded when our customers needed us, paying all prevented planting claims in record time. Rain and Hail shined in 2019, making it a year when we extended the value of the brand."

North America Personal P&C Insurance

Chubb is the leading provider of personal lines insurance for successful individuals and families in the U.S. and Canada. It's been 40 years since Chubb pioneered insurance solutions crafted for this discerning market segment. Over the years, the company has built and maintained its leadership by continuing to raise the bar for the coverage and services it offers customers, including a broad product offering, superior claims and risk consulting services, and access to Chubb's extensive branch network in the U.S. and Canada. Clients of Chubb Personal Risk Services also benefit from the company's global presence, which offers protection for their assets around the world.

Net premiums written for the North America Personal P&C Insurance segment were $4.8 billion. The 2019 combined ratio was 91.1%. The current accident year combined ratio excluding catastrophe losses was 81.4%. Segment income was $660 million.

As the risk environment evolves, Chubb continues to find innovative ways to help protect clients from the everyday risks of owning a home and automobile as well as the unique risks that come with achieving considerable success in their lives and professions.

"Our clients are becoming increasingly aware of the risks they may be facing from severe weather events, distracted drivers texting and using social media, social movements like #MeToo, and the need to protect their data and their privacy," said Mr. Krump. "As a result, customers want to engage with us at a much higher level in order to understand what they can do to mitigate their potential for a loss."

Chubb's investments in digital capabilities are making it easier for customers, agents and brokers to interact with us on their preferred terms, from the web and mobile app to phone and in-person. Two years ago, Chubb Personal Risk Services significantly expanded the capabilities of its web portal. By the end of 2019, more than half of all customers were actively using it. Adoption of the mobile app, with features that include biometric login, voice commands, text and email alerts, has been accelerating: An average of 3,000 clients per month downloaded the app in 2019. Customers are using the web portal and app to quickly access their auto identification information, file a first notice of loss digitally or to find a trusted service provider, such as a fine-art transit service or home alarm company.

Chubb Personal Risk Services has continued to expand and deepen the services available to clients. In 2019, the company introduced a first-of-its-kind solution to protect personally identifiable information when an auto is totaled. Chubb's service, available at no additional cost to auto clients who experience an insured total loss, will wipe all sensitive information stored on the vehicle's electronics system, such as mobile contacts, text messages, GPS data and garage and gate opening codes.

Chubb Property Manager℠ provides policyholders with assistance for second homes that suffer damage from hurricane-force winds. Once an area is safely accessible, Chubb will dispatch a representative to inspect the home and provide a detailed report on its condition.

For policyholders in states prone to wildfires, Chubb offers Wildfire Defense Services to monitor and protect homes threatened by this peril. Wildfire Defense Services will take actions such as clearing of hazardous objects and material around the home to create a more defensible space, installing sprinklers, addressing hot spots and, as a last line of defense in home protection, applying fire retardant gel to the home. Tens of thousands of policyholders in 18 states are enrolled in this complimentary service.

Chubb also engages with clients to raise awareness about risks such as flooding and internal water leaks. Water damage from burst pipes, frayed hoses and other plumbing failures remains the number one loss a homeowner is likely to face. Through awareness and education campaigns directed at both customers and agents, Chubb encourages policyholders to install water leak detection devices or to turn off their main water valve when they leave their home for extended periods of time.

In 2019, Chubb Personal Risk Services launched a pilot program for clients with wine collections to install sensors to monitor temperature and humidity. When a change that could lead to damage is detected, the homeowner is alerted via an app to take preventative action before damage or a claim occurs. Chubb's risk consultants also visit customers' homes to identify potential exposures and advise clients on actions that could prevent a loss. Thermographic scans, for example, can detect moisture and hot spots behind walls that could indicate threats from water damage or electrical fires.

Benefiting from decades of experience, a broad dataset and increasingly sophisticated analytics capabilities, Chubb identifies clients that have a higher propensity for a loss, and is working with them and their agents proactively to mitigate or prevent a loss from happening in the first place.

"We're very optimistic about the opportunities for Personal Risk Services," said Mr. Krump. "With clients increasingly aware of the risks they face, they are looking for a company that can provide products and services to help them manage those risks. With our deep history and capabilities across the Chubb organization, we have so much to offer them."

"Chubb is well positioned to serve our customers and distribution partners across all of our North American businesses because of the investments we've made in technology, product and distribution," said Mr. Keogh. "But our most important investments are in our people – training, developing and growing the men and women who are the future of this company."

Key Financial Results

Dollars in millions

Overseas General Insurance

2019	
Gross premiums written	$11,408
Net premiums written	$9,262
Combined ratio	91.6%
P&C current accident year combined ratio excluding catastrophe losses	90.9%
Segment income	$1,273

"Chubb is able to transport best practices from one strategic distribution partnership to another, enabling us to create unique customer experiences that match our partners' digital assets."

– Juan Luis Ortega

Chubb's international general insurance operation is comprised of two main businesses: one with retail operations in five regions of the world and the other an excess and surplus (E&S) lines operation in the London wholesale market and a presence at Lloyd's.

As in North America, the major theme in 2019 for Chubb's international general insurance operations was the operating environment. When the year began, firming conditions were already underway in a few select locations including the London wholesale market and the commercial P&C market in Australia. The trend gained momentum during the year, and extended to the U.K. retail market and Continental Europe.

"The market momentum in 2019 was notable, but it is only part of the story," said Juan Luis Ortega, Executive Vice President, Chubb Group and President, Overseas General Insurance. "Our progress and performance also reflect the investments we have made in recent years to advance our market segmentation strategies for commercial P&C, digital initiatives to enhance the customer experience, and distribution partnerships that give us access to millions of customers for both our consumer and commercial product offerings."

"Chubb's capabilities – our diversity in geography, products and distribution – have taken years to build," said Mr. Keogh. "They are a sustainable competitive advantage that is getting stronger by the day."

Overseas General Insurance generated net premiums written of $9.3 billion in 2019, up 8.4% in constant dollars. The combined ratio for the year was 91.6%. The current accident year combined ratio excluding catastrophe losses was 90.9%, and segment income was $1.3 billion.

Commercial P&C insurance represents about 60% of Chubb's international business. In 2019, Chubb's retail commercial P&C segments – Major Accounts and middle market and small businesses – benefited from a more favorable operating environment as well as initiatives to further build out the company's capabilities. Highlights for Major Accounts included strong growth across Asia Pacific, the U.K. and Ireland, as well as Continental Europe.

In the middle market, Chubb's focus on key markets and on expanding industry practices helped to drive results. Double-digit growth in the small commercial segment was highlighted by strong results in Australia. By the end of 2019, small commercial represented 21% of international commercial P&C premiums.

Alongside P&C insurance, Chubb offers accident and health and personal lines coverage globally. These two businesses meet the protection needs of consumers against accidents, hospitalization, critical illness and protect things that consumers own, such as their home, car and even their phone.

Chubb's ever-expanding digital capabilities, along with product breadth and claims service, have positioned the company as the distribution partner of choice for banks, retailers, airlines and mobile network operators that want to be able to offer best-in-class protection to their customers. Four major partnerships established in the past two years alone – with Citibanamex, Banco de Chile, DBS and Grab – provide access to over 60 million customers. Worldwide, Chubb has more than 150 distribution partnerships.

Chubb's Overseas General Insurance Business Units

International		Commercial P&C, A&H and traditional and specialty personal lines sold by retail brokers, agents and other channels in five regions:
	Europe	Operations in the U.K. and 18 other countries comprised of P&C commercial lines and consumer lines, including A&H and specialty personal lines
	Asia Pacific	Operations in 14 countries and territories serving commercial customers and consumers with P&C, A&H and personal lines
	Latin America	Operations in nine countries serving commercial customers with P&C products and consumers through A&H and personal lines
	Far East	Operations in Japan serving commercial customers with P&C products and consumers through A&H and personal lines
	Eurasia & Africa	Operations in eight countries serving commercial customers with P&C products and consumers through A&H and personal lines
Chubb Global Markets		Commercial P&C excess and surplus lines and A&H sold by wholesale brokers in the London market and through Lloyd's

"With our consistency in local delivery, Chubb is able to transport best practices from one strategic distribution partnership to another, enabling us to create unique customer experiences that match our partners' digital assets," said Mr. Ortega. "In 2019, we gained real traction on digital distribution of consumer insurance across Asia and Latin America."

In Chubb's core direct marketing business, Korea was a standout, achieving a new milestone of 2 million policyholders. During the year, Chubb closed 20 new direct marketing sponsorships. In Chubb's travel insurance business, a new partnership with Aeromexico announced in early 2020 was one of 25 new relationships secured in the past year. Other highlights in Chubb's international A&H insurance business include Europe and Japan, which both generated the highest growth in several years.

Personal lines generated strong growth in 2019, particularly in the emerging markets of Asia and Latin America. Highlights included the company's motor insurance business in Mexico, which is recognized for its top-tier sales and service capabilities. Another highlight is specialty personal lines, where Chubb has a market-leading position in the distribution of cell phone insurance to customers of mobile network operators across Europe. This business, which had a strong year in 2019, is a showcase for the company's claims handling and service – customers want their phones fixed or replaced quickly – as well as evolving digital capabilities. Today, most cell phone replacement claims are handled with straight-through processing without any human intervention.

Chubb's international general insurance operations benefit from the movement of people within the organization. One of the principal ways the company develops talent is by promoting intra- and inter-regional mobility that exposes employees to different markets and cultures. In the past three years, nearly 300 colleagues have undertaken international assignments. Every year, more than 1,200 colleagues are promoted into a new job or granted expanded responsibilities. These career progression opportunities recognize the performance of colleagues and create an environment for continuous learning.

Chubb's **Asia Pacific** region generated gross premiums written of $2.9 billion, up 9% in constant dollars from prior year, which represents 7% of the company total.

In its partnership with Grab, the leading ride-hailing and mobile payments company in Southeast Asia, Chubb introduced an affordable daily travel product, called Travel Cover, which offers a simple and convenient way for Singapore-based customers to purchase travel insurance on the Grab app right up to the time of departure. Six other new products were launched in 2019 on Grab's passenger and driver apps in Singapore and Malaysia.

Premium growth from Chubb's partnership with DBS, the largest financial services group in Southeast Asia, was driven by A&H products for retail customers in Singapore and by P&C coverages for businesses in Hong Kong. Chubb was also a partner in the 2019 launch of DBS Travel Marketplace, the first one-stop integrated travel marketplace in Singapore. Through this platform, consumers can find airfares and hotel rates for more than 25,000 global destinations, as well as free travel insurance coverage underwritten by Chubb.

Digital capabilities, including API technology, are enabling these and other partnerships, which offer consumers and businesses innovative products and an enhanced customer experience. Chubb's partnership with Grab, for example, has produced the first end-to-end API-integrated insurance product that covers policy issuance, administration and claims investigation in a single app.

The growth of the A&H business in Korea reflects several Chubb strengths in direct marketing, including a sponsor base comprised of every major credit card issuer in the country; a diverse range of products; multiple distribution channels, including outbound telemarketing and home shopping; and advanced data and analytical capabilities.

In retail commercial P&C, Chubb continued to develop its Major Accounts practice serving large corporations in Asia, Australia and New Zealand, including establishing Client Advisory Boards in each sub-region of Asia Pacific. Another major focus in Australia was navigating customers through market disruptions stemming from the operating environment for property and directors and officers insurance.

Chubb's middle-market and small business segments in Australia generated double-digit premium growth. During the year, Chubb launched an online broker platform in this market that is designed to improve efficiency in the quote, bind and policy fulfillment process for the small commercial customer segment. The platform leverages the capabilities of Marketplace, which was introduced in North America in 2017. In Australia, the initial product focus is business package and cyber ERM products.

In **China**, the largest economy in Asia and the second-largest in the world, Chubb focused on building and deepening its presence. The company has a significant and increasing ownership stake in Huatai Insurance Group, a holding company with P&C, life and asset management subsidiaries. When pending transactions and agreements are completed, Chubb is expected to own a majority of Huatai Insurance Group. The group's insurance operations have more than 600 branches and 11 million customers.

Chubb also operates a fully licensed, 100% Chubb-owned subsidiary with branch offices in Shanghai, Beijing, Jiangsu and Guangdong. Chubb China offers one of the largest commercial P&C product portfolios in the Chinese insurance market. It also offers a series of protection products such as personal accident, homeowners, travel and personal devices insurance via the rapidly growing internet channel to Chinese families and individuals across the country.

Chubb's **Latin America** region generated gross premiums written of $2.9 billion, up 11% in constant dollars from 2018, representing 7% of the company total. Continuing execution of its growth strategies contributed to strong premium revenue in the company's personal lines and commercial P&C businesses.

Overseas General Business Unit Leaders

(From left)

Darryl Page
Vice President,
Chubb Group;
Division President,
Personal Insurance

John Thompson
Division President,
International
Accident & Health

Timothy O'Donnell
Vice President,
Chubb Group;
Division President,
Commercial Property
and Casualty

Chubb's business across Latin America is well balanced. In Brazil, the company has the second-largest commercial P&C business, which is distinguished by its track record of superior technical ability and multiple affinity distribution partnerships. In Mexico, the company is a leading provider of personal lines insurance, large corporate P&C, as well as surety. Chubb also has a strong presence in the Andean region – Colombia, Ecuador, Peru, Argentina and Chile – that accounts for about 30% of the total region, and where the company operates in all segments of commercial P&C through brokers and affinity partners. In the Caribbean and Central America, Chubb operates through wholly owned subsidiaries in Puerto Rico and Panama as well as corporate P&C insurance and bancassurance partnerships in other locations.

Like Asia, Latin America has favorable long-term growth characteristics, including GDP, a growing middle class and new small business creation. Through its strategies, investments and local presence, Chubb is positioned to further grow in these developing markets. A decade ago, Asia and Latin America represented about one-third of Chubb's international general insurance premium revenue. Today, those regions account for more than half of premium revenue.

In 2019, Chubb made good progress developing its distribution partnerships with leading banks in Mexico and Chile. With Banco de Chile, a major focus was building out the product offering. During the year, the team launched dedicated campaigns for residential, personal lines and commercial P&C coverages across multiple channels, including branches, ATMs, telemarketing and digital.

With Citibanamex in Mexico, Chubb introduced a dozen new products in 2019 and has plans to introduce a dozen more in 2020. These market-driven products are designed in part based on an analysis of purchasing behavior. By the end of 2019, Chubb was selling more than 30,000 policies per month through digital platforms, branches and telesales.

Other highlights in the region included another year of strong results in Mexico personal lines, driven by the auto insurance business. In A&H lines, Chubb's partnership with LATAM airlines contributed to strong premium growth in travel insurance. Chubb has long-term distribution agreements with many of the top airlines based in the region.

Europe is Chubb's second largest region behind North America, operating in 19 countries, with $3.7 billion of gross premiums written, representing 9% of the company total. In 2019, Chubb achieved its best growth in many years and underwriting profitability in an improving operating environment.

Chubb European Group's first order of business in 2019 was completing the redomicile of its EU business from London to Paris as planned on January 1 related to Brexit. Throughout the year, the business remained focused on delivering clarity, continuity of service and certainty for customers, brokers and other partners to ensure continuous, uninterrupted service as Brexit deadlines approached.

Highlights included growth in Major Accounts across the U.K., Ireland and Continental Europe. In Germany and the Netherlands, the upper middle-market segment also performed well. Chubb's global presence, servicing capability, broad product range, financial strength and underwriting leadership contributed to this success.

Other 2019 initiatives included the launch of a new media industry practice for the U.K. and Ireland. The practice offers a range of bespoke coverages for media liability, cyber, property and casualty as well as personal accident and travel coverages for middle market and multinational advertising, public relations, branding and publishing companies. This industry practice also provides value-added services, including a free legal advice helpline staffed by senior media lawyers.

Beginning in 2019, commercial customers of all sizes across Europe had access to Chubb's Environmental Incident Alert, a free service that helps clients identify qualified incident-response contractors, monitor clean-up costs and mitigate potential liabilities associated with environmental releases. The Environmental Incident Alert service uses customized alerts via email and/or text message and also provides response coordination assistance and incident documentation. It is available 24/7 and is now operational in more than 50 countries.

In Germany, the company launched a new digital partnership, called Quick Cargo Insurance, with Hapag-Lloyd AG, one of the world's largest cargo container carriers. The partnership is facilitated through a bespoke online system that quotes and binds single-shipment coverage for small commercial clients of Hapag-Lloyd when they place business orders for marine cargo online. This capability embodies Chubb's drive to offer a superior customer experience by engaging directly with partners and delivering an offering that benefits the partner, their client and Chubb.

During the year, Chubb also launched Easy Solutions Vin in France, which includes a range of property and casualty insurance coverages for wine producers.

Chubb's international A&H business introduced an extended range of new eLearning modules as part of its Chubb Travel Smart app for business travelers, including pre-travel eLearning, direct access to medical and security assistance and live location-based alerts to help avoid trouble and stay safe. Chubb Travel Smart is the company's duty of care solution designed specifically for employers to help manage and mitigate travel risks of their employees.

In specialty personal lines, Chubb entered into several large relationships with European mobile network operators, strengthening its leadership in this market.

Chubb's **Far East** region, which encompasses Japan, had a record year, with growth in premium revenue significantly outpacing the overall market. The business benefited from both an improving operating environment and continued focus on executing its growth strategies. All product lines and distribution channels contributed to the strong results.

Highlights included double-digit growth in property, casualty, financial lines and surety. In the large commercial segment, Chubb's strong underwriting and risk engineering capabilities were strengths in a firming market. For small and middle-market businesses, the company expanded its industry practices, including entertainment, infotech and life sciences.

A&H remains a significant growth engine in Japan with Chubb further building out its multi-channel distribution with agents, brokers, direct marketing and online. Chubb is focused on adding direct marketing partners through customer-segmented campaigns as well as new online travel partners by seamlessly integrating insurance products into their digital purchase path. Relevant and flexible products, such as personal accident and trip cancellation coverages, helped to differentiate Chubb in the marketplace. Each channel is supported by continuous enhancements to product offerings within personal accident, supplemental medical and travel categories.

Overseas General Regional Leaders

(From left)

David Furby
Senior Vice President, Chubb Group; Regional President, European Group

Paul McNamee
Senior Vice President, Chubb Group; Regional President, Asia Pacific

Marcos Gunn
Senior Vice President, Chubb Group; Regional President, Latin America

In 2020, Chubb celebrates a century of doing business in Japan.

Eurasia and Africa also experienced a changing market environment in 2019, with pricing moving closer to the realities of risk in the region, especially in energy and financial lines. The region generated strong premium revenue growth and posted solid underwriting results, recording a combined ratio of 88%. Investment in new IT infrastructure and refinements of the operating model again contributed to an improved expense ratio and will enable future efficiencies.

Chubb Global Markets

Chubb Global Markets, the company's London market wholesale and international excess and surplus business, provides global access to specialist underwriters in aviation, energy, financial lines, marine, political risk and credit, property, and accident and health.

For several years, pricing for risk in the P&C E&S insurance too often failed to meet the company's targets to maintain an adequate underwriting profit. In response, Chubb shrank the business. The overall London market, however, continued to grow, even as Chubb's share of it fell.

The rate environment began to change in 2018, and accelerated throughout 2019, as many carriers narrowed their risk appetites or withdrew from certain classes. The stress was most evident in property and marine lines, but increasingly moved into casualty and professional lines.

"Because we had kept our powder dry, we had the ability to deploy capacity when pricing became adequate again," said Mr. Ortega. "That time came in 2019, and our patience and discipline were rewarded with four consecutive quarters of double-digit growth."

"Overseas General is a big and important contributor to Chubb's success, and our company has never been better positioned to take advantage of the vast opportunities outside North America," said Mr. Keogh. "It's an expanding and profitable organization with plenty of runway for future growth in the years ahead. We will continue to be on our front foot to meet the evolving needs of our customers and distribution partners while creating opportunities for our employees."

Key Financial Results

Dollars in millions

Life Insurance	
2019	
Net premiums written	$2,392
Segment income	$366
International life insurance segment income	$152

"The progress we have made building this business in recent years is gaining momentum. We are well positioned to continue to build the breadth and depth of our life business across Asia."

– Russell Bundschuh

Chubb's Life Insurance segment comprises two businesses. Chubb Life is an international life insurer, primarily focused on Asia, that provides protection and savings-oriented life insurance products to individuals and groups. Combined Insurance provides personal accident and supplemental health insurance coverages to consumers in North America.

For the year, the Life segment generated net premiums written of $2.4 billion, up 5.3%, or 6.4% in constant dollars, from prior year. Segment income was $366 million, up 18.6%.

Chubb Life

Chubb Life serves the needs of consumers through a variety of distribution channels including primarily captive agents, but also through banks, retailers, brokers, independent agents and direct marketing. Chubb Life has operations in seven Asian markets – Hong Kong, Indonesia, Korea, Taiwan, Thailand, Vietnam and, beginning in 2019, Myanmar. In China, the company is also a joint venture partner in Huatai Life, a fast-growing life insurer that serves more than 1.3 million customers with a broad portfolio of savings and protection products. Together, Chubb Life and Huatai Life have nearly 630 offices, 5,000 employees and 85,000 agents.

Life insurance is a long-term business, and Chubb has been pursuing a consistent strategy to build Chubb Life primarily through organic growth. With its growing scale, Chubb's international life business has begun to emerge as a meaningful contributor to the company's growth and profitability. In 2018, international life earnings reached $100 million for the first time.

In 2019, earnings rose 48% to $152 million. International life insurance net premiums written were up 12.6% in constant dollars.

"In 2019, we continued to diversify and expand our captive agency force across several countries, opened new offices and looked for ways to do more for our external distribution partners, including banks and affinity groups," said Russell Bundschuh, Senior Vice President, Chubb Group and President of Chubb Life. "We made good progress advancing our digital initiatives focused on enhancing the customer experience, launching new digitally enabled products and making it easier for agents and distribution partners to interact with us and serve customers."

In an environment of continuing low interest rates, the business kept its sales focus on protection-oriented products. At the same time, Chubb Life increased its emphasis on developing and launching health and wellness products.

One of the business's milestones in 2019 was establishing a 100% owned life insurance subsidiary in Myanmar, a nation of more than 54 million people. Following a competitive review process, Chubb was one of five foreign companies awarded a license for a wholly owned life insurance business by the Myanmar Ministry of Planning and Finance. Chubb is committed to working with the Myanmar government, regulators and local organizations to help build and strengthen the nation's life insurance sector. The headquarters in Yangon is up and running, and the business has already recruited hundreds of agents.

Global A&H, Life Insurance and Reinsurance Business Unit Leaders

(From left)

Joe Vasquez
Senior Vice President,
Chubb Group;
Global Accident & Health;
President,
Combined Insurance

Russell Bundschuh
Senior Vice President,
Chubb Group;
President,
Chubb Life

James E. Wixtead
Senior Vice President,
Chubb Group;
President,
Chubb Tempest Re Group

Cunqiang Li
Chief Operating Officer,
Chubb Life

In 2019, Chubb Life Thailand experienced double-digit growth in total premium. The agency business benefited from its focus on productivity, supported by new health and critical illness riders launched with whole life. In the group business, growth was driven by expanding existing client relationships as well as the addition of two new partners.

Vietnam also delivered double-digit growth with an agency force that has now surpassed 40,000 agents. In early 2019, Chubb Life Vietnam launched an e-submission app that enables agents to prepare and submit insurance applications online via their tablet or laptop. By the end of 2019, 94% of all insurance applications submitted to the company were via the new app. Vietnam plans to eliminate the use of printed insurance application forms in 2020.

In Hong Kong SAR, Chubb Life introduced a new digital platform for agents to engage with and serve their customers. With Chubb Link℠, each agent has a unique URL, enabling them to highlight their own individual experience, product knowledge, and professional awards and achievements. Customers can contact individual agents directly through the hub as well as find news and information about promotions and products. Currently, nearly two-thirds of agents are using the new tool.

While protests in Hong Kong SAR in 2019 made it more challenging for agents to meet with their clients, the broker channel continued to perform well. Across the region, Chubb Life has been developing strategies to expand sales through brokers, an effective channel to market protection-oriented products, as well as banks. In 2019, Chubb Life forged 44 new brokerage partnerships.

In China, Huatai Life had a strong year in 2019, with its rate of growth again outpacing the overall market. Huatai Life now operates in 20 provinces and has approximately 35,000 agents. Chubb has a significant and increasing ownership stake in Huatai Life's parent, Huatai Insurance Group, a financial services holding company that has property and casualty, asset management and other subsidiaries.

In Korea, Chubb Life launched a new initiative offering life products to non-life customers by leveraging the multi-product telemarketing sales channel of the company's international A&H business. This approach generates synergies coupled with a superior product value proposition and enhanced customer purchase experience. Term life and new critical illness products were launched.

Early in 2020, the business launched a new health and well-being initiative in the form of a new mobile app, called Chubb LifeBalance, in Hong Kong SAR and Thailand. Chubb LifeBalance better engages customers by providing support and guidance to live a healthier, more balanced life. It gives personalized AI-powered coaching following a 360-degree approach to a user's health and well-being.

While Chubb Life is focused on Asia, it has operations in other parts of the world. In 2019, Chubb Life expanded its presence in Chile with the acquisition of Banchile Seguros de Vida (Banchile Life), a Santiago-based life insurance company with a long-standing insurance relationship with Banco de Chile, the largest bank based in Chile. Banchile Life, which offers a broad range of life, personal accident and supplemental health insurance products, generated over $200 million of gross premiums written in 2018.

The addition of Banchile Life, along with Chubb's exclusive distribution partnership with Banco de Chile for P&C and A&H products, significantly extends Chubb's distribution and presence in Chile, enabling the company to reach and serve millions of new customers, including in digitally advanced ways.

"The progress we have made building this business in recent years is gaining momentum," said Mr. Bundschuh. "We are well positioned to continue to build the breadth and depth of our life business across Asia."

Combined Insurance

Combined Insurance generated solid results in 2019, driven by double-digit growth in Chubb Workplace Benefits, which serves large and middle-market companies by partnering with benefit brokers, agents and consultants to offer a line of supplemental insurance products, including accident, critical illness, hospital indemnity, life and disability income. Chubb has been investing in this business, which brings together the strengths of Combined Insurance's workplace products, Chubb's extensive branch network and the company's substantial relationships with national and regional insurance brokerage firms.

Combined Insurance is focused on building out its capabilities, sales organization and distribution to be fully aligned with Chubb's North American field organization, and to better serve commercial clients of all sizes – large, middle market and small businesses. As enrollment in voluntary benefits programs has moved online, the company is making investments to enhance customer-facing and back-office systems as the business grows.

"Since it was launched in 2016, Chubb Workplace Benefits has made significant progress, and we're committed to building this business with the people, products, technology and capabilities to keep pace with our growth," said Joe Vasquez, Senior Vice President, Chubb Group, Global Accident & Health and President of Combined Insurance. "The continued expansion of our workplace benefits business shows the breadth of our A&H offerings as well as the power of the Chubb branch network in the U.S."

The Combined Insurance core agency force – which now numbers more than 3,300 agents in the U.S. and Canada – has historically focused on distributing personal accident, life and supplemental health insurance coverages directly to consumers. Now, Combined Insurance is putting more emphasis on tapping the small commercial market. Proprietors and employers of Main Street businesses, as well as the individuals who work for them, fit the customer profile for the company's affordable A&H products. Combined Insurance is supporting this initiative with learning and development programs to help agents adapt to selling in a small business workplace instead of over a kitchen table.

In building its agency force, Combined Insurance continues to focus on Spanish-speaking agents, who bring the company's insurance offering to the underserved Latino market in the U.S., as well as build on its signature success recruiting veterans looking to re-enter the workforce.

In 2019, Combined Insurance again was recognized for its military-friendly hiring practices. For example, VIQTORY named the company the number one Military Friendly® Employer in the over $1 billion revenue category – the eighth consecutive year on the top 10 list and fifth consecutive year in the top five.

"We truly value the service veterans have provided to our country, and in return, we give them the tools they need to help them be successful in their career here," Mr. Vasquez said.

Key Financial Results

Dollars in millions

Global Reinsurance

2019	
Gross premiums written	$719
Net premiums written	$649
Combined ratio	85.0%
P&C current accident year combined ratio excluding catastrophe losses	82.1%
Segment income	$376

"The market took a turn in 2019, making it an interesting year. We quoted a lot more business in 2019 than we had in recent years."

– James Wixtead

Chubb's reinsurance business, which operates under the Chubb Tempest Re brand, offers a broad range of products to a diverse group of primary property and casualty insurers worldwide. Doing business globally with offices in Bermuda, Stamford, London, Montreal and Zurich, the business has deep underwriting, actuarial and claims expertise. Chubb Tempest Re's position as a subsidiary of a leading global P&C insurer sets it apart from many other reinsurance companies: The business can be patient and deploy capital only when there are opportunities to achieve rate adequacy.

Reinsurance is a cyclical business, and the operating environment for reinsurers has been challenging. Chubb Tempest Re has consistently demonstrated underwriting discipline, which has enabled it to perform in the top quartile of reinsurers in terms of profitability as measured by combined ratio. In 2019, Chubb's Global Reinsurance segment posted net written premiums of $649 million, down 3.2% from prior year. The combined ratio was 85.0%, and the current accident year combined ratio excluding catastrophe losses was 82.1%. Segment income was $376 million, up 35.7% from 2018.

In 2019, there were signs that the market was transitioning and the trading environment becoming more attractive. The shift could be seen in reduced limits and increases in pricing in many lines and jurisdictions that accelerated throughout the year.

"The market took a turn in 2019, making it an interesting year. We quoted a lot more business in 2019 than we had in recent years," said James Wixtead, Senior Vice President, Chubb Group and President of Chubb Tempest Re Group. "But while improving, the market needs to move a bit more in order to match our appetite for deploying significantly more capital."

As the market continues to transition, Chubb Tempest Re will be looking for more opportunities, including more emphasis on higher-margin long-tail lines, a part of the overall portfolio that was significantly reduced in recent years.

"Our view of risk is very consistent," said Mr. Wixtead. "Many members of our team have been with us for 20 years or more. They understand how we fit into the Chubb organization, and where we can add value to our client and broker partners. This team, along with our systems, infrastructure and the financial strength of Chubb, position us well as we look to the trading environment for Chubb Tempest Re to improve in 2020."

Corporate and Global Functional Leaders

(From left)

Joseph Wayland
Executive Vice President,
Chubb Group;
General Counsel

Ivy Kusinga
Chief Culture Officer,
Chubb Group

Sean Ringsted
Executive Vice President,
Chubb Group;
Chief Risk Officer and Chief Digital Officer

Michael W. Smith
Senior Vice President,
Chubb Group;
Global Claims Officer

(From left)

Timothy Boroughs
Executive Vice President,
Chubb Group;
Chief Investment Officer

Philip Bancroft
Executive Vice President,
Chubb Group;
Chief Financial Officer

Paul Medini
Senior Vice President,
Chubb Group;
Chief Accounting Officer

Julie Dillman
Senior Vice President,
Chubb Group;
Global Head of Operations

(From left)

Paul O'Connell
Senior Vice President,
Chubb Group;
Chief Actuary

Rainer Kirchgaessner
Executive Vice President,
Chubb Group;
Global Corporate
Development Officer

Jo Ann Rabitz
Global Human Resources
Officer,
Chubb Group

Our Mission

Protecting the Present and Building a Better Future

Good corporate citizenship lies at our core – how we practice our craft of insurance, how we work together to serve our customers, how we treat each other, and how we work to help make a better world for our communities and our planet. Citizenship is about responsibility – and we express that responsibility in a way that reflects our core values and our mission to protect the present and build a better future.

We accomplish our mission by providing the security from risk that allows people and businesses to grow and prosper. Our mission is realized by sustaining a culture that values and rewards excellence, integrity, inclusion and opportunity; by working to protect our planet and assisting less fortunate individuals and communities in achieving and sustaining productive and healthy lives; and by promoting the rule of law.

From our roots in 18th century Philadelphia, we have built Chubb to be a dynamic, forward-looking global enterprise with a commitment to responsible citizenship. We act on this promise of responsibility through a wide range of activities that include our contributions of time and money.

Philanthropy

Chubb recognizes its responsibility to assist less fortunate individuals and communities in achieving and sustaining productive and healthy lives in geographic areas where the company operates. The company's philanthropy is funded principally through the Chubb Charitable Foundation and the Chubb Rule of Law Fund.

The Chubb Charitable Foundation addresses actionable problems and contributes to helping alleviate poverty, improve the health of at-risk populations, provide access to quality education and protect the environment. In the last 10 years, the company has contributed more than $100 million to the Foundation.

For many years, for example, the Foundation has supported the International Rescue Committee, including its efforts to help refugees get settled and establish productive lives. The Foundation has helped build schools in China and Vietnam, fund micro-finance projects in Mexico and Colombia, and serve as a major partner for Teach for America and Teach for All programs in the United States and around the globe.

Environment

Chubb recognizes the reality of climate change and the substantial impact of human activity on our planet. Our environmental initiatives reflect our desire to take actions that reduce Chubb's environmental footprint and, through our philanthropy, strengthen the resilience of communities and protect biodiversity against the effects of climate change.

The Chubb Charitable Foundation and the company's employees support a range of environmental philanthropies, including The Nature Conservancy and the Conservation Fund, as well as volunteer activities in local communities around the world. Chubb Charitable Foundation grants have helped preserve sensitive lands and habitats, finance green business entrepreneurs, and support educational programs that promote a healthy and sustainable environment in the U.S. and around the world.

In 2019, Chubb adopted a new policy concerning coal-related underwriting and investment and established new science-based greenhouse gas (GHG) emissions reduction goals using 2016 as the baseline. By year-end, the company achieved its first goal to reduce absolute GHG emissions by 20%. These goals are being achieved through a combination of real estate portfolio optimization, energy efficiency projects and the purchase of renewable electricity. In 2019, the company earned a score of B on the CDP's climate change program ranking.

Diversity and Inclusion

At Chubb, we recognize our responsibility to ensure opportunity within our own organization, where we foster a diverse and inclusive meritocracy. We can't succeed unless we give everyone the opportunity to thrive and advance in our company, and we hold our leaders accountable for achieving a diverse mix of talent, regardless of creed or background.

The company's extensive efforts in this area include mentorships, affinity groups, diversity awareness training, management development programs, and mandating diverse slates in recruiting and promotion.

Examples of initiatives include the company's Business Roundtables and Regional Inclusion Councils, which promote dynamic networking across the business and engage hundreds of employees in constructive dialogue. Other initiatives include Chubb Start, a program that supports the continuous professional development of early career women, and Chubb Signatures, a global and regional lecture series for successful senior women, diverse men and inclusion champions to share their unique backgrounds, experiences and hard-earned lessons in business.

Chubb Rule of Law Fund

As a corporate citizen, Chubb recognizes the rule of law as the foundation of a liberal world order that the company embraces as essential to the proper functioning of markets and the protection of personal freedoms. Through the Chubb Rule of Law Fund, a unique corporate initiative, we support projects around the world that promote the preservation and advancement of the rule of law.

Since it was founded in 2008, the Fund has supported 55 projects in countries around the world focused on improving access to justice, strengthening courts, fighting corruption and creating the conditions of security and freedom in which our customers, employees and fellow citizens can thrive.

The Chubb Rule of Law Fund is funded by the Chubb Charitable Foundation and contributions from 15 of Chubb's partner law firms. In 2019, 10 new projects were funded. Among them were initiatives to strengthen the independence of the judiciary in Guatemala; litigation support for juveniles facing life imprisonment without parole in the U.S.; supporting administrative law in Vietnam; and protecting the rights of children in mental health units in England and Wales.

Officers and Executives

Chubb Group Corporate Officers

Evan G. Greenberg*
Chairman and Chief Executive Officer, Chubb Group

John Keogh*
Executive Vice Chairman, Chubb Group;
Chief Operating Officer

John Lupica**
Vice Chairman, Chubb Group;
President, North America Major Accounts and Specialty Insurance

Paul J. Krump**
Executive Vice President, Chubb Group;
President, North America Commercial and Personal Insurance

Juan Luis Ortega**
Executive Vice President, Chubb Group;
President, Overseas General Insurance

Philip Bancroft*
Executive Vice President, Chubb Group;
Chief Financial Officer

Timothy Boroughs**
Executive Vice President, Chubb Group;
Chief Investment Officer

Rainer Kirchgaessner
Executive Vice President, Chubb Group;
Global Corporate Development Officer

Sean Ringsted**
Executive Vice President, Chubb Group;
Chief Risk Officer and Chief Digital Officer

Joseph Wayland*
Executive Vice President, Chubb Group;
General Counsel

Brad Bennett
Senior Vice President, Chubb Group;
Regional President, Far East

Russell Bundschuh
Senior Vice President, Chubb Group;
President, Chubb Life

Julie Dillman
Senior Vice President, Chubb Group;
Global Head of Operations

David Furby
Senior Vice President, Chubb Group;
Regional President, European Group

Marcos Gunn
Senior Vice President, Chubb Group;
Regional President, Latin America

Bruce L. Kessler
Senior Vice President, Chubb Group;
Division President, Westchester

Ken Koreyva
Senior Vice President, Chubb Group;
Finance

Christopher A. Maleno
Senior Vice President, Chubb Group;
Division President, North America Field Operations

Patrick McGovern
Senior Vice President, Chubb Group;
Chief Communications Officer

Paul McNamee
Senior Vice President, Chubb Group;
Regional President, Asia Pacific

Paul Medini
Senior Vice President, Chubb Group;
Chief Accounting Officer

Matthew Merna
Senior Vice President, Chubb Group;
Division President, North America Major Accounts

Scott A. Meyer
Senior Vice President, Chubb Group;
Division President, North America Financial Lines

Frances D. O'Brien
Senior Vice President, Chubb Group;
Division President, North America Personal Risk Services

Paul O'Connell
Senior Vice President, Chubb Group;
Chief Actuary

Michael W. Smith
Senior Vice President, Chubb Group;
Global Claims Officer

Derek Talbott
Senior Vice President, Chubb Group;
Division President, North America Property

Joe Vasquez
Senior Vice President, Chubb Group;
Global Accident & Health;
President, Combined Insurance

*Chubb Limited Executive Management and Executive Officer for SEC reporting purposes
**Executive Officer for SEC reporting purposes

James E. Wixtead
Senior Vice President, Chubb Group;
President, Chubb Tempest Re Group

Scott Arnold
Vice President, Chubb Group;
Division President, Chubb Agriculture;
President, Rain and Hail

Ross Bertossi
Vice President, Chubb Group;
Global Underwriting

Joseph S. Clabby
Vice President, Chubb Group;
Chairman, Chubb Bermuda;
Executive Vice President, North America Field Operations

Sean Corridon
Vice President, Chubb Group;
Deputy Chief Investment Officer

Judy Gonsalves
Vice President, Chubb Group;
Division President, Chubb Bermuda

Stephen M. Haney
Vice President, Chubb Group;
Division President, North America Surety;
Chief Underwriting Officer, Global Surety

Michael Kessler
Vice President, Chubb Group;
Chief Reinsurance Officer

Timothy O'Donnell
Vice President, Chubb Group;
Division President, Commercial Property and Casualty
Overseas General Insurance

Darryl Page
Vice President, Chubb Group;
Division President, Personal Insurance
Overseas General Insurance

Benjamin Rockwell
Vice President, Chubb Group;
Division President, North America Middle Market

James Williamson
Vice President, Chubb Group;
Division President, North America Small Business

Other Executives

Adam Clifford
Division President, Continental Europe

Samantha Froud
Chief Administration Officer, Bermuda Operations

Mark Hammond
Treasurer, Chubb Group

Jason Keen
Division President, Chubb Global Markets

Ivy Kusinga
Chief Culture Officer, Chubb Group

Eric Larson
Chief Compliance Officer, Chubb Group

Cunqiang Li
Chief Operating Officer, Chubb Life

David Lupica
Chief Operating & Distribution Management Officer
Westchester

Timothy Mardon
Division President, Chubb Tempest Re Bermuda

Sara Mitchell
Division President, U.K and Ireland

Michael O'Donnell
Division President, Chubb Tempest Re USA

George Ohsiek
Chief Auditor, Chubb Group

Jo Ann Rabitz
Global Human Resources Officer, Chubb Group

Steve Roberts
Division President, Chubb Tempest Re International

John Thompson
Division President, International Accident & Health
Overseas General Insurance

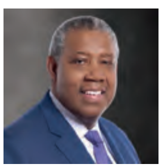
Giles Ward
Regional President, Eurasia & Africa

Chubb Limited Board of Directors

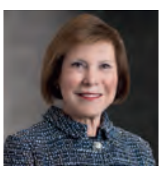
Evan G. Greenberg
Chairman and
Chief Executive Officer
Chubb Limited

Michael G. Atieh
Retired Chief Financial
and Business Officer
Ophthotech Corporation

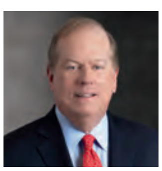
Sheila P. Burke
Faculty Research Fellow
John F. Kennedy School
of Government
Harvard University



James I. Cash
Emeritus Professor of
Business Administration
Harvard University



Mary Cirillo
Retired Executive
Vice President and
Managing Director
Deutsche Bank



Michael P. Connors
Chairman and
Chief Executive Officer
Information Services
Group, Inc.

John A. Edwardson
Retired Chairman and
Chief Executive Officer
CDW Corporation

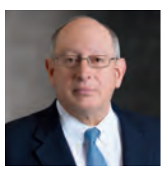
Robert M. Hernandez
Lead Director
Chubb Limited

Retired Vice Chairman
and Chief Financial Officer
USX Corporation

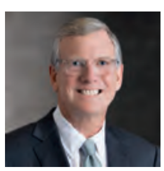
Kimberly A. Ross
Chief Financial Officer
WeWork

Robert W. Scully
Retired Co-President
Morgan Stanley

Eugene B. Shanks, Jr.
Retired President
Bankers Trust Company



Theodore E. Shasta
Retired Partner
Wellington Management
Company



David H. Sidwell
Retired Chief
Financial Officer
Morgan Stanley

Olivier Steimer
Former Chairman
Banque Cantonale
Vaudoise

Board Committees

Audit Committee
Robert W. Scully, Chair
James I. Cash
Kimberly A. Ross
Theodore E. Shasta
David H. Sidwell

Compensation Committee
Michael P. Connors, Chair
Mary Cirillo
John A. Edwardson
Robert M. Hernandez

Nominating & Governance Committee
Mary Cirillo, Chair
Michael P. Connors
John A. Edwardson
Robert M. Hernandez

Risk & Finance Committee
Olivier Steimer, Chair
Michael G. Atieh
Sheila P. Burke
Eugene B. Shanks, Jr.

Executive Committee
Evan G. Greenberg, Chair
Mary Cirillo
Michael P. Connors
Robert M. Hernandez
Robert W. Scully
Olivier Steimer

Shareholder Information

Visit investors.chubb.com, write to the Investor Relations Department at Chubb Limited or e-mail investorrelations@chubb.com for copies of the company's reports to the Securities and Exchange Commission on Form 10-K, Form 10-Q or Form 8-K, all of which are available without charge.

Address Investor Relations Inquiries to:

Investor Relations
Chubb Limited
1133 Avenue of the Americas
11th Floor
New York, NY 10036
Tel: 212 827 4445
E-mail: investorrelations@chubb.com

Transfer Agent & Registrar

Computershare
462 South 4th Street
Louisville, KY 40202 USA
U.S.: 877 522 3752
Outside the U.S.: 201 680 6898

Address Shareholder Inquiries to:

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Computershare
P.O. Box 505000
Louisville, KY 40233-5000 USA

By overnight delivery:
Computershare
462 South 4th Street
Louisville, KY 40202 USA
Website:
www-us.computershare.com/Investor

Send Certificates for Transfer and Address Changes to:

Computershare
P.O. Box 505000
Louisville, KY 40233-5000 USA

Independent Auditors

PricewaterhouseCoopers AG
Birchstrasse 160
8050 Zurich
Switzerland
Tel: 41 58 792 44 00

PricewaterhouseCoopers LLP
Two Commerce Square, Suite 1800
Philadelphia, PA 19103 USA
Tel: 267 330 3000

New York Stock Exchange Symbol

CB

Chubb Common Shares CUSIP Number

H1467J 104

Price Range of Common Shares and Dividends

As of February 13, 2020, the company had 451,907,796 Common Shares outstanding with 6,902 registered holders of Common Shares. The accompanying table sets forth the cash dividends and the high/low closing sales prices of the company's Common Shares, as reported on the NYSE Composite Tape for the periods indicated. We have paid dividends each quarter since we became a public company in 1993. The method of payment of our dividend approved at our May 2019 and May 2018 annual general meetings was a distribution from capital contribution reserves (additional paid-in capital).

	2019				2018			
			Dividends				Dividends	
Quarter Ending	**High**	**Low**	**USD**	**CHF**	High	Low	USD	CHF
March 31	**$140.08**	**$124.67**	**$0.73**	**0.72**	$156.15	$134.57	$0.71	0.66
June 30	**$150.94**	**$136.57**	**$0.75**	**0.75**	$138.29	$124.57	$0.73	0.73
September 30	**$161.44**	**$146.74**	**$0.75**	**0.73**	$140.12	$126.81	$0.73	0.72
December 31	**$162.06**	**$147.72**	**$0.75**	**0.74**	$136.59	$120.19	$0.73	0.73

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Non-GAAP Financial Measures
This document contains non-GAAP financial measures. The below non-GAAP financial measures, which may be defined differently by other companies, are important for an understanding of our overall results of operations and financial condition. However, these measures should not be viewed as a substitute for measures determined in accordance with generally accepted accounting principles (GAAP).

We provide certain financial measures on a constant-dollar basis (i.e., excluding the impact of foreign exchange). We believe it is useful to evaluate the trends in our results exclusive of the effect of fluctuations in exchange rates between the U.S. dollar and the currencies in which our international business is transacted, as these exchange rates could fluctuate significantly between periods and distort the analysis of trends. The impact is determined by assuming constant foreign exchange rates between periods by translating prior period results using the same local currency exchange rates as the comparable current period.

Core operating income, net of tax, excludes from net income the after-tax impact of adjusted net realized gains (losses), Chubb integration expenses, and the amortization of fair value adjustment of acquired invested assets and long-term debt related to the Chubb Corp acquisition. We believe this presentation enhances the understanding of our results of operations by highlighting the underlying profitability of our insurance business. We exclude adjusted net realized gains (losses) because the amount of these gains (losses) are heavily influenced by, and fluctuate in part according to, the availability of market opportunities. We exclude the amortization of the fair value adjustments related to purchased invested assets and long-term debt and Chubb integration expenses due to the size and complexity of this acquisition. These integration expenses are distortive to our results and are not indicative of our underlying profitability. We believe that excluding these integration expenses facilitates the comparison of our financial results to our historical operating results. References to core operating income measures mean net of tax, whether or not noted.

The following table presents the reconciliation of Net income to Core operating income:

(in millions of U.S. dollars except share and per share data)	Full Year 2019	Full Year 2018
Net income, as reported	$4,454	$3,962
Amortization of fair value adjustment of acquired invested assets and long-term debt, pre-tax	(140)	(215)
Tax benefit on amortization adjustment	26	40
Chubb integration expenses, pre-tax	(23)	(59)
Tax benefit on Chubb integration expenses	4	12
Adjusted realized gains (losses), pre-tax[1]	(522)	(649)
Net realized gains (losses) related to unconsolidated entities, pre-tax[2]	483	431
Tax (expense) benefit on adjusted net realized gains (losses)	(15)	(5)
Core operating income	$4,641	$4,407
Denominator	458,914,663	466,802,348
Diluted earnings per share		
Net income	$9.71	$8.49
Amortization of fair value adjustment of acquired invested assets and long-term debt, net of tax	(0.25)	(0.37)
Chubb integration expenses, net of tax	(0.04)	(0.10)
Adjusted net realized gains (losses), net of tax	(0.11)	(0.48)
Core operating income	$10.11	$9.44
% Change from prior year	7.1%	

[1] Excludes realized losses on crop derivatives of $8 million and $3 million for 2019 and 2018, respectively.
[2] Realized gains (losses) on partially owned entities, which are investments where we hold more than an insignificant percentage of the investee's shares. The net income or loss is included in other income (expense).

Core operating return on equity (ROE) and Core operating return on tangible equity (ROTE) are annualized non-GAAP financial measures. The numerator includes core operating income, net of tax. The denominator includes the average shareholders' equity for the period adjusted to exclude unrealized gains (losses) on investments, net of tax. For the ROTE calculation, the denominator is also adjusted to exclude goodwill and other intangible assets, net of tax. These measures enhance the understanding of the return on shareholders' equity by highlighting the underlying profitability relative to shareholders' equity and tangible equity excluding the effect of unrealized gains and losses on our investments.

(in millions of U.S. dollars except ratios)	Full Year 2019	Full Year 2018
Net income	$4,454	$3,962
Core operating income	$4,641	$4,407
Equity – beginning of period as reported [1]	$50,300	$51,172
Less: unrealized gains (losses) on investments, net of deferred tax	(545)	1,154
Equity – beginning of period, as adjusted	$50,845	$50,018
Less: goodwill and other intangible assets, net of tax	$20,054	$20,621
Equity – beginning of period, as adjusted, excluding goodwill and other intangible assets	$30,791	$29,397
Equity – end of period, as reported	$55,331	$50,312
Less: unrealized gains (losses) on investments, net of deferred tax	2,543	(545)
Equity – beginning of period, as adjusted	$52,788	$50,857
Less: goodwill and other intangible assets, net of tax	$20,012	$20,054
Equity – end of period, as adjusted, excluding goodwill and other intangible assets	$32,776	$30,803
Weighted average equity, as reported	$52,816	$50,742
Weighted average equity, as adjusted	$51,817	$50,438
Weighted average equity, as adjusted, excluding goodwill and other intangible assets	$31,784	$30,100
ROE	8.4%	7.8%
Core operating ROE	9.0%	8.7%
Core operating ROTE	14.6%	14.6%

[1] January 1, 2019 included a $12 million after-tax reduction to beginning equity related to the adoption of new accounting guidance on premium amortization of purchased callable debt securities.

Combined ratio measures the underwriting profitability of our property and casualty business. **P&C combined ratio** and **Current accident year (CAY) P&C combined ratio excluding catastrophe losses (CATs)** are non-GAAP financial measures. Refer to the Non-GAAP Reconciliation section in the 2019 Form 10-K, on pages 70-73 for the definition of these non-GAAP financial measures and reconciliation to the Combined ratio.

CAY P&C combined ratio with expected level of CATs is a non-GAAP financial measure which excludes CATs above or below managements' view of expected CATs for that period. For this purpose, the normalized level of CATs, **or expected level of CATs**, is not intended to represent a probability weighted expectation for the company but rather to represent management's view of what might be more typical for a given period based on various factors, including historical experience, seasonal patterns, and consideration of both modeled CATs (e.g., windstorm and earthquake) as well as non-modeled CATs (e.g., wildfires, floods and freeze).

	Full Year 2019	Full Year 2018
Combined ratio	90.6%	90.6%
Add: impact of gains and losses on crop derivatives	0.0%	0.0%
P&C combined ratio	90.6%	90.6%
Less: Catastrophe losses	4.1%	5.9%
Less: Prior period development	-2.7%	-3.3%
CAY P&C combined ratio excluding CATs	89.2%	88.0%
Add: Expected level of CATs	3.4%	3.4%
CAY P&C combined ratio with expected level of CATs	92.6%	91.4%

The following table presents the reconciliation of Catastrophe losses, pre-tax, to Catastrophe losses above expected levels, pre-tax:

(in millions of U.S. dollars)	Full Year 2019
Catastrophe losses, pre-tax	$1,187
Less: Expected levels of CATs, pre-tax	969
Catastrophe losses above expected levels, pre-tax	$218

Tangible book value per common share is shareholders' equity less goodwill and other intangible assets, net of tax, divided by the shares outstanding. We believe that goodwill and other intangible assets are not indicative of our underlying insurance results or trends and make book value comparisons to less acquisitive peer companies less meaningful.

(in millions of U.S. dollars, except share and per share data)	December 31 2019	December 31 2018	% Change
Shareholders' equity	$55,331	$50,312	
Less: goodwill and other intangible assets, net of tax	20,012	20,054	
Numerator for tangible book value per share	$35,319	$30,258	
Shares outstanding	451,971,567	459,203,378	
Book value per common share	$122.42	$109.56	11.7%
Tangible book value per common share	$78.14	$65.89	18.6%

P&C underwriting income is a non-GAAP financial measure which excludes the Life Insurance segment. P&C underwriting income is used to monitor results of operations without the impact of certain factors as detailed below. We believe that P&C underwriting income is a useful measure as it enhances the understanding of our results of operations by highlighting the underlying profitability of our P&C insurance business.

The following table presents a reconciliation of Net income to P&C underwriting income:

(In millions of U.S. dollars)		Full Year 2019	Full Year 2018
Net income		$4,454	$3,962
Less:	Income tax (expense) benefit	(795)	(695)
	Chubb integration expenses	(23)	(59)
	Amortization expense of purchased intangibles	(305)	(339)
	Other income (expense)	596	434
	Interest expense	(552)	(641)
	Net investment income	3,426	3,305
	Net realized gains (losses)	(530)	(652)
	Life Insurance underwriting loss [(1)]	(97)	(5)
Add:	Realized losses on crop derivatives	(8)	(3)
	P&C underwriting income	$2,726	$2,611

[(1)] Excludes gains (losses) from fair value changes in separate account assets of $44 million in 2019 and $(38) million in 2018 and Life Insurance net investment income of $373 million in 2019 and $341 million in 2018.

International life insurance net premiums written and deposits is a non-GAAP financial measure which includes International life insurance net premiums written and deposits collected on universal life and investment contracts. Deposits collected on universal life and investment contracts (life deposits) are not reflected as revenues in our consolidated statements of operations in accordance with GAAP. However, new life deposits are an important component of production and key to our efforts to grow our business.

(in millions of U.S. dollars)	Full Year 2019
International life insurance net premiums written	$981
International life insurance deposits	1,463
Total international life insurance net premiums written and deposits [(1)]	$2,444

[(1)] Excludes Combined North America and Life reinsurance businesses.

Adjusted net investment income is net investment income excluding the amortization of the fair value adjustment on acquired invested assets. We believe this measure is meaningful as it highlights the underlying performance of our invested assets and portfolio management in support of our lines of business.

The following table presents a reconciliation of net investment income to adjusted net investment income:

(in millions of U.S. dollars)		Full Year 2019	Full Year 2018
Net investment income		$3,426	$3,305
Less:	Amortization expense of fair value adjustment on acquired invested assets	(161)	(248)
	Adjusted net investment income	$3,587	$3,553
	% Change from prior year	1.0%	

Net premiums written on an adjusted basis is net premiums written in the company's North America Personal P&C Insurance segment adjusted to exclude the year-over-year net impact for the quarter of additional reinsurance and reinstatement premiums. We believe this measure is meaningful to evaluate trends in the underlying business on a comparable basis.

The following table presents a reconciliation of North America Personal P&C Insurance net premiums written change versus prior year to change versus prior year on an adjusted basis:

	% Change 4Q-19 vs. 4Q-18
Net premiums written	9.2%
Net premiums written adjustments	-4.6%
Net premiums written on an adjusted basis	4.6%

UNITED STATES SECURITIES AND EXCHANGE COMMISSION
Washington, D.C. 20549

FORM 10-K

☑ ANNUAL REPORT PURSUANT TO SECTION 13 OR 15(d) OF THE SECURITIES EXCHANGE ACT OF 1934
For the fiscal year ended December 31, 2019
OR

☐ TRANSITION REPORT PURSUANT TO SECTION 13 OR 15(d) OF THE SECURITIES EXCHANGE ACT OF 1934
For the Transition Period from to
Commission File No. 1-11778

CHUBB LIMITED
(Exact name of registrant as specified in its charter)

Switzerland	**98-0091805**
(State or other jurisdiction of incorporation or organization)	(I.R.S. Employer Identification No.)

Baerengasse 32
Zurich, Switzerland CH-8001
(Address of principal executive offices) (Zip Code)
+41 (0)43 456 76 00
(Registrant's telephone number, including area code)

Securities registered pursuant to Section 12(b) of the Act:

Title of each class	Trading Symbol(s)	Name of each exchange on which registered
Common Shares, par value CHF 24.15 per share	CB	New York Stock Exchange
Guarantee of Chubb INA Holdings Inc. 0.30% Senior Notes due 2024	CB/24A	New York Stock Exchange
Guarantee of Chubb INA Holdings Inc. 0.875% Senior Notes due 2027	CB/27	New York Stock Exchange
Guarantee of Chubb INA Holdings Inc. 1.55% Senior Notes due 2028	CB/28	New York Stock Exchange
Guarantee of Chubb INA Holdings Inc. 0.875% Senior Notes due 2029	CB/29A	New York Stock Exchange
Guarantee of Chubb INA Holdings Inc. 1.40% Senior Notes due 2031	CB/31	New York Stock Exchange
Guarantee of Chubb INA Holdings Inc. 2.50% Senior Notes due 2038	CB/38A	New York Stock Exchange

Securities registered pursuant to Section 12(g) of the Act: None

Indicate by check mark if the registrant is a well-known seasoned issuer, as defined in Rule 405 of the Securities Act. Yes ☑ No ☐

Indicate by check mark if the registrant is not required to file reports pursuant to Section 13 or Section 15(d) of the Act. Yes ☐ No ☑

Indicate by check mark whether the registrant (1) has filed all reports required to be filed by Section 13 or 15 (d) of the Securities Exchange Act of 1934 during the preceding 12 months (or for such shorter period that the registrant was required to file such reports), and (2) has been subject to such filing requirements for the past 90 days. Yes ☑ No ☐

Indicate by check mark whether the registrant has submitted electronically every Interactive Data File required to be submitted pursuant to Rule 405 of Regulation S-T (§232.405 of this chapter) during the preceding 12 months (or for such shorter period that the registrant was required to submit such files). Yes ☑ No ☐

Indicate by check mark whether the registrant is a large accelerated filer, an accelerated filer, a non-accelerated filer, a smaller reporting company, or an emerging growth company. See the definitions of "large accelerated filer," "accelerated filer," "smaller reporting company," and "emerging growth company" in Rule 12b-2 of the Exchange Act.

Large accelerated filer	☑	Accelerated filer	☐
Non-accelerated filer	☐	Smaller reporting company	☐
		Emerging growth company	☐

If an emerging growth company, indicate by check mark if the registrant has elected not to use the extended transition period for complying with any new or revised financial accounting standards provided pursuant to Section 13(a) of the Exchange Act. ☐

Indicate by check mark whether the registrant is a shell company (as defined in Rule 12b-2 of the Act). Yes ☐ No ☑

The aggregate market value of voting stock held by non-affiliates as of June 28, 2019 (the last business day of the registrant's most recently completed second fiscal quarter), was approximately $67 billion. For the purposes of this computation, shares held by directors and officers of the registrant have been excluded. Such exclusion is not intended, nor shall it be deemed, to be an admission that such persons are affiliates of the registrant.

As of February 13, 2020 there were 451,907,796 Common Shares par value CHF 24.15 of the registrant outstanding.

Documents Incorporated by Reference

Certain portions of the registrant's definitive proxy statement relating to its 2020 Annual General Meeting of Shareholders are incorporated by reference into Part III of this report.

CHUBB LIMITED INDEX TO 10-K

PART I

ITEM 1. Business

General

Chubb Limited is the Swiss-incorporated holding company of the Chubb Group of Companies. Chubb Limited, which is headquartered in Zurich, Switzerland, and its direct and indirect subsidiaries (collectively, the Chubb Group of Companies, Chubb, we, us, or our) are a global insurance and reinsurance organization, serving the needs of a diverse group of clients worldwide. At December 31, 2019, we had total assets of $177 billion and shareholders' equity of $55 billion. Chubb was incorporated in 1985 at which time it opened its first business office in Bermuda and continues to maintain operations in Bermuda. We have grown our business through increased premium volume, expansion of product offerings and geographic reach, and the acquisition of other companies to become a global property and casualty (P&C) leader.

With operations in 54 countries and territories, Chubb provides commercial and personal property and casualty insurance, personal accident and supplemental health insurance (A&H), reinsurance, and life insurance to a diverse group of clients. We offer commercial insurance products and service offerings such as risk management programs, loss control, and engineering and complex claims management. We provide specialized insurance products ranging from Directors & Officers (D&O) and professional liability to various specialty-casualty and umbrella and excess casualty lines to niche areas such as aviation and energy. We also offer personal lines insurance coverage including homeowners, automobile, valuables, umbrella liability, and recreational marine products. In addition, we supply personal accident, supplemental health, and life insurance to individuals in select countries.

We serve multinational corporations, mid-size and small businesses with property and casualty insurance and risk engineering services; affluent and high net worth individuals with substantial assets to protect; individuals purchasing life, personal accident, supplemental health, homeowners, automobile, and specialty personal insurance coverage; companies and affinity groups providing or offering accident and health insurance programs and life insurance to their employees or members; and insurers managing exposures with reinsurance coverage.

At December 31, 2019, we employed approximately 33,000 people. We believe that employee relations are satisfactory.

We make available free of charge through our website (investors.chubb.com, under Financials) our annual report on Form 10-K, quarterly reports on Form 10-Q, current reports on Form 8-K, and amendments to those reports, if any, filed or furnished pursuant to Section 13(a) or 15(d) of the Exchange Act as soon as reasonably practicable after they have been electronically filed with or furnished to the U.S. Securities and Exchange Commission (SEC). Also available through our website (under Investor Relations / Corporate Governance) are our Corporate Governance Guidelines, Code of Conduct, and Charters for the Committees of the Board of Directors (the Board). Printed documents are available by contacting our Investor Relations Department (Telephone: +1 (212) 827-4445, E-mail: investorrelations@chubb.com).

We also use our website as a means of disclosing material, non-public information and for complying with our disclosure obligations under SEC Regulation FD (Fair Disclosure). Accordingly, investors should monitor the Investor Relations portion of our website, in addition to following our press releases, SEC filings, and public conference calls and webcasts. The information contained on, or that may be accessed through, our website is not incorporated by reference into, and is not a part of, this report. The SEC maintains an Internet site (www.sec.gov) that contains reports, proxy and information statements, and other information regarding issuers that file with the SEC.

Customers

For most commercial and personal lines of business we offer, insureds typically use the services of an insurance broker or agent. An insurance broker acts as an agent for the insureds, offering advice on the types and amount of insurance to purchase, and assists in the negotiation of price and terms and conditions. We obtain business from the local and major international insurance brokers and typically pay a commission to brokers for any business accepted and bound. Loss of all or a substantial portion of the business provided by one or more of these brokers could have a material adverse effect on our business. In our opinion, no material part of our business is dependent upon a single insured or group of insureds. We do not believe that the loss of any one insured would have a material adverse effect on our financial condition or results of operations, and no one insured or group of affiliated insureds account for as much as 10 percent of our total revenues.

Competition

Competition in the insurance and reinsurance marketplace is substantial. We compete on an international and regional basis with major U.S., Bermuda, European, and other international insurers and reinsurers and with underwriting syndicates, some of which have greater financial, technological, marketing, distribution and management resources than we do. In addition, capital market participants have created alternative products that are intended to compete with reinsurance products. We also compete with new companies and existing companies that move into the insurance and reinsurance markets. Competitors include other stock companies, mutual companies, alternative risk sharing groups (such as group captives and catastrophe pools), and other underwriting organizations. Competitors sell through various distribution channels and business models, across a broad array of product lines, and with a high level of variation regarding geographic, marketing, and customer segmentation. We compete for business not only on the basis of price but also on the basis of availability of coverage desired by customers and quality of service.

The insurance industry is changing rapidly. Our ability to compete is dependent on a number of factors, particularly our ability to maintain the appropriate financial strength ratings as assigned by independent rating agencies and effectively utilize new technology in our business. Our broad market capabilities in personal, commercial, specialty, and A&H lines made available by our underwriting expertise, business infrastructure, and global presence, help define our competitive advantage. Our strong balance sheet is attractive to businesses, and our strong capital position and global platform affords us opportunities for growth not available to smaller, less diversified insurance companies. Refer to "Segment Information" for competitive environment by segment.

Trademarks and Trade Names

Various trademarks and trade names we use protect names of certain products and services we offer and are important to the extent they provide goodwill and name recognition in the insurance industry. We use commercially reasonable efforts to protect these proprietary rights, including various trade secret and trademark laws. We intend to retain material trademark rights in perpetuity, so long as it satisfies the use and registration requirements of applicable countries. One or more of the trademarks and trade names could be material to our ability to sell our products and services. We have taken appropriate steps to protect our ownership of key names, and we believe it is unlikely that anyone would be able to prevent us from using names in places or circumstances material to our operations.

Segment Information

Chubb operates through six business segments: North America Commercial P&C Insurance, North America Personal P&C Insurance, North America Agricultural Insurance, Overseas General Insurance, Global Reinsurance, and Life Insurance.

In 2019, consolidated net premiums earned was $31,290 million. Additional financial information about our segments, including net premiums earned by geographic region, is included in Note 15 to the Consolidated Financial Statements.

North America Commercial P&C Insurance (41 percent of 2019 Consolidated NPE)

Overview

The North America Commercial P&C Insurance segment comprises operations that provide P&C insurance and services to large, middle market, and small commercial businesses in the U.S., Canada, and Bermuda. This segment includes:

- Major Accounts, the retail division focused on large institutional organizations and corporate companies
- Commercial Insurance, which includes the retail division focused on middle market customers and small businesses
- Westchester and Chubb Bermuda, our wholesale and specialty divisions

Products and Distribution

Major Accounts provides a broad array of traditional and specialty P&C, A&H, and risk management products and services to large U.S. and Canadian-based institutional organizations and corporate companies. Major Accounts distributes its insurance products primarily through a limited number of retail brokers. In addition to using brokers, certain products are also distributed through general agents, independent agents, managing general agents (MGA), managing general underwriters, alliances, affinity groups, and direct marketing operations. Products and services offered include property, professional liability, cyber risk, excess casualty, workers' compensation, general liability, automobile liability, commercial marine, surety, environmental, construction, medical risk, inland marine, A&H coverages, as well as claims and risk management products and services.

The Major Accounts operations, which represented approximately 40 percent of North America Commercial P&C Insurance's net premiums earned in 2019, are organized into the following distinct business units, each offering specialized products and services targeted at specific markets:

- Chubb Global Casualty offers a range of customized risk management primary casualty products designed to help large insureds, including national accounts, address the significant costs of financing and managing risk for workers' compensation, general liability and automobile liability coverages as well as offering casualty insurance solutions for commercial real estate. Chubb Global Casualty also provides products which insure specific global operating risks of U.S.-based multinational companies and include deductible programs, captive programs, and paid or incurred loss retrospective plans. Within Chubb Global Casualty, Chubb Alternative Risk Solutions Group underwrites contractual indemnification policies which provides prospective coverage for loss events within the insured's policy retention levels and underwrites assumed loss portfolio transfer (LPT) contracts in which insured loss events have occurred prior to the inception of the contract.
- Property provides products and services including primary, quota share and excess all-risk insurance, risk management programs and services, commercial, inland marine, and aerospace products.
- Casualty Risk provides coverages including umbrella and excess liability, environmental risk, casualty programs for commercial construction related projects for companies and institutions, and medical risk specialty liability products for the healthcare industry.
- Surety offers a wide variety of surety products and specializes in underwriting both commercial and contract bonds and has the capacity for bond issuance on an international basis.
- Accident & Health (A&H) products include employee benefit plans, occupational accident, student accident, and worldwide travel accident and global medical programs. With respect to products that include supplemental medical and hospital indemnity coverages, we typically pay fixed amounts for claims and are therefore insulated from rising healthcare costs. A&H also provides specialty personal lines products, including credit card enhancement programs (identity theft, rental car collision damage waiver, trip travel, and purchase protection benefits) distributed through affinity groups.
- Financial Lines provides management liability and professional liability (D&O and E&O), transactional risk and cyber risk products to public companies as well as to private and not for profit organizations.
- ESIS Inc. (ESIS) is an in-house third-party claims administrator that performs claims management and risk control services for domestic and international organizations as well as for the North America Commercial P&C Insurance segment. ESIS services include comprehensive medical managed care; integrated disability services; pre-loss control and risk management; health, safety and environmental consulting; salvage and subrogation; and healthcare recovery services. The net results for ESIS are included in North America Commercial P&C Insurance's administrative expenses.

The Commercial Insurance operations, which include Small Commercial, represented approximately 40 percent of North America Commercial P&C Insurance's net premiums earned in 2019. Commercial Insurance provides a broad range of P&C, financial lines, and A&H products targeted to U.S and Canadian-based middle market customers in a variety of industries, while the Small Commercial operations provide a broad range of property and casualty, workers' compensation, small commercial management and professional liability for small businesses based in the U.S.

- Commercial Insurance products and services offered include traditional property and casualty lines of business, including Package, which combines property and general liability, workers' compensation, automobile, umbrella; financial lines of business, including professional liability, management liability and cyber risk coverage; and other lines including environmental, A&H, and international coverages. Commercial Insurance distributes its insurance products through a North American network of independent retail agents, and regional, multinational and digital brokers. Generally, our customers purchase insurance through a single retail agent or broker, do not employ a risk management department, and do not retain significant risk through self-insured retentions. The majority of our customers purchase a Package product or a portfolio of products, which is a collection of insurance offerings designed to cover various needs.
- Small Commercial Insurance products and services offered include property and casualty lines of business, including a business owner policy which contains property and general liability; financial lines, including professional liability, management liability, cyber risk; and other lines including workers' compensation, automobile liability, and international coverages. Products are generally offered through a North American network of independent agents and brokers, as well as eTraditional, which are digital platforms where we electronically quote, bind, and issue for agents and brokers. An example of this is the Chubb Marketplace.

Wholesale and Specialty, which represented approximately 20 percent of North America Commercial P&C Insurance's net premiums earned in 2019, comprises Westchester and Chubb Bermuda.

- Westchester serves the market for business risks that tend to be hard to place or not easily covered by traditional policies due to unique or complex exposures and provides specialty products for property, casualty, environmental, professional liability, inland marine, product recall, small business, binding and program coverages in the U.S., Canada, and Bermuda. Products are offered through the wholesale distribution channel.
- Chubb Bermuda provides commercial insurance products on an excess basis including excess liability, D&O, professional liability, property, and political risk, the latter being written by Sovereign Risk Insurance Ltd., a wholly-owned managing agent. Chubb Bermuda focuses on Fortune 1000 companies and targets risks that are generally low in frequency and high in severity. Products are offered primarily through the Bermuda offices of major, internationally recognized insurance brokers.

Competitive Environment
Major Accounts competes against a number of large, global carriers as well as regional competitors and other entities offering risk alternatives such as self-insured retentions and captive programs. The markets in which we compete are subject to significant cycles of fluctuating capacity and wide disparities in price adequacy. We pursue a specialist strategy and focus on market opportunities where we can compete effectively based on service levels and product design, while still achieving an adequate level of profitability. We also achieve a competitive advantage through Major Accounts' innovative product offerings and our ability to provide multiple products to a single client due to our nationwide local presence. In addition, all our domestic commercial units are able to deliver global products and coverage to customers in concert with our Overseas General Insurance segment.

The Commercial Insurance operations compete against numerous insurance companies ranging from large national carriers to small and mid-size insurers who provide specialty coverages and standard P&C products. Recent competitive developments include the growth of new digital-based distribution models.

Westchester competes against a number of large, national carriers as well as regional competitors and other entities offering risk alternatives such as self-insured retentions and captive programs. Chubb Bermuda competes against international commercial carriers writing business on an excess of loss basis.

North America Personal P&C Insurance (15 percent of 2019 Consolidated NPE)

Overview
The North America Personal P&C Insurance segment includes the business written by Chubb Personal Risk Services division, which includes high net worth personal lines business, with operations in the U.S. and Canada. This segment provides affluent and high net worth individuals and families with homeowners, automobile and collector cars, valuable articles (including fine arts), personal and excess liability, travel insurance, and recreational marine insurance and services. Our homeowners business, including valuable articles, represented 68 percent of North America Personal P&C Insurance's net premiums earned in 2019.

Products and Distribution
Chubb Personal Risk Services offers comprehensive personal insurance products and services to meet the evolving needs of high net worth families and individuals. Our seamless customer experience and superior coverage protect not only our clients' most valuable possessions, but also their standard of living. Our target customers consist of high net worth consumers with insurance needs that typically extend beyond what mass market carriers can offer. These coverages are offered solely through independent regional agents and brokers.

Competitive Environment
Chubb Personal Risk Services competes against insurance companies of varying sizes that sell personal lines products through various distribution channels, including retail agents as well as online distribution channels. We achieve a competitive advantage through our ability to address the specific needs of high net worth families and individuals, to provide superior service to our customers, and to develop and deploy digital production and processes.

North America Agricultural Insurance (6 percent of 2019 Consolidated NPE)

Overview
The North America Agricultural Insurance segment comprises our U.S. and Canadian-based businesses that provide a variety of coverages including crop insurance, primarily Multiple Peril Crop Insurance (MPCI) and crop-hail insurance through Rain and Hail Insurance Service, Inc. (Rain and Hail) as well as farm and ranch and specialty P&C commercial insurance products and services through our Chubb Agribusiness unit.

Products and Distribution
Rain and Hail provides comprehensive MPCI and crop-hail insurance coverages.

- MPCI is federally subsidized crop protection from numerous causes of loss, including drought, excessive moisture, freeze, disease and more. The MPCI program is offered in conjunction with the U.S. Department of Agriculture. MPCI products include revenue protection (defined as providing both commodity price and yield coverages), yield protection, margin protection, prevented planting coverage and replant coverage. For additional information on our MPCI program, refer to "Crop Insurance" under Item 7.
- Crop-Hail coverage provides crop protection from damage caused by hail and/or fire, with options in some markets for other perils such as wind or theft. Coverage is provided on an acre-by-acre basis and is available in the U.S. and in some parts of Canada. Crop-Hail can be used in conjunction with MPCI or other comprehensive coverages to offset the deductible and provide protection up to the actual cash value of the crop.

Chubb Agribusiness comprises Commercial Agribusiness and Farm and Ranch Agribusiness.

- Commercial Agribusiness offers specialty P&C coverages for commercial companies that manufacture, process and distribute agricultural products. Commercial products and services include property, general liability for premises/operations and product liability, commercial automobile, workers' compensation, employment practices liability coverage, built-in coverage for premises pollution, cyber and information security, and product withdrawal.

- Farm and Ranch Agribusiness offers an extensive line of coverages for farming operations from Hobby/Gentleman farms to complex corporate farms and equine services including personal use, boarding, and training. Coverages include farm and ranch structures, machinery and other equipment, automobile and other vehicle coverages, and livestock.

Competitive Environment
Rain and Hail primarily operates in a federally regulated program where all approved providers offer the same product forms and rates through independent and/or captive agents. We seek a competitive advantage through our ability to provide superior service to our customers, including the development of digital solutions. Chubb Agribusiness competes against both national and regional competitors offering specialty P&C insurance coverages to companies that manufacture, process, and distribute agricultural products.

Overseas General Insurance (28 percent of 2019 Consolidated NPE)

Overview
The Overseas General Insurance segment comprises Chubb International and Chubb Global Markets (CGM). CGM, our London-based international specialty and excess and surplus lines business, includes Lloyd's of London (Lloyd's) Syndicate 2488, a wholly-owned Chubb syndicate supported by funds at Lloyd's provided by Chubb Corporate Members. Syndicate 2488 has an underwriting capacity of £480 million for the Lloyd's 2020 account year. The syndicate is managed by Chubb's Lloyd's managing agency, Chubb Underwriting Agencies Limited.

Products and Distribution
Chubb International maintains a presence in every major insurance market in the world and is organized geographically along product lines as follows: Europe, Asia Pacific and Far East, Eurasia and Africa, and Latin America. Products offered include P&C, A&H, specialty coverages, and personal lines insurance products and services. Chubb International's P&C business is generally written, on both a direct and assumed basis, through major international, regional, and local brokers and agents. Certain European branded products are also offered via an eTraditional digital-commerce platform, Chubb Online, that allows brokers to quote, bind, and issue specialty policies online. Asia Pacific also utilizes similar eTraditional platforms to quote, bind,

and issue policies. Property insurance products include traditional commercial fire coverage as well as energy industry-related, marine, construction, and other technical coverages. Principal casualty products are commercial primary and excess casualty, environmental, and general liability. A&H and other consumer lines products are distributed through brokers, agents, direct marketing programs, including thousands of telemarketers, and sponsor relationships. The A&H operations primarily offer personal accident and supplemental medical coverages including accidental death, business/holiday travel, specified disease, disability, medical and hospital indemnity, and income protection. We are not in the primary healthcare business. With respect to our supplemental medical and hospital indemnity products, we typically pay fixed amounts for claims and are therefore largely insulated from the direct impact of rising healthcare costs. Chubb International specialty coverages include D&O, professional indemnity, energy, aviation, political risk, and specialty personal lines products. Chubb International's personal lines operations provide specialty products and services designed to meet the needs of specific target markets and include property damage, automobile, homeowners, and personal liability.

Chubb International’s presence in China also includes its 30.9 percent ownership interest in Huatai Insurance Group Company Limited (Huatai Group). Huatai Group wholly owns Huatai Property & Casualty Insurance Co., Ltd. (Huatai P&C). Therefore, Chubb owns an approximately 30.9 percent indirect ownership interest in Huatai P&C, which provides a range of commercial and personal P&C products in China, including property, professional liability, product liability, employer liability, business interruption, marine cargo, personal accident and specialty risk. These products are marketed through a variety of distribution channels including over 200 licensed sales locations in 28 Chinese provinces. Chubb is in the process of increasing its ownership interest in Huatai Group.

CGM offers products through its parallel distribution network via two legal entities, Chubb European Group SE (CEG) and Chubb Underwriting Agencies Limited, managing agent of Syndicate 2488. CGM uses the Syndicate to underwrite P&C business on a global basis through Lloyd's worldwide licenses. CGM uses CEG to underwrite similar classes of business through its network of U.K. and European licenses, and in the U.S. where it is eligible to write excess and surplus lines business. Factors influencing the decision to place business with the Syndicate or CEG include licensing eligibilities, capitalization requirements, and client/broker preference. All business underwritten by CGM is accessed through registered brokers. The main lines of business include aviation, property, energy, professional lines, marine, financial lines, political risk, and A&H.

Competitive Environment

Chubb International's primary competitors include U.S.-based companies with global operations, as well as non-U.S. global carriers and indigenous companies in regional and local markets. For the A&H lines of business, locally based competitors also include financial institutions and bank owned insurance subsidiaries. Our international operations have the distinct advantage of being part of one of the few international insurance groups with a global network of licensed companies able to write policies on a locally admitted basis. The principal competitive factors that affect the international operations are underwriting expertise and pricing, relative operating efficiency, product differentiation, producer relations, and the quality of policyholder services. A competitive strength of our international operations is our global network and breadth of insurance programs, which assist individuals and business organizations to meet their risk management objectives, while also having a significant presence in all of the countries in which we operate, giving us the advantage of accessing local technical expertise and regulatory environments, understanding local markets and culture, accomplishing a spread of risk, and offering a global network to service multinational accounts.

CGM is one of the preeminent international specialty insurers in London and is an established lead underwriter on a significant portion of the risks it underwrites for all lines of business. All lines of business face competition, depending on the business class, from Lloyd's syndicates, the London market, and other major international insurers and reinsurers. Competition for international risks is also seen from domestic insurers in the country of origin of the insured. CGM differentiates itself from competitors through long standing experience in its product lines, its multiple insurance entities (Syndicate 2488 and CEG), and the quality of its underwriting and claims service.

Global Reinsurance (2 percent of 2019 Consolidated NPE)

Overview

The Global Reinsurance segment represents Chubb's reinsurance operations comprising Chubb Tempest Re Bermuda, Chubb Tempest Re USA, Chubb Tempest Re International, and Chubb Tempest Re Canada. Global Reinsurance markets reinsurance products worldwide under the Chubb Tempest Re brand name and provides solutions for small to mid-sized clients and multinational ceding companies. Global Re offers a broad array of traditional and non-traditional (e.g., loss portfolio transfer) property and casualty products.

Products and Distribution

Global Reinsurance services clients globally through its major units. Major international brokers submit business to one or more of these units' underwriting teams who have built strong relationships with both key brokers and clients by providing a responsive, client-focused approach to risk assessment and pricing.

Chubb Tempest Re Bermuda principally provides property catastrophe reinsurance globally to insurers of commercial and personal property. Property catastrophe reinsurance is on an occurrence or aggregate basis and protects a ceding company against an accumulation of losses covered by its issued insurance policies, arising from a common event or occurrence. Chubb Tempest Re Bermuda underwrites reinsurance principally on an excess of loss basis, meaning that its exposure only arises after the ceding company's accumulated losses have exceeded the attachment point of the reinsurance policy. Chubb Tempest Re Bermuda also writes other types of reinsurance on a limited basis for selected clients. Chubb Tempest Re Bermuda's business is produced through reinsurance intermediaries.

Chubb Tempest Re USA writes all lines of traditional and specialty P&C reinsurance for the North American market, principally on a treaty basis, with a focus on writing property per risk and casualty reinsurance. Chubb Tempest Re USA underwrites reinsurance on both a proportional and excess of loss basis. This unit's diversified portfolio is produced through reinsurance intermediaries.

Chubb Tempest Re International provides traditional and specialty P&C reinsurance to insurance companies worldwide, with emphasis on non-U.S. and Canadian risks. Chubb Tempest Re International writes all lines of traditional and specialty reinsurance including property risk, property catastrophe, casualty, marine, aviation, and specialty through our London- and Zurich-based offices. The London-based office of Chubb Tempest Re International focuses on the development of business sourced through London market brokers. The Zurich-based office focuses on providing reinsurance to continental European insurers via continental European brokers while also serving Asian and Latin American markets. The London- and Zurich-based offices write a diverse book of international business using Syndicate 2488, CEG, and Chubb Insurance (Switzerland) Limited. Chubb Tempest Re International underwrites reinsurance on both a proportional and excess of loss basis.

Chubb Tempest Re Canada offers a full array of traditional and specialty P&C, and reinsurance to the Canadian market, including casualty, property risk, property catastrophe, surety, and crop hail. Chubb Tempest Re Canada provides coverage through its Canadian company platform and also offers clients access to Syndicate 2488. Chubb Tempest Re Canada underwrites reinsurance on both a proportional and excess of loss basis.

Competitive Environment

The Global Reinsurance segment competes worldwide with major U.S. and non-U.S. reinsurers as well as reinsurance departments of numerous multi-line insurance organizations. In addition, capital markets participants have developed alternative capital sources intended to compete with traditional reinsurance. Additionally, government sponsored or backed catastrophe funds can affect demand for reinsurance. Global Reinsurance is considered a lead reinsurer and is typically involved in the negotiation and quotation of the terms and conditions of the majority of the contracts in which it participates. Global Reinsurance competes effectively in P&C markets worldwide because of its strong capital position, analytical capabilities and quality customer service. The key competitors in our markets vary by geographic region and product line. An advantage of our international platform is that we can change our mix of business in response to changes in competitive conditions in the territories in which we operate. Our geographic reach is also sought by multinational ceding companies since our offices, except for Bermuda, provide local reinsurance license capabilities which benefit our clients in dealing with country regulators.

Life Insurance (8 percent of 2019 Consolidated NPE)

Overview

The Life Insurance segment comprises Chubb's international life operations (Chubb Life), Chubb Tempest Life Re (Chubb Life Re), and the North American supplemental A&H and life business of Combined Insurance.

Products and Distribution

Chubb Life provides individual life and group benefit insurance primarily in Asia, including Hong Kong, Indonesia, South Korea, Taiwan, Thailand, and Vietnam; throughout Latin America; selectively in Europe; Egypt; and in China through a non-consolidated joint venture insurance company. Chubb Life offers a broad portfolio of protection and savings products including whole life, endowment plans, individual term life, group term life, medical and health, personal accident, credit life, universal life, Group Employee benefits, unit linked contracts, and credit protection insurance for automobile, motorcycle and home loans.

The policies written by Chubb Life generally provide funds to beneficiaries of insureds after death and/or protection and/or savings benefits while the contract owner is living. Chubb Life sells to consumers through a variety of distribution channels including captive and independent agencies, bancassurance, worksite marketing, retailers, brokers, telemarketing, mobilassurance, and direct to consumer marketing. We continue to expand Chubb Life with a focus on opportunities in developing markets that we believe will result in strong and sustainable operating profits as well as a favorable return on capital commitments over time. Our dedicated captive agency distribution channel, whereby agents sell Chubb Life products exclusively, enables us to maintain direct contact with the individual consumer, promote quality sales practices, and exercise greater control over the future of the business. We have developed a substantial sales force of agents principally located in our Asia-Pacific countries. As of December 31, 2019, Chubb had a 45 percent direct and indirect ownership interest in Huatai Life Insurance Co., Ltd. (Huatai Life), comprising a 20 percent direct ownership interest as well as a 25 percent indirect ownership interest through Huatai Group, the parent company of Huatai Life. Huatai Life commenced operations in 2005 and has since grown to become one of the larger life insurance foreign joint ventures in China. Huatai Life offers a broad portfolio of insurance products including whole life, universal life, medical and health, personal accident and disability. These products are marketed through a variety of distribution channels including approximately 454 licensed sales locations in 20 Chinese provinces. Chubb is in the process of increasing its ownership interest in Huatai Group.

Chubb Life Re's core business is a Bermuda-based operation which provides reinsurance to primary life insurers, focusing on guarantees included in certain variable annuity products and also on more traditional mortality reinsurance protection. Chubb Life Re's U.S.-based traditional life reinsurance operation was discontinued for new business in January 2010. Since 2007, Chubb Life Re has not quoted on new opportunities in the variable annuity reinsurance marketplace and our focus has been on managing the current portfolio of risk, both in the aggregate and on a contract basis. This business is managed with a long-term perspective and short-term earnings volatility is expected.

Combined Insurance distributes specialty supplemental A&H and life insurance products targeted to middle income consumers and businesses in the U.S. and Canada. Combined Insurance's substantial North American sales force distributes a wide range of supplemental accident and sickness insurance products, including personal accident, short-term disability, critical illness, Medicare supplement products, and hospital confinement/recovery. Most of these products are primarily fixed-indemnity benefit obligations and are not directly subject to escalating medical cost inflation.

Competitive Environment
Chubb Life's competition differs by location but generally includes multinational insurers, and in some locations, local insurers, joint ventures, or state-owned insurers. Chubb's financial strength and reputation as an entrepreneurial organization with a global presence gives Chubb Life a strong base from which to compete. While Chubb Life Re is not currently quoting on new opportunities in the variable annuity reinsurance marketplace, we continue to monitor developments in this market. Combined Insurance competes for A&H business in the U.S. against numerous A&H and life insurance companies across various industry segments.

Corporate

Corporate results primarily include results of all run-off asbestos and environmental (A&E) exposures, the results of our run-off Brandywine business, the results of Westchester specialty operations for 1996 and prior years, certain other run-off exposures, and income and expenses not attributable to reportable segments and the results of our non-insurance companies. The run-off operations do not actively sell insurance products, but are responsible for the management of existing policies and settlement of related claims.

Our exposure to A&E claims principally arises out of liabilities acquired when we purchased Westchester Specialty in 1998, CIGNA's P&C business in 1999, and The Chubb Corporation in 2016. The A&E liabilities principally relate to claims arising from bodily-injury claims related to asbestos products and remediation costs associated with hazardous waste sites.

Underwriting

Chubb is an underwriting company and we strive to emphasize quality of underwriting rather than volume of business or market share. Our underwriting strategy is to manage risk by employing consistent, disciplined pricing and risk selection. This, coupled with writing a number of less cyclical product lines, has helped us develop flexibility and stability of our business, and has allowed us to maintain a profitable book of business throughout market cycles. Clearly defined underwriting authorities, standards, and guidelines coupled with a strong underwriting audit function are in place in each of our local operations and global profit centers. Global product boards ensure consistency of approach and the establishment of best practices throughout the world. Our priority is to help ensure adherence to criteria for risk selection by maintaining high levels of experience and expertise in our underwriting staff. In addition, we employ a business review structure that helps ensure control of risk quality and appropriate use of policy limits and terms and conditions. Underwriting discipline is at the heart of our operating philosophy.

Actuaries in each region work closely with the underwriting teams to provide additional expertise in the underwriting process. We use internal and external data together with sophisticated analytical, catastrophe loss and risk modeling techniques to ensure an appropriate understanding of risk, including diversification and correlation effects, across different product lines and territories. We recognize that climate changes and weather patterns are integral to our underwriting process and we continually adjust our process to address these changes. This is intended to help ensure that losses are contained within our risk tolerance and appetite for individual product lines, businesses, and Chubb as a whole. Our use of such tools and data also reflects an understanding of their inherent limitations and uncertainties.

We also purchase protection from third parties, including, but not limited to, reinsurance as a tool to diversify risk and limit the net loss potential of catastrophes and large or unusually hazardous risks. For additional information refer to "Risk Factors" under Item 1A, “Reinsurance Protection”, below, “Catastrophe Management” and “Natural Catastrophe Property Reinsurance Program”, under Item 7, and Note 5 to the Consolidated Financial Statements, under Item 8.

Reinsurance Protection

As part of our risk management strategy, we purchase reinsurance protection to mitigate our exposure to losses, including certain catastrophes, to a level consistent with our risk appetite. Although reinsurance agreements contractually obligate our reinsurers to reimburse us for an agreed-upon portion of our gross paid losses, reinsurance does not discharge our primary liability to our insureds and, thus, we ultimately remain liable for the gross direct losses. In certain countries, reinsurer selection is limited by local laws or regulations. In most countries there is more freedom of choice, and the counterparty is selected based upon its financial strength, claims settlement record, management, line of business expertise, and its price for assuming the risk transferred. In support of this process, we maintain a Chubb authorized reinsurer list that stratifies these authorized reinsurers by classes of business and acceptable limits. This list is maintained by our Reinsurance Security Committee (RSC), a committee comprising senior management personnel and a dedicated reinsurer security team. Changes to the list are authorized by the RSC and recommended to the Chair of the Risk and Underwriting Committee. The reinsurers on the authorized list and potential new markets are regularly reviewed and the list may be modified following these reviews. In addition to the authorized list, there is a formal exception process that allows authorized reinsurance buyers to use reinsurers already on the authorized list for higher limits or different lines of business, for example, or other reinsurers not on the authorized list if their use is supported by compelling business reasons for a particular reinsurance program.

A separate policy and process exists for captive reinsurance companies. Generally, these reinsurance companies are established by our clients or our clients have an interest in them. It is generally our policy to obtain collateral equal to the expected losses that may be ceded to the captive. Where appropriate, exceptions to the collateral requirement are granted but only after senior management review. Specific collateral guidelines and an exception process are in place for the North America Commercial P&C Insurance, North America Personal P&C Insurance, and Overseas General Insurance segments, all of which have credit management units evaluating the captive's credit quality and that of their parent company. The credit management units, working with actuaries, determine reasonable exposure estimates (collateral calculations), ensure receipt of collateral in an acceptable form, and coordinate collateral adjustments as and when needed. Financial reviews and expected loss evaluations are performed annually for active captive accounts and as needed for run-off exposures. In addition to collateral, parental guarantees are often used to enhance the credit quality of the captive.

In general, we seek to place our reinsurance with highly rated companies with which we have a strong trading relationship. For additional information refer to “Catastrophe Management” and “Natural Catastrophe Property Reinsurance Program” under Item 7, and Note 5 to the Consolidated Financial Statements, under Item 8.

Unpaid Losses and Loss Expenses

We establish reserves for unpaid losses and loss expenses, which are estimates of future payments on reported and unreported claims for losses and related expenses, with respect to insured events that have occurred. These reserves are recorded in Unpaid losses and loss expenses in the Consolidated balance sheets. The process of establishing loss and loss expense reserves for P&C claims can be complex and is subject to considerable uncertainty as it requires the use of informed estimates and judgments based on circumstances known at the date of accrual. These estimates and judgments are based on numerous factors, and may be revised as additional experience and other data become available and are reviewed, as new or improved methodologies are developed, or as laws change. Internal actuaries regularly analyze the levels of loss and loss expense reserves, taking into consideration factors that may impact the ultimate settlement value of the unpaid losses and loss expenses. These analyses could result in future changes in the estimates of loss and loss expense reserves or reinsurance recoverables and any such changes would be reflected in our results of operations in the period in which the estimates are changed. Losses and loss expenses are charged to income as incurred. The reserve for unpaid losses and loss expenses represents the estimated ultimate losses and loss expenses less paid losses and loss expenses, and comprises case reserves and incurred but not reported (IBNR) reserves. With the exception of certain structured settlements, for which the timing and amount of future claim payments are reliably determinable, and certain reserves for unsettled claims, our loss reserves are not discounted for the time value of money. In connection with such structured settlements and certain reserves for unsettled claims, we carried net discounted reserves of $74 million at December 31, 2019.

For each product line, management, after consultation with internal actuaries, develops a “best estimate” of the ultimate settlement value of the unpaid losses and loss expenses that it believes provides a reasonable estimate of the required reserve. We evaluate our estimates of reserves quarterly in light of developing information. While we are unable at this time to determine whether additional reserves may be necessary in the future, we believe that our reserves for unpaid losses and loss expenses are adequate at December 31, 2019. Future additions to reserves, if needed, could have a material adverse effect on our financial condition, results of operations, and cash flows. For additional information refer to “Critical Accounting Estimates – Unpaid losses and loss expenses”, under Item 7, and Note 7 to the Consolidated Financial Statements, under Item 8.

Investments

Our objective is to maximize investment income and total return while ensuring an appropriate level of liquidity, investment quality, and diversification. As such, Chubb's investment portfolio is invested primarily in investment-grade fixed-income securities as measured by the major rating agencies. We do not allow leverage in our investment portfolio.

The critical aspects of the investment process are controlled by Chubb Asset Management, an indirect wholly-owned subsidiary of Chubb. These aspects include asset allocation, portfolio and guideline design, risk management, and oversight of external asset managers. In this regard, Chubb Asset Management:

- conducts formal asset allocation modeling for each of the Chubb subsidiaries, providing formal recommendations for the portfolio's structure;
- establishes recommended investment guidelines that are appropriate to the prescribed asset allocation targets;
- provides the analysis, evaluation, and selection of our external investment advisors;
- establishes and develops investment-related analytics to enhance portfolio engineering and risk control;
- monitors and aggregates the correlated risk of the overall investment portfolio; and
- provides governance over the investment process for each of our operating companies to ensure consistency of approach and adherence to investment guidelines.

Under our guidance and direction, external asset managers conduct security and sector selection and transaction execution. Use of multiple managers benefits Chubb in several ways – it provides us with operational and cost efficiencies, diversity of styles and approaches, innovations in investment research and credit and risk management, all of which enhance the risk adjusted returns of our portfolios.

Chubb Asset Management determines the investment portfolio's allowable, targeted asset allocation and ranges for each of the segments. These asset allocation targets are derived from sophisticated asset and liability modeling that measures correlated histories of returns and volatility of returns. Allowable investment classes are further refined through analysis of our operating environment including expected volatility of cash flows, potential impact on our capital position, and regulatory and rating agency considerations.

The Board has established a Risk & Finance Committee which helps execute the Board's supervisory responsibilities pertaining to enterprise risk management including investment risk. Under the overall supervision of the Risk & Finance Committee, Chubb's governance over investment management is rigorous and ongoing. Among its responsibilities, the Risk & Finance Committee of the Board:

- reviews and approves asset allocation targets and investment policy to ensure that it is consistent with our overall goals, strategies, and objectives;
- reviews and approves investment guidelines to ensure that appropriate levels of portfolio liquidity, credit quality, diversification, and volatility are maintained; and
- systematically reviews the portfolio's exposures including any potential violations of investment guidelines.

We have long-standing global credit limits for our entire portfolio across the organization and for individual obligors. Exposures are aggregated, monitored, and actively managed by our Global Credit Committee, comprising senior executives, including our Chief Financial Officer, our Chief Risk Officer, our Chief Investment Officer, and our Treasurer.

Within the guidelines and asset allocation parameters established by the Risk & Finance Committee, individual investment committees of the segments determine tactical asset allocation. Additionally, these committees review all investment-related activity that affects their operating company, including the selection of outside investment advisors, proposed asset allocation changes, and the systematic review of investment guidelines.

For additional information regarding the investment portfolio, including breakdowns of the sector and maturity distributions, refer to Note 3 to the Consolidated Financial Statements under Item 8.

Regulation

Our insurance and reinsurance subsidiaries conduct business globally, including in all 50 states of the United States and the District of Columbia. Our business is subject to varying degrees of regulation and supervision in each of the jurisdictions in which our insurance and reinsurance subsidiaries are domiciled and on a group basis. The laws and regulations of the jurisdictions in which our insurance and reinsurance subsidiaries are domiciled require among other things that these subsidiaries maintain minimum levels of statutory capital, surplus, and liquidity, meet solvency standards, and submit to periodic examinations of their financial condition. The complex regulatory environments in which Chubb operates are subject to change and are regularly monitored.

Group Supervision

In 2012, the Pennsylvania Insurance Department (Department), in consultation with other insurance regulatory bodies that oversee Chubb's insurance activities, convened the first Chubb Supervisory College (College). Regulators from approximately ten jurisdictions attended the College in Philadelphia, Pennsylvania, during which the supervisors reviewed information on Chubb. The Department, in cooperation with the other supervisory college regulators, published a notice of its determination that it is the appropriate group-wide supervisor for Chubb.

Since 2012, the College has convened bi-annually in-person; and, in July 2017, the College convened its first interim College teleconference, with the most recent teleconference held in September 2019. During these meetings, the College reviewed extensive information about Chubb, without material adverse comment. The next in-person College is scheduled for September 2020 in Philadelphia, Pennsylvania.

The following is an overview of regulations for our operations in Switzerland, the U.S., Bermuda, and other international locations.

Swiss Operations

The Swiss Financial Market Supervisory Authority (FINMA) has the discretion to supervise Chubb on a group-wide basis. However, FINMA acknowledges the Department's assumption of group supervision over us.

In 2008, we formed Chubb Insurance (Switzerland) Limited which offers property and casualty insurance to Swiss companies, A&H insurance for individuals of Swiss Corporations as well as reinsurance predominantly in Continental Europe. We have also formed a reinsurance subsidiary named Chubb Reinsurance (Switzerland) Limited, which we operate as primarily a provider of reinsurance to Chubb entities. Both companies are licensed and governed by FINMA.

U.S. Operations
Our U.S. insurance subsidiaries are subject to extensive regulation and supervision by the states in which they do business. The laws of the various states establish departments of insurance with broad authority to regulate, among other things: the standards of solvency that must be met and maintained, the licensing of insurers and their producers, approval of policy forms and rates, the nature of and limitations on investments, restrictions on the size of the risks which may be insured under a single policy, deposits of securities for the benefit of policyholders, requirements for the acceptability of reinsurers, periodic examinations of the affairs of insurance companies, the form and content of reports of financial condition required to be filed, and the adequacy of reserves for unearned premiums, losses, and other exposures.

Our U.S. insurance subsidiaries are required to file detailed annual and quarterly reports with state insurance regulators. In addition, our U.S. insurance subsidiaries' operations and financial records are subject to examination at regular intervals by state regulators.

All states have enacted legislation that regulates insurance holding companies. This legislation provides that each insurance company in the insurance holding company system (system) is required to register with the insurance department of its state of domicile and furnish information concerning the operations of companies within the system that may materially affect the operations, management, or financial condition of the insurers within the system. We are required to file an annual enterprise risk report with the Department, identifying the material risks within our system that could pose enterprise risk to the insurance subsidiaries in the system. All transactions within a system must be fair and equitable. Notice to the insurance departments is required prior to the consummation of transactions affecting the ownership or control of an insurer and of certain material transactions between an insurer and an entity in its system. In addition, certain transactions may not be consummated without the department's prior approval.

We are also required to file an annual report with the Department, reflecting our internal assessment of material risks associated with our current business plan and the sufficiency of our capital resources to support those risks.

Statutory surplus is an important measure used by the regulators and rating agencies to assess our U.S. insurance subsidiaries' ability to support business operations and provide dividend capacity. Our U.S. insurance subsidiaries are subject to various state statutory and regulatory restrictions that limit the amount of dividends that may be paid without prior approval from regulatory authorities. These restrictions differ by state, but are generally based on calculations incorporating statutory surplus, statutory net income, and/or investment income.

The National Association of Insurance Commissioners (NAIC) has a risk-based capital requirement for P&C insurance companies. This risk-based capital formula is used by many state regulatory authorities to identify insurance companies that may be undercapitalized and which merit further regulatory attention. These requirements are designed to monitor capital adequacy using a formula that prescribes a series of risk measurements to determine a minimum capital amount for an insurance company, based on the profile of the individual company. The ratio of a company's actual policyholder surplus to its minimum capital requirement will determine whether any state regulatory action is required. There are progressive risk-based capital failure levels that trigger more stringent regulatory action. If an insurer's policyholders' surplus falls below the Mandatory Control Level (70 percent of the Authorized Control Level, as defined by the NAIC), the relevant insurance commissioner is required to place the insurer under regulatory control.

However, an insurance regulator may allow a P&C company operating below the Mandatory Control Level that is writing no business and is running off its existing business to continue its run-off. Brandywine is running off its liabilities consistent with the terms of an order issued by the Insurance Commissioner of Pennsylvania. This includes periodic reporting obligations to the Department.

Government intervention continued in the insurance and reinsurance markets in relation to terrorism coverage in the U.S. (and through industry initiatives in other countries). The U.S. Terrorism Risk Insurance Act (TRIA), which was enacted in 2002 to ensure the availability of insurance coverage for certain types of terrorist acts in the U.S., was extended in December 2019 through December 31, 2027, and applies to certain of our operations.

From time to time, Chubb and its subsidiaries and affiliates receive inquiries from state agencies and attorneys general, with which we generally comply, seeking information concerning business practices, such as underwriting and non-traditional or loss mitigation insurance products. Moreover, many recent factors, such as consequences of and reactions to industry and economic conditions and focus on domestic issues, have contributed to the potential for change in the legal and regulatory framework applicable to Chubb's U.S. operations and businesses. We cannot assure that changes in laws or investigative or enforcement activities in the various states in the U.S. will not have a material adverse impact on our financial condition, results of operations, or business practices.

We are subject to numerous U.S. federal and state laws governing the protection of personal and confidential information of our clients or employees. These laws and regulations are increasing in complexity, and the requirements are extensive and detailed. Numerous states require us to certify our compliance with their data protection laws.

We are subject to the New York Department of Financial Services' Cybersecurity Regulation (the NYDFS Cybersecurity Regulation) which mandates detailed cybersecurity standards for all institutions, including insurance entities, authorized by the NYDFS to operate in New York. Among the requirements are the maintenance of a cybersecurity program with governance controls, risk-based minimum data security standards for technology systems, cyber breach preparedness and response requirements, including reporting obligations, vendor oversight, training, and program record keeping and certification obligations. Because our North America systems are integrated, our companies domiciled in other states may also be impacted by this requirement.

Additionally, the NAIC adopted an Insurance Data Security Model Law, which require licensed insurance entities to comply with detailed information security requirements. The NAIC model law is similar in many respects to the NYDFS Cybersecurity Regulation.

Bermuda Operations
The Insurance Act 1978 of Bermuda and related regulations, as amended (the Insurance Act), regulates the insurance business of our Bermuda domiciled (re)insurance subsidiaries (Bermuda domiciled subsidiaries) and provides that no person may carry on any insurance business in or from within Bermuda unless registered as an insurer by the Bermuda Monetary Authority (BMA). The Insurance Act imposes solvency and liquidity standards and auditing and reporting requirements on Bermuda insurance companies and grants the BMA powers to supervise, investigate, and intervene in the affairs of insurance companies.

Bermuda domiciled subsidiaries must prepare and file with the BMA, audited annual statutory financial statements and audited annual financial statements prepared in accordance with accounting principles generally accepted in the U.S. (GAAP), International Financial Reporting Standards (IFRS), or any such other generally accepted accounting principles as the BMA may recognize. These audited financial statements are made public by the BMA. The Insurance Act prescribes rules for the preparation and content of the statutory financial statements that require Bermuda domiciled subsidiaries to give detailed information and analyses regarding premiums, claims, reinsurance, and investments. In addition, the Bermuda domiciled subsidiaries are required to prepare and publish a Financial Condition Report (FCR). The FCR provides details of measures governing the business operations, corporate governance framework, solvency and financial performance. The FCR must be filed with the BMA and requires Bermuda insurance companies to make the FCR publicly available.

Bermuda's regulatory regime provides a risk-based capital model, termed the Bermuda Solvency Capital Requirement (BSCR), as a tool to assist the BMA both in measuring risk and in determining appropriate levels of capitalization. The BSCR employs a standard mathematical model that correlates the risk underwritten by Bermuda insurers to their capital. The BSCR framework applies a standard measurement format to the risk associated with an insurer's assets, liabilities, and premiums, including a formula to take into account catastrophe risk exposure.

The BMA established risk-based regulatory capital adequacy and solvency margin requirements for Bermuda insurers that mandate that a Bermuda domiciled subsidiary's Enhanced Capital Requirement (ECR) be calculated by either (a) BSCR, or (b) an internal capital model which the BMA has approved for use for this purpose. The Bermuda domiciled subsidiaries use the BSCR in calculating their solvency requirements. Bermuda statutory reporting rules include an Economic Balance Sheet (EBS) framework. The EBS framework is embedded as part of the BSCR and forms the basis of our ECR.

In order to minimize the risk of a shortfall in capital arising from an unexpected adverse deviation and in moving towards the implementation of a risk based capital approach, the BMA has established a threshold capital level, (termed the Target Capital Level (TCL)), set at 120 percent of ECR, that serves as an early warning tool for the BMA. Failure to maintain statutory capital at least equal to the TCL would likely result in increased BMA regulatory oversight.

Under the Insurance Act, Chubb's Bermuda domiciled subsidiaries are prohibited from declaring or paying any dividends of more than 25 percent of total statutory capital and surplus, as shown in its previous financial year unconsolidated statutory balance sheet, unless at least seven days before payment of the dividends, it files with the BMA an affidavit that it will continue to meet its required solvency margins. Furthermore, Bermuda domiciled subsidiaries may only declare and pay a dividend from retained earnings and a dividend or distribution from contributed surplus if it has no reasonable grounds for believing that it is, or would after the payment be, unable to pay its liabilities as they become due, or if the realizable value of its assets would be less than the aggregate of its liabilities and its issued share capital and share premium accounts.

In addition, Chubb's Bermuda domiciled subsidiaries must obtain the BMA's prior approval before reducing total statutory capital, as shown in its previous financial year statutory balance sheet, by 15 percent or more.

Other International Operations
The extent of insurance regulation varies significantly among the countries in which non-U.S. Chubb operations conduct business. While each country imposes licensing, solvency, auditing, and financial reporting requirements, the type and extent of the requirements differ substantially. For example:

- in some countries, insurers are required to prepare and file monthly and/or quarterly financial reports, and in others, only annual reports;
- some regulators require intermediaries to be involved in the sale of insurance products, whereas other regulators permit direct sales contact between the insurer and the customer;
- the extent of restrictions imposed upon an insurer's use of local and offshore reinsurance vary;
- policy form filing and rate regulation vary by country;
- the frequency of contact and periodic on-site examinations by insurance authorities differ by country; and
- regulatory requirements relating to insurer dividend policies vary by country.

Significant variations can also be found in the size, structure, and resources of the local regulatory departments that oversee insurance activities. Certain regulators prefer close relationships with all subject insurers and others operate a risk-based approach.

Chubb operates in some countries through subsidiaries and in some countries through branches of subsidiaries. Local capital requirements applicable to a subsidiary generally include its branches. Certain Chubb companies are jointly owned with local companies to comply with legal requirements for local ownership. Other legal requirements include discretionary licensing procedures, compulsory cessions of reinsurance, local retention of funds and records, data privacy and protection program requirements, and foreign exchange controls. Chubb's international companies are also subject to multinational application of certain U.S. laws.

There are various regulatory bodies and initiatives that impact Chubb in multiple international jurisdictions and the potential for significant impact on Chubb could be heightened as a result of recent industry and economic developments.

In 2016, the United Kingdom (UK) voted in a national referendum to withdraw from the EU. In anticipation of the UK leaving the EU, effective January 1, 2019, we redomiciled the headquarters of our European carriers to Paris, France, which is also the principal office for our Continental European operations. Chubb continues to have a substantial presence in London in addition to its offices and operations across the UK and EU.

In 2018, the EU’s General Data Protection Regulation (GDPR) came into effect. The GDPR is a privacy regulation with protection for the personal data of EU residents on a global basis.

Enterprise Risk Management
As an insurer, Chubb is in the business of profitably managing risk for its customers. Since risk management must permeate an organization conducting a global insurance business, we have an established Enterprise Risk Management (ERM) framework that is integrated into management of our businesses and is led by Chubb's senior management. As a result, ERM is a part of the day-to-day management of Chubb and its operations.

Our global ERM framework is broadly multi-disciplinary and its strategic objectives include:

- **External Risks**: identify, analyze, quantify, and where possible, mitigate significant external risks that could materially hamper the financial condition of Chubb and/or the achievement of corporate business objectives over the next 36 months;

- **Exposure Accumulations**: identify and quantify the accumulation of exposure to individual counterparties, products or industry sectors, particularly those that materially extend across or correlate between business units or divisions and/or the balance sheet;
- **Risk Modeling**: develop and use various data-sets, analytical tools, metrics and processes (including economic capital models and advanced analytics, including catastrophe models to quantify natural catastrophe risk for product pricing, risk management, capital allocation and to simulate and estimate hurricane losses) that help business and corporate leaders make informed underwriting, portfolio management and risk management decisions within a consistent risk/reward framework;
- **Governance**:
  - establish and coordinate risk guidelines that reflect the corporate appetite for risk;
  - monitor exposure accumulations relative to established guidelines; and
  - ensure effective internal risk management communication up to management and the Board, (including our Risk & Finance Committee and our Nominating & Governance Committee), down to the various business units and legal entities, and across the firm; and
- **Disclosure**: develop protocols and processes for risk-related disclosure internally as well as externally to rating agencies, regulators, shareholders and analysts.

Chubb Group's Risk and Underwriting Committee (RUC) reports to and assists the Chief Executive Officer in the oversight and review of the ERM framework which covers the processes and guidelines used to manage insurance risk, financial risk, strategic risk, and operational risk. The RUC is chaired by Chubb Group's Chief Risk Officer. The RUC meets at least monthly, and is comprised of Chubb Group's most senior executives, in addition to the Chair, including the Chief Executive Officer, Chief Operating Officer, Chief Financial Officer, Chief Investment Officer, Chief Actuary, Chief Claims Officer, General Counsel, President – North America Commercial and Personal Insurance, President – North America Major Accounts and Specialty Insurance, President – Overseas General Insurance, and Chief Underwriting Officer.

The RUC is assisted in its activities by Chubb's Enterprise Risk Unit (ERU) and Product Boards. The ERU is responsible for the collation and analysis of risk insight in two key areas. First, external information that provides insight to the RUC on existing or emerging risks that might significantly impact Chubb's key objectives and second, internal risk aggregations arising from Chubb's business writings and other activities such as investments and operations. The ERU is independent of the operating units and reports to our Chief Risk Officer. The Product Boards exist to provide oversight for products that we offer globally. A Product Board currently exists for each of Chubb's major product areas. Each Product Board is responsible for ensuring consistency in underwriting and pricing standards, identification of emerging issues, and guidelines for relevant accumulations.

Chubb's Chief Risk Officer also reports to the Board's Risk & Finance Committee, which helps execute the Board's supervisory responsibilities pertaining to ERM. The role of the Risk & Finance Committee includes evaluation of the integrity and effectiveness of our ERM procedures, systems, and information; governance on major policy decisions pertaining to risk aggregation and minimization; and assessment of our major decisions and preparedness levels pertaining to perceived material risks. The Audit Committee meets annually and on an as-needed basis with the Risk & Finance Committee in order to exercise its duties under New York Stock Exchange Rules.

Others within the ERM structure contribute toward accomplishing Chubb's ERM objectives, including regional management, Corporate Underwriting, Internal Audit, Compliance, external consultants, and managers of our internal control processes and procedures.

Tax Matters

Refer to "Risk Factors", under Item 1A and Note 1 o) and Note 8 to the Consolidated Financial Statements, under Item 8.

Information about our Executive Officers

Name	Age	Position
Evan G. Greenberg	65	Chairman, President, Chief Executive Officer, and Director
John W. Keogh	55	Executive Vice Chairman and Chief Operating Officer
Philip V. Bancroft	60	Executive Vice President and Chief Financial Officer
John J. Lupica	54	Vice Chairman; President, North America Major Accounts & Specialty Insurance
Joseph F. Wayland	62	Executive Vice President and General Counsel
Sean Ringsted	57	Executive Vice President, Chief Digital Officer, and Chief Risk Officer
Timothy A. Boroughs	70	Executive Vice President and Chief Investment Officer
Paul J. Krump	60	Executive Vice President; President, North America Commercial and Personal Insurance
Juan Luis Ortega	45	Executive Vice President; President, Overseas General Insurance

Evan G. Greenberg has been a director of Chubb Limited since August 2002. Mr. Greenberg was elected Chairman of the Board of Directors in May 2007. Mr. Greenberg was a director of The Coca-Cola Company from February 2011 until his resignation in October 2016. Mr. Greenberg was appointed to the position of President and Chief Executive Officer of Chubb Limited in May 2004, and in June 2003, was appointed President and Chief Operating Officer of Chubb Limited. Mr. Greenberg was appointed to the position of Chief Executive Officer of Chubb Overseas General in April 2002. He joined Chubb as Vice Chairman, Chubb Limited, and Chief Executive Officer of Chubb Tempest Re in November 2001. Prior to joining Chubb, Mr. Greenberg was most recently President and Chief Operating Officer of American International Group (AIG), a position he held from 1997 until 2000.

John W. Keogh was appointed Executive Vice Chairman of Chubb Limited in November 2015. Mr. Keogh has served as Chief Operating Officer of Chubb Limited since July 2011 and Vice Chairman of Chubb Limited and Chubb Group Holdings since August 2010. Mr. Keogh joined Chubb as Chief Executive Officer of Overseas General Insurance in April 2006 and became Chairman of Overseas General Insurance in August 2010. Prior to joining Chubb, Mr. Keogh served as Senior Vice President, Domestic General Insurance of AIG, and President and Chief Executive Officer of National Union Fire Insurance Company, AIG's member company that specializes in D&O and fiduciary liability coverages. Mr. Keogh joined AIG in 1986. He served in a number of other senior positions there including as Executive Vice President of AIG's Domestic Brokerage Group and as President and Chief Operating Officer of AIG's Lexington Insurance Company unit.

Philip V. Bancroft was appointed Chief Financial Officer of Chubb Limited in January 2002. For nearly 20 years, Mr. Bancroft worked for PricewaterhouseCoopers LLP. Prior to joining Chubb, he served as partner-in-charge of the New York Regional Insurance Practice. Mr. Bancroft had been a partner with PricewaterhouseCoopers LLP for ten years.

John J. Lupica was appointed President, North America Major Accounts & Specialty Insurance in January 2016, Vice Chairman of Chubb Limited and Chubb Group Holdings in November 2013 and Chairman, Insurance - North America, in July 2011. Mr. Lupica had been Chief Operating Officer, Insurance - North America, since 2010 and President of ACE USA since 2006. He also previously served as Division President of U.S. Professional Risk business and U.S. Regional Operations. Mr. Lupica joined Chubb as Executive Vice President of Professional Risk in 2000. Prior to joining Chubb, he served as Senior Vice President for Munich-American Risk Partners, Inc. He also held various management positions at AIG.

Joseph F. Wayland was appointed Executive Vice President of Chubb Limited in January 2016, General Counsel and Secretary of Chubb Limited in July 2013. Mr. Wayland joined Chubb from the law firm of Simpson Thacher & Bartlett LLP, where he was a partner since 1994. From 2010 to 2012, he served in the United States Department of Justice, first as Deputy Assistant Attorney General of the Antitrust Division, and was later appointed as the Acting Assistant Attorney General in charge of that division.

Sean Ringsted was appointed Executive Vice President and Chief Digital Officer in February 2017 and Chief Risk Officer in November 2008. Mr. Ringsted previously served as Chief Actuary of Chubb Limited from November 2008 to January 2017. Mr. Ringsted's previous roles at Chubb also include Chief Actuary for Chubb Group from 2004 to 2008, Executive Vice President and Chief Risk Officer for Chubb Tempest Re from 2002 to 2004, and Senior Vice President and Chief Actuary for Chubb Tempest Re from 1998 to 2002. Prior to joining Chubb, Mr. Ringsted was a consultant at Tillinghast-Towers Perrin.

Timothy A. Boroughs was appointed Executive Vice President and Chief Investment Officer of Chubb Group in June 2000. Prior to joining Chubb, Mr. Boroughs was Director of Fixed Income at Tudor Investment Corporation from 1997 to 2000, and Managing Partner and Director of Global Leveraged Investment Activity at Fischer Francis Trees & Watts from 1976 to 1997.

Paul J. Krump was appointed Executive Vice President, Chubb Group and President North America Commercial and Personal Insurance in January 2016. Prior to Chubb Limited's January 2016 acquisition of The Chubb Corporation, Mr. Krump was Chief Operating Officer of The Chubb Corporation, responsible for the company's Commercial, Specialty, Personal and Accident & Health insurance lines; Claims; Global Field Operations; Information Technology; Human Resources; Communications; and External Affairs. Mr. Krump joined The Chubb Corporation in 1982 as a commercial underwriting trainee in the Minneapolis office. He held numerous headquarters and field positions in the United States and Europe, including President of Personal Lines and Claims and President of Commercial and Specialty Lines.

Juan Luis Ortega was appointed Executive Vice President, Chubb Group and President, Overseas General Insurance in August 2019. Mr. Ortega previously served as Senior Vice President, Chubb Group and Regional President of Latin America since 2016 and Regional President of Asia Pacific from 2013 to 2016. Mr. Ortega's previous roles at Chubb also include Senior Vice President, Accident & Health, for the Asia Pacific region from 2011 to 2013 and Senior Vice President and Regional Head of Accident & Health for the Latin America region from 2008 to 2010. Mr. Ortega joined Chubb in 1999 and advanced through a series of accident and health and credit insurance management positions in Miami, Puerto Rico and Mexico, before being named Country President of Chile in 2005.

ITEM 1A. Risk Factors

Factors that could have a material impact on our results of operations or financial condition are outlined below. Additional risks not presently known to us or that we currently deem insignificant may also impair our business or results of operations as they become known or as facts and circumstances change. Any of the risks described below could result in a material adverse effect on our results of operations or financial condition.

Insurance

Our results of operations or financial condition could be adversely affected by the occurrence of natural and man-made disasters.

We have substantial exposure to losses resulting from natural disasters, man-made catastrophes such as terrorism or cyber-attack, and other catastrophic events, including pandemics. This could impact a variety of our businesses, including our commercial and personal lines, and life and accident and health (A&H) products. Catastrophes can be caused by various events, including hurricanes, typhoons, earthquakes, hailstorms, droughts, explosions, severe winter weather, fires, war, acts of terrorism, nuclear accidents, political instability, and other natural or man-made disasters, including a global or other wide-impact pandemic or a significant cyber-attack. The incidence and severity of catastrophes are inherently unpredictable and our losses from catastrophes could be substantial. In addition, climate change and resulting changes in global temperatures, weather patterns, and sea levels may both increase the frequency and severity of natural catastrophes and the resulting losses in the future and impact our risk modeling assumptions. We cannot predict the impact that changing climate conditions, if any, may have on our results of operations or our financial condition. Additionally, we cannot predict how legal, regulatory and/or social responses to concerns around global climate change may impact our business. The occurrence of claims from catastrophic events could result in substantial volatility in our results of operations or financial condition for any fiscal quarter or year. Although we attempt to manage our exposure to such events through the use of underwriting controls, risk models, and the purchase of third-party reinsurance, catastrophic events are inherently unpredictable and the actual nature of such events when they occur could be more frequent or severe than contemplated in our pricing and risk management expectations. As a result, the occurrence of one or more catastrophic events could have an adverse effect on our results of operations and financial condition.

If actual claims exceed our loss reserves, our financial results could be adversely affected.

Our results of operations and financial condition depend upon our ability to accurately assess the potential losses associated with the risks that we insure and reinsure. We establish reserves for unpaid losses and loss expenses, which are estimates of future payments of reported and unreported claims for losses and related expenses, with respect to insured events that have occurred at or prior to the balance sheet date. The process of establishing reserves can be highly complex and is subject to considerable variability as it requires the use of informed estimates and judgments.

Actuarial staff in each of our segments regularly evaluates the levels of loss reserves. Any such evaluation could result in future changes in estimates of losses or reinsurance recoverables and would be reflected in our results of operations in the period in which the estimates are changed. Losses and loss expenses are charged to income as incurred. During the loss settlement period, which can be many years in duration for some of our lines of business, additional facts regarding individual claims and trends often will become known which may result in a change in overall reserves. In addition, application of statistical and actuarial methods may require the adjustment of overall reserves upward or downward from time to time.

Included in our loss reserves are liabilities for latent claims such as asbestos and environmental (A&E), which are principally related to claims arising from remediation costs associated with hazardous waste sites and bodily-injury claims related to exposure to asbestos products and environmental hazards. At December 31, 2019, gross A&E liabilities represented approximately 3.2 percent of our gross loss reserves. The estimation of these liabilities is subject to many complex variables including: the current legal environment; specific settlements that may be used as precedents to settle future claims; assumptions regarding trends with respect to claim severity and the frequency of higher severity claims; assumptions regarding the ability to allocate liability among defendants (including bankruptcy trusts) and other insurers; the ability of a claimant to bring a claim in a state in which it has no residency or exposure; the ability of a policyholder to claim the right to non-products coverage; whether high-level excess policies have the potential to be accessed given the policyholder's claim trends and liability situation; payments to unimpaired claimants; and the potential liability of peripheral defendants. Accordingly, the ultimate settlement of losses, arising from either latent or non-latent causes, may be significantly greater or less than the loss and loss expense reserves held at the balance sheet date. In addition, the amount and timing of the settlement of our P&C liabilities are uncertain and our actual payments could be higher than contemplated in our loss reserves owing to the impact of insurance, judicial decisions, and/or social inflation. If our loss reserves are determined to be inadequate, we may be required to increase loss reserves at the time of the determination and our net income and capital may be reduced.

The effects of emerging claim and coverage issues on our business are uncertain.
As industry practices and legislative, regulatory, judicial, social, financial, technological and other environmental conditions change, unexpected and unintended issues related to claims and coverage may emerge. These issues may adversely affect our business by either extending coverage beyond our underwriting intent or by increasing the frequency and severity of claims. In some instances, these changes may not become apparent until after we have issued insurance or reinsurance contracts that are affected by the changes. For example, recently enacted "reviver" legislation in certain states does allow civil claims relating to molestation and abuse to be asserted against policyholders that would otherwise be barred by statutes of limitations. As a result, the full extent of liability under our insurance or reinsurance contracts may not be known for many years after issuance.

The failure of any of the loss limitation methods we use could have an adverse effect on our results of operations and financial condition.
We seek to manage our loss exposure by maintaining a disciplined underwriting process throughout our insurance operations. We also look to limit our loss exposure by writing a number of our insurance and reinsurance contracts on an excess of loss basis. Excess of loss insurance and reinsurance indemnifies the insured against losses in excess of a specified amount. In addition, we limit program size for each client and purchase third-party reinsurance for our own account. In the case of our assumed proportional reinsurance treaties, we seek per occurrence limitations or loss and loss expense ratio caps to limit the impact of losses ceded by the client. In proportional reinsurance, the reinsurer shares a proportional part of the premiums and losses of the reinsured. We also seek to limit our loss exposure by geographic diversification. Geographic zone limitations involve significant underwriting judgments, including the determination of the area of the zones and the inclusion of a particular policy within a particular zone's limits.

However, there are inherent limitations in all of these tactics and no assurance can be given against the possibility of an event or series of events that could result in loss levels that could have an adverse effect on our financial condition or results of operations. It is also possible that losses could manifest themselves in ways that we do not anticipate and that our risk mitigation strategies are not designed to address. Additionally, various provisions of our policies, such as limitations or exclusions from coverage or choice of forum negotiated to limit our risks, may not be enforceable in the manner we intend. As a result, one or more natural catastrophes and/or terrorism or other events could result in claims that substantially exceed our expectations, which could have an adverse effect on our results of operations and financial condition.

We may be unable to purchase reinsurance, and/or if we successfully purchase reinsurance, we are subject to the possibility of non-payment.
We purchase protection from third parties including, but not limited to, reinsurance to protect against catastrophes and other sources of volatility, to increase the amount of protection we can provide our clients, and as part of our overall risk management strategy. Our reinsurance business also purchases retrocessional protection which allows a reinsurer to cede to another company all or part of the reinsurance originally assumed by the reinsurer. A reinsurer's or retrocessionaire's insolvency or inability or unwillingness to make timely payments under the terms of its reinsurance agreement with us could have an adverse effect on us because we remain liable to the insured. From time to time, market conditions have limited, and in some cases have prevented, insurers and reinsurers from obtaining the types and amounts of reinsurance or retrocessional reinsurance that they consider adequate for their business needs.

There is no guarantee our desired amounts of reinsurance or retrocessional reinsurance will be available in the marketplace in the future. In addition to capacity risk, the remaining capacity may not be on terms we deem appropriate or acceptable or with companies with whom we want to do business. Finally, we face some degree of counterparty risk whenever we purchase reinsurance or retrocessional reinsurance. Consequently, the insolvency of these counterparties, or the inability, or unwillingness of any of our present or future reinsurers to make timely payments to us under the terms of our reinsurance or retrocessional agreements could have an adverse effect on us. At December 31, 2019, we had $15.4 billion of reinsurance recoverables, net of reserves for uncollectible recoverables.

Certain active Chubb companies are primarily liable for A&E and other exposures they have reinsured to our inactive run-off company Century Indemnity Company (Century). At December 31, 2019, the aggregate reinsurance balances ceded by our active subsidiaries to Century were approximately $1.5 billion. Should Century's loss reserves experience adverse development in the future and should Century be placed into rehabilitation or liquidation, the reinsurance recoverables due from Century to its affiliates would be payable only after the payment in full of third-party expenses and liabilities, including administrative expenses and direct policy liabilities. Thus, the intercompany reinsurance recoverables would be at risk to the extent of the shortage of assets remaining to pay these recoverables. While we believe the intercompany reinsurance recoverables from Century are not impaired at this time, we cannot assure that adverse development with respect to Century's loss reserves, if manifested, will not result in Century's insolvency, which could result in our recognizing a loss to the extent of any uncollectible reinsurance from Century. This could have an adverse effect on our results of operations and financial condition.

Our net income may be volatile because certain products sold by our Life Insurance business expose us to reserve and fair value liability changes that are directly affected by market and other factors and assumptions.
Our pricing, establishment of reserves for future policy benefits and valuation of life insurance and annuity products, including reinsurance programs, are based upon various assumptions, including but not limited to equity market changes, interest rates, mortality rates, morbidity rates, and policyholder behavior. The process of establishing reserves for future policy benefits relies on our ability to accurately estimate insured events that have not yet occurred but that are expected to occur in future periods. Significant deviations in actual experience from assumptions used for pricing and for reserves for future policy benefits could have an adverse effect on the profitability of our products and our business.

Under reinsurance programs covering variable annuity guarantees, we assumed the risk of guaranteed minimum death benefits (GMDB) and guaranteed living benefits (GLB), principally guaranteed minimum income benefits (GMIB), associated with variable annuity contracts. We ceased writing this business in 2007. Our net income is directly impacted by changes in the reserves calculated in connection with the reinsurance of GMDB and GLB liabilities. In addition, our net income is directly impacted by the change in the fair value of the GLB liability. Reported liabilities for both GMDB and GLB reinsurance are determined using internal valuation models which require considerable judgment and are subject to significant uncertainty. Refer to the “Critical Accounting Estimates – Guaranteed living benefits (GLB) derivatives” under Item 7 and “Quantitative and Qualitative Disclosures about Market Risk – Reinsurance of GMDB and GLB guarantees” under Item 7A for additional information on the assumptions used in this program. We view our variable annuity reinsurance business as having a similar risk profile to that of catastrophe reinsurance, with the probability of long-term economic loss relatively small at the time of pricing. Adverse changes in market factors and policyholder behavior will have an impact on both Life Insurance underwriting income and consolidated net income.

Payment of obligations under surety bonds could have an adverse effect on our results of operations.
The surety business tends to be characterized by infrequent but potentially high severity losses. The majority of our surety obligations are intended to be performance-based guarantees. When losses occur, they may be mitigated, at times, by recovery rights to the customer’s assets, contract payments, and collateral and bankruptcy recoveries. We have substantial commercial and construction surety exposure for current and prior customers. In that regard, we have exposures related to surety bonds issued on behalf of companies that have experienced or may experience deterioration in creditworthiness. If the financial condition of these companies were adversely affected by the economy or otherwise, we may experience an increase in filed claims and may incur high severity losses, which could have an adverse effect on our results of operations.

Our exposure to various commercial and contractual counterparties, our reliance on brokers, and certain of our policies may subject us to credit risk.
We have exposure to counterparties through a variety of commercial transactions and arrangements, including reinsurance transactions; agreements with banks, hedge funds and other investment vehicles; and derivative transactions, that expose us to credit risk in the event our counterparty fails to perform its obligations. This includes exposure to financial institutions in the form of secured and unsecured debt instruments and equity securities. Moreover, we paid deposits in connection with our pending acquisition of additional shares of Huatai Insurance Group Company Limited (Huatai Group), which exposes us to risk if the transactions are not completed.

In accordance with industry practice, we generally pay amounts owed on claims to brokers who, in turn, remit these amounts to the insured or ceding insurer. Although the law is unsettled and depends upon the facts and circumstances of the particular case, in some jurisdictions, if a broker fails to make such a payment, we might remain liable to the insured or ceding insurer for the deficiency. Conversely, in certain jurisdictions, if a broker does not remit premiums paid for these policies over to us, these premiums might be considered to have been paid and the insured or ceding insurer will no longer be liable to us for those amounts, whether or not we have actually received the premiums from the broker. Consequently, we assume a degree of credit risk associated with a broker with whom we transact business. However, due to the unsettled and fact-specific nature of the law, we are unable to quantify our exposure to this risk. To date, we have not experienced any material losses related to this credit risk.

Under the terms of certain high-deductible policies which we offer, such as workers’ compensation and general liability, our customers are responsible to reimburse us for an agreed-upon dollar amount per claim. In nearly all cases we are required under such policies to pay covered claims first, and then seek reimbursement for amounts within the applicable deductible from our customers. This obligation subjects us to credit risk from these customers. While we generally seek to mitigate this risk through collateral agreements and maintain a provision for uncollectible accounts associated with this credit exposure, an increased inability of customers to reimburse us in this context could have an adverse effect on our financial condition and results of operations. In addition, a lack of credit available to our customers could impact our ability to collateralize this risk to our satisfaction, which in turn, could reduce the amount of high-deductible policies we could offer.

Since we depend on a few distribution and bancassurance partners for a large portion of our revenues, loss of business provided by any one of them could adversely affect us.
We market our insurance and reinsurance worldwide primarily through independent insurance agents, insurance and reinsurance brokers, and bancassurance relationships. Accordingly, our business is dependent on the willingness of these agents and brokers to recommend our products to their customers, who may also promote and distribute the products of our competitors. Deterioration in relationships with our agent and broker distribution network or their increased promotion and distribution of our competitors' products could adversely affect our ability to sell our products. Loss of all or a substantial portion of the business provided by one or more of these agents and brokers could have an adverse effect on our business.

Financial

Our investment performance may affect our financial results and our ability to conduct business.
Our investment assets are invested by professional investment management firms under the direction of our management team in accordance with investment guidelines approved by the Risk & Finance Committee of the Board of Directors. Although our investment guidelines stress diversification of risks and conservation of principal and liquidity, our investments are subject to market risks and risks inherent in individual securities. Interest rates are highly sensitive to many factors, including inflation, monetary and fiscal policies, and domestic and international political conditions. Given the risk that London Interbank Offered Rate (LIBOR) will no longer be available, we are monitoring industry efforts via our external investment managers to transition away from LIBOR by the end of 2021. The volatility of our losses may force us to liquidate securities, which may cause us to incur capital losses. Realized and unrealized losses in our investment portfolio would reduce our book value, and if significant, can affect our ability to conduct business.

Volatility in interest rates could impact the performance of our investment portfolio which could have an adverse effect on our investment income and operating results. Although we take measures to manage the risks of investing in a changing interest rate environment, we may not be able to effectively mitigate interest rate sensitivity. Our mitigation efforts include maintaining a high quality portfolio of primarily fixed income investments with a relatively short duration to reduce the effect of interest rate changes on book value. A significant increase in interest rates would generally have an adverse effect on our book value. Our life insurance investments typically focus on longer duration bonds to better match the obligations of this business. For the life insurance business, policyholder behavior may be influenced by changing interest rate conditions and require a re-balancing of duration to effectively manage our asset/liability position.

As stated, our fixed income portfolio is primarily invested in high quality, investment-grade securities. However, a smaller portion of the portfolio, approximately 16 percent at December 31, 2019, is invested in below investment-grade securities. These securities, which pay a higher rate of interest, also have a higher degree of credit or default risk and may also be less liquid in times of economic weakness or market disruptions. While we have put in place procedures to monitor the credit risk and liquidity of our invested assets, it is possible that, in periods of economic weakness (such as recession), we may experience credit or default losses in our portfolio, which could adversely affect our results of operations and financial condition.

As a part of our ongoing analysis of our investment portfolio, we are required to assess whether the fixed maturities we hold for which we have recorded an unrealized loss have been “other-than-temporarily impaired” under GAAP, which implies an inability to recover the full economic benefits of these securities. Refer to Note 2 to the Consolidated Financial Statements for additional information. This analysis requires a high degree of judgment and requires us to make certain assessments about the potential for recovery of the assets we hold. Declines in relevant stock and other financial markets, and other factors impacting the value of our investments, could result in impairments and could adversely affect our net income and other financial results.

We may require additional capital or financing sources in the future, which may not be available or may be available only on unfavorable terms.
Our future capital and financing requirements depend on many factors, including our ability to write new business successfully and to establish premium rates and reserves at levels sufficient to cover losses, as well as our investment performance and capital expenditure obligations, including with respect to acquisitions. We may need to raise additional funds through financings

or access funds through existing or new credit facilities or through short-term repurchase agreements. We also from time to time seek to refinance debt or credit as amounts become due or commitments expire. Any equity or debt financing or refinancing, if available at all, may be on terms that are not favorable to us. In the case of equity financings, dilution to our shareholders could result, and in any case, such securities may have rights, preferences, and privileges that are senior to those of our Common Shares. Our access to funds under existing credit facilities is dependent on the ability of the banks that are parties to the facilities to meet their funding commitments. Under Swiss law we would be prohibited from selling shares in an equity financing at a purchase price below our then-current par value. If we cannot obtain adequate capital or sources of credit on favorable terms, or at all, we could be forced to use assets otherwise available for our business operations, and our business, results of operations, and financial condition could be adversely affected.

We may be required to post additional collateral because of changes in our reinsurance liabilities to regulated insurance companies, or because of regulatory changes that affect our companies.
If our reinsurance liabilities increase, including in our property & casualty and variable annuity reinsurance businesses, we may be required to post additional collateral for insurance company clients. In addition, regulatory changes sometimes affect our obligations to post collateral. The need to post this additional collateral, if significant enough, may require us to sell investments at a loss in order to provide securities of suitable credit quality or otherwise secure adequate capital at an unattractive cost. This could adversely impact our net income and liquidity and capital resources.

U.S. and global economic and financial industry events and their consequences could harm our business, our liquidity and financial condition, and our stock price.
The consequences of adverse global or regional market and economic conditions may affect (among other aspects of our business) the demand for and claims made under our products, the ability of customers, counterparties, and others to establish or maintain their relationships with us, our ability to access and efficiently use internal and external capital resources, the availability of reinsurance protection, the risks we assume under reinsurance programs covering variable annuity guarantees, and our investment performance. The increasing impact of climate change could affect our cost of claims, loss ratios, and financial results. Volatility in the U.S. and other securities markets may adversely affect our stock price.

A decline in our financial strength ratings could affect our standing among distribution partners and customers and cause our premiums and earnings to decrease. A decline in our debt ratings could increase our borrowing costs and impact our ability to access capital markets.
Ratings are an important factor in establishing the competitive position of insurance and reinsurance companies. The objective of these rating systems is to provide an opinion of an insurer's financial strength and ability to meet ongoing obligations to its policyholders. A ratings downgrade could result in a substantial loss of business as insureds, ceding companies, and brokers move to other insurers and reinsurers with higher ratings. If one or more of our debt ratings were downgraded, we could also incur higher borrowing costs, and our ability to access the capital markets could be impacted. Additionally, we could be required to post collateral or be faced with the cancellation of policies and resulting premium in certain circumstances. We cannot give any assurance regarding whether or to what extent any of the rating agencies might downgrade our ratings in the future.

Our ability to pay dividends and/or to make payments on indebtedness may be constrained by our holding company structure.
Chubb Limited is a holding company that owns shares of its operating insurance and reinsurance subsidiaries along with several loans receivable from affiliates. Beyond this it does not itself have any significant operations or liquid assets. Repayment of loans receivable, guarantee fees and dividends and other permitted distributions from our insurance subsidiaries are its primary sources of funds to meet ongoing cash requirements, including any future debt service payments, other expenses, repurchases of its shares, and to pay dividends to our shareholders. Some of our insurance subsidiaries are subject to significant regulatory restrictions limiting their ability to declare and pay dividends. The inability of our insurance subsidiaries to pay dividends (or other intercompany amounts due, such as intercompany debt obligations) in an amount sufficient to enable us to meet our cash requirements at the holding company level could have an adverse effect on our operations and our ability to repurchase shares and pay dividends to our shareholders.

Swiss law imposes certain restrictions on our ability to repurchase our shares.
Swiss law imposes certain withholding tax and other restrictions on a Swiss company's ability to return earnings or capital to its shareholders, including through the repurchase of its own shares. We may only repurchase shares to the extent that sufficient freely distributable reserves are available. In addition, Swiss law requires that the total par value of Chubb's acquisition of treasury shares must not be in excess of 10 percent of its total share capital. As a result, in order to maintain our share repurchase program, our shareholders must periodically authorize, through ballot item approval at our annual general meeting,

a reduction in our share capital through the cancellation of designated blocks of repurchased shares held in treasury. If our shareholders do not approve the cancellation of previously repurchased shares, we may be unable to return capital to shareholders through share repurchases in the future. Furthermore, our current repurchase program relies on a Swiss tax ruling. Any future revocation or loss of our Swiss tax ruling or the inability to conduct repurchases in accordance with the ruling could also jeopardize our ability to continue repurchasing our shares.

Our operating results and shareholders' equity may be adversely affected by currency fluctuations.
Our reporting currency is the U.S. dollar. In general, we match assets and liabilities in local currencies. Where possible, capital levels in local currencies are limited to satisfy minimum regulatory requirements and to support local insurance operations. The principal currencies creating foreign exchange risk are the British pound sterling, the euro, the Mexican peso, the Brazilian real, the Korean won, the Canadian dollar, the Japanese yen, the Thai baht, the Australian dollar, and the Hong Kong dollar. At December 31, 2019, approximately 16.6 percent of our net assets were denominated in foreign currencies. We may experience losses resulting from fluctuations in the values of non-U.S. currencies, which could adversely impact our results of operations and financial condition.

Operational

The regulatory and political regimes under which we operate, and their volatility, could have an adverse effect on our business.
We may from time to time face challenges resulting from changes in applicable law and regulations in particular jurisdictions, or changes in approach to oversight of our business from insurance or other regulators.

Our insurance and reinsurance subsidiaries conduct business globally. Our businesses in each jurisdiction are subject to varying degrees of regulation and supervision. The laws and regulations of the jurisdictions in which our insurance and reinsurance subsidiaries are domiciled require, among other things, maintenance of minimum levels of statutory capital, surplus, and liquidity; various solvency standards; and periodic examinations of subsidiaries' financial condition. In some jurisdictions, laws and regulations also restrict payments of dividends and reductions of capital. Applicable statutes, regulations, and policies may also restrict the ability of these subsidiaries to write insurance and reinsurance policies, to make certain investments, and to distribute funds. The purpose of insurance laws and regulations generally is to protect policyholders and ceding insurance companies, not our shareholders. For example, some jurisdictions have enacted various consumer protection laws that make it more burdensome for insurance companies to sell policies and interact with customers in personal lines businesses. Failure to comply with such regulations can lead to significant penalties and reputational injury.

The foreign and U.S. federal and state laws and regulations that are applicable to our operations are complex and may increase the costs of regulatory compliance or subject our business to the possibility of regulatory actions or proceedings. Laws and regulations not specifically related to the insurance industry include trade sanctions that relate to certain countries, anti-money laundering laws, and anti-corruption laws. The insurance industry is also affected by political, judicial, and legal developments that may create new and expanded regulations and theories of liability. The current economic and financial climates present additional uncertainties and risks relating to increased regulation and the potential for increased involvement of the U.S. and other governments in the financial services industry.

Regulators in countries where we have operations are working with the International Association of Insurance Supervisors (IAIS) to consider changes to insurance company supervision, including with respect to group supervision and solvency requirements. The IAIS has developed a Common Framework for the Supervision of Internationally Active Insurance Groups (ComFrame) which is focused on the effective group-wide supervision of international active insurance groups (IAIGs), such as Chubb. As part of ComFrame, the IAIS has announced plans to develop an international capital standard for insurance groups. The details of ComFrame including this global capital standard and its applicability to Chubb are uncertain at this time. In addition, Chubb businesses across the EU are subject to Solvency II, a capital and risk management regime and our Bermuda businesses are subject to an equivalent of the EU's Solvency II regime. Also applicable to Chubb businesses are the requirements of the Swiss Financial Market Supervisory Authority (FINMA) whose regulations include Swiss Solvency Tests. There are also Risk Based Capital (RBC) requirements in the U.S. which are also subject to revision in response to global developments. While it is not certain how or if these actions will impact Chubb, we do not currently expect that our capital management strategies, results of operations and financial condition will be materially affected by these regulatory changes.

Evolving privacy and data security regulations could adversely affect our business.
We are subject to numerous U.S. federal and state laws and non-U.S. regulations governing the protection of personal and confidential information of our clients and employees, including in relation to medical records, credit card data and financial

information. These laws and regulations are increasing in complexity and number, change frequently, sometimes conflict, and could expose Chubb to significant monetary damages, regulatory enforcement actions, fines and/or criminal prosecution in one or more jurisdictions.

We are subject to the New York Department of Financial Services' Cybersecurity Regulation (the NYDFS Cybersecurity Regulation) which mandates detailed cybersecurity standards for all institutions, including insurance entities, authorized by the NYDFS to operate in New York. The NYDFS Cybersecurity Regulation has increased our compliance costs and could increase the risk of noncompliance and subject us to regulatory enforcement actions and penalties, as well as reputation risk.

Additionally, in 2017, the National Association of Insurance Commissioners (NAIC) adopted an Insurance Data Security Model Law, which requires licensed insurance entities to comply with detailed information security requirements. It is not yet known whether or not, and to what extent, states legislatures or insurance regulators where we operate will enact the Insurance Data Security Model Law in whole or in part, or in a modified form. Such enactments, especially if inconsistent between states or with existing laws and regulations could raise compliance costs or increase the risk of noncompliance, with the attendant risk of being subject to regulatory enforcement actions and penalties, as well as reputational harm.

The EU General Data Protection Regulation (the "GDPR"), which became effective in 2018, is a comprehensive regulation applying across all EU member states. All our business units (regardless of whether they are located in the EU) may be subject to the GDPR when personal data is processed in relation to the offer of goods and services to individuals within the EU. Our failure to comply with GDPR and other countries' privacy or data security-related laws, rules or regulations could result in significant penalties imposed by regulators, which could have an adverse effect on our business, financial condition and results of operations.

Significant other comprehensive privacy laws have been enacted by other jurisdictions, most notably the California Consumer Privacy Act (CCPA) and Brazil's Lei Geral de Protecao de Dados, which may affect our use of data and could affect our operations and subject us to fines and actions for noncompliance. In the U.S., several other states are considering similar legislation, and there are ongoing discussions regarding a National Privacy Law. New laws similar to the GDPR and the CCPA are expected to be enacted in coming years in various countries and jurisdictions in which we operate.

Political uncertainty in the United Kingdom and the European Union may lead to volatility and/or have an adverse effect on our business, our liquidity and financial condition, and our stock price.
On June 23, 2016, the United Kingdom (U.K.) voted in a national referendum to withdraw from the European Union (EU). On March 29, 2017, the U.K. government gave notice to the EU, under Article 50(2) of the Treaty on EU, of the U.K.'s intention to withdraw from the EU. The U.K. ratified the withdrawal agreement and ceased to be a Member State of the EU (Brexit) on January 31, 2020.

We have significant operations in the U.K. and other EU member states that, operationally, have been affected by Brexit. In anticipation of Brexit, we redomiciled the headquarters of our European carriers to France effective January 1, 2019. Paris is the principal office for our Continental European operations. We have a significant investment there in both financial and human resources, as well as a large portfolio of commercial and consumer insurance business throughout France. Following Brexit, Chubb will continue to have a substantial presence in London, in addition to its offices and operations across the U.K. and the EU.

Prior to Brexit, the rules governing the EU Single Market (which is made up of the 27 other EU member states and to some extent, Iceland, Liechtenstein, and Norway (together, the European Economic Area or EEA)) permitted U.K. insurers (as well as EEA insurers operating as passported branches in the U.K., such as our French companies Chubb European Group SE and ACE Europe Life SE), to underwrite risks from the U.K. into EEA member states via a "passport" prior to Brexit.

The withdrawal agreement between the U.K. and the EU includes, following Brexit, a transition or implementation period to avoid a "cliff edge" Brexit, meaning that the U.K. remains subject to, and has the benefit of, all EU legislation, including passporting rights, until December 31, 2020. This period is intended to enable the EU and the U.K. to negotiate a trade agreement for the post-Brexit relationship between the U.K. and the EU and can, pursuant to the withdrawal agreement, be extended beyond the end of 2020 with the consent of both the U.K. and the EU. However, the U.K. government included a section in the European Union (United Kingdom Withdrawal Agreement) Act 2020 that has made it illegal for the U.K. Parliament to seek an extension of the transition or implementation period from the EU. To the extent, therefore, that it proves impossible to negotiate a trade agreement between the U.K. and the EU by December 31, 2020, there remains a risk that a "cliff edge" Brexit may nevertheless arise, including the benefits of passporting rights.

Even if a free trade agreement is concluded between the U.K. and the EU prior to the end of the transition or implementation period, such free trade agreement may not maintain the passporting rights of U.K. insurers, nor deem relevant U.K. regulations to be equivalent to those of the EU. In the event that, following the end of the transition or implementation period, U.K. insurers are unable to access the EU Single Market via a passporting arrangement, a regulatory equivalence regime or other similar arrangement, such insurers may not be able to underwrite risks into EEA member states except through local branches incorporated in the EEA. Such branches might require local authorization, regulatory and prudential supervision, and capital to be deposited.

Our worldwide operations, particularly in developing nations, expose us to global geopolitical developments that could have an adverse effect on our business, liquidity, results of operations, and financial condition.
With operations in 54 countries and territories, we provide insurance and reinsurance products and services to a diverse group of clients worldwide, including operations in various developing nations. Both current and future foreign operations could be adversely affected by unfavorable geopolitical developments including law changes; tax changes; changes in trade policies; changes to visa or immigration policies; regulatory restrictions; government leadership changes; political events and upheaval; sociopolitical instability; social, political or economic instability resulting from climate change; and nationalization of our operations without compensation. Adverse activity in any one country could negatively impact operations, increase our loss exposure under certain of our insurance products, and could, otherwise, have an adverse effect on our business, liquidity, results of operations, and financial condition depending on the magnitude of the events and our net financial exposure at that time in that country.

A failure in our operational systems or infrastructure or those of third parties, including due to security breaches or cyber-attacks, could disrupt business, damage our reputation, and cause losses.
Our operations rely on the secure processing, storage, and transmission of confidential and other information and assets, including in our computer systems and networks and those of third-party service providers. Our business depends on effective information security and systems and the integrity and timeliness of the data our information systems use to run our business. Our ability to adequately price products and services, to establish reserves, to provide effective, efficient and secure service to our customers, to value our investments and to timely and accurately report our financial results also depends significantly on the integrity and availability of the data we maintain, including that within our information systems, as well as data in and assets held through third-party service providers and systems. Although we have implemented administrative and technical controls and have taken protective actions to reduce the risk of cyber incidents and to protect our information technology and assets, and although we additionally endeavor to modify such procedures as circumstances warrant and negotiate agreements with third-party providers to protect our assets, such measures may be insufficient to prevent unauthorized access, computer viruses, malware or other malicious code or cyber-attack, business compromise attacks, catastrophic events, system failures and disruptions, employee errors or malfeasance, third party (including outsourced service providers) errors or malfeasance, loss of assets and other events that could have security consequences (each, a Security Event). As the breadth and complexity of our security infrastructure continues to grow, the potential risk of a Security Event increases. Such an event or events may jeopardize Chubb's or its clients' or counterparties' confidential and other information processed and stored within Chubb, and transmitted through its computer systems and networks, or otherwise cause interruptions, delays, or malfunctions in Chubb's, its clients', its counterparties', or third parties' operations, or result in data loss or loss of assets which could result in significant losses, reputational damage or an adverse effect on our operations and critical business functions. Chubb may be required to expend significant additional resources to modify our protective measures or to investigate and remediate vulnerabilities or other exposures and to pursue recovery of lost data or assets and we may be subject to litigation and financial losses that are either not insured against or not fully covered by insurance maintained.

Despite the contingency plans and facilities we have in place and our efforts to observe the regulatory requirements surrounding information security, our ability to conduct business may be adversely affected by a disruption of the infrastructure that supports our business in the communities in which we are located, or of outsourced services or functions. This may include a disruption involving electrical, communications, transportation, or other services used by Chubb. If a disruption occurs in one location and Chubb employees in that location are unable to occupy our offices and conduct business or communicate with or travel to other locations, our ability to service and interact with clients may suffer and we may not be able to successfully implement contingency plans that depend on communication or travel.

We use analytical models to assist our decision making in key areas such as underwriting, claims, reserving, and catastrophe risks but actual results could differ materially from the model outputs and related analyses.
We use various modeling techniques (e.g., scenarios, predictive, stochastic and/or forecasting) and data analytics to analyze and estimate exposures, loss trends and other risks associated with our assets and liabilities. We use the modeled outputs and

related analyses to assist us in decision-making (e.g., underwriting, pricing, claims, reserving, reinsurance, and catastrophe risk) and to maintain competitive advantage. The modeled outputs and related analyses are subject to various assumptions, uncertainties, model errors and the inherent limitations of any statistical analysis, including the use of historical internal and industry data. In addition, the modeled outputs and related analyses may from time to time contain inaccuracies, perhaps in material respects, including as a result of inaccurate inputs or applications thereof. Climate change may make modeled outcomes less certain or produce new, non-modeled risks. Consequently, actual results may differ materially from our modeled results. If, based upon these models or other factors, we misprice our products or underestimate the frequency and/or severity of loss events, or overestimate the risks we are exposed to, new business growth and retention of our existing business may be adversely affected which could have an adverse effect on our results of operations and financial condition.

We could be adversely affected by the loss of one or more key executives or by an inability to attract and retain qualified personnel.
Our success depends on our ability to retain the services of our existing key executives and to attract and retain additional qualified personnel in the future. The loss of the services of any of our key executives or the inability to hire and retain other highly qualified personnel in the future could adversely affect our ability to conduct or grow our business. This risk may be particularly acute for us relative to some of our competitors because some of our senior executives work in countries where they are not citizens and work permit and immigration issues could adversely affect the ability to retain or hire key persons. We do not maintain key person life insurance policies with respect to our employees.

Employee error and misconduct may be difficult to detect and prevent and could adversely affect our business, results of operations, and financial condition.
Losses may result from, among other things, fraud, errors, failure to document transactions properly, failure to obtain proper internal authorization, failure to comply with underwriting or other internal guidelines, or failure to comply with regulatory requirements. It is not always possible to deter or prevent employee misconduct and the precautions that we take to prevent and detect this activity may not be effective in all cases. Resultant losses could adversely affect our business, results of operations, and financial condition.

Strategic

The continually changing landscape, including competition, technology and products, and existing and new market entrants could reduce our margins and adversely impact our business and results of operations.
Insurance and reinsurance markets are highly competitive. We compete on an international and regional basis with major U.S., Bermuda, European, and other international insurers and reinsurers and with underwriting syndicates, some of which have greater financial, technological, marketing, distribution and/or management resources than we do. In addition, capital market participants have created alternative products that are intended to compete with reinsurance products. We also compete with new companies and existing companies that move into the insurance and reinsurance markets. If competition, or technological or other changes to the insurance markets in which we operate, limits our ability to retain existing business or write new business at adequate rates or on appropriate terms, our business and results of operations could be materially and adversely affected. Increased competition could also result in fewer submissions, lower premium rates, and less favorable policy terms and conditions, which could reduce our profit margins and adversely impact our net income and shareholders' equity.

Recent technological advancements in the insurance industry and information technology industry present new and fast-evolving competitive risks as participants seek to increase transaction speeds, lower costs and create new opportunities. Advancements in technology are occurring in underwriting, claims, distribution and operations at a pace that may quicken, including as companies increase use of data analytics and technology as part of their business strategy. We will be at a competitive disadvantage if, over time, our competitors are more effective than us in their utilization of technology and evolving data analytics. If we do not anticipate or keep pace with these technological and other changes impacting the insurance industry, it could also limit our ability to compete in desired markets.

Insurance and reinsurance markets are historically cyclical, and we expect to experience periods with excess underwriting capacity and unfavorable premium rates.
The insurance and reinsurance markets have historically been cyclical, characterized by periods of intense price competition due to excessive underwriting capacity as well as periods when shortages of capacity permitted favorable premium levels. An increase in premium levels is often offset by an increasing supply of insurance and reinsurance capacity, either by capital provided by new entrants or by the commitment of additional capital by existing insurers or reinsurers, which may cause prices to decrease. Any of these factors could lead to a significant reduction in premium rates, less favorable policy terms, and fewer submissions for our underwriting services. In addition to these considerations, changes in the frequency and severity of losses

suffered by insureds and insurers may affect the cycles of the insurance and reinsurance markets significantly, as could periods of economic weakness (such as recession).

The integration of acquired companies may not be as successful as we anticipate.
Acquisitions involve numerous operational, strategic, financial, accounting, legal, tax, and other risks; potential liabilities associated with the acquired businesses; and uncertainties related to design, operation and integration of acquired businesses' internal controls over financial reporting. Difficulties in integrating an acquired company, along with its personnel, may result in the acquired company performing differently than we expected, in operational challenges or in our failure to realize anticipated expense-related efficiencies. This may also apply to companies in which we acquire majority ownership. Our existing businesses could also be negatively impacted by acquisitions. In addition, goodwill and intangible assets recorded in connection with insurance company acquisitions may be impaired if premium growth, underwriting profitability, agency retention and policy persistency, among other factors, differ from expectations.

There is also the potential that proposed acquisitions that have been publicly announced will not be consummated, even if a definitive agreement has been signed by the parties. If an agreement is terminated before closing, the result would be that our proposed acquisition would not occur, which could, among other things, expose us to damages or liability and adversely impact our stock price and future operations.

We may be subject to U.S. tax and Bermuda tax which may have an adverse effect on our results of operations and shareholder investment.
Chubb Limited and our non-U.S. subsidiaries operate in a manner so that none of these companies should be subject to U.S. tax (other than U.S. excise tax on insurance and reinsurance premium income attributable to insuring or reinsuring U.S. risks and U.S. withholding tax on some types of U.S. source investment income), because none of these companies should be treated as engaged in a trade or business within the U.S. However, because there is considerable uncertainty as to the activities that constitute being engaged in a trade or business within the U.S., we cannot be certain that the Internal Revenue Service (IRS) will not contend successfully that Chubb Limited or its non-U.S. subsidiaries are engaged in a trade or business in the U.S. If Chubb Limited or any of its non-U.S. subsidiaries were considered to be engaged in a trade or business in the U.S., such entity could be subject to U.S. corporate income and branch profits taxes on the portion of its earnings effectively connected to such U.S. business, in which case our results of operations and our shareholders' investments could be adversely affected.

The Bermuda Minister of Finance, under the Exempted Undertakings Tax Protection Act 1966 of Bermuda, as amended, has given Chubb Limited and its Bermuda insurance subsidiaries a written assurance that if any legislation is enacted in Bermuda that would impose tax computed on profits or income, or computed on any capital asset, gain, or appreciation, or any tax in the nature of estate duty or inheritance tax, then the imposition of any such tax would not be applicable to those companies or any of their respective operations, shares, debentures, or other obligations until March 31, 2035, except insofar as such tax would apply to persons ordinarily resident in Bermuda or is payable by us in respect of real property owned or leased by us in Bermuda. We cannot be certain that we will not be subject to any Bermuda tax after March 31, 2035.

We could be adversely affected by certain features of the 2017 U.S. tax reform legislation.
New tax legislation known as the Tax Cuts and Jobs Act (2017 Tax Act) was enacted in the U.S. on December 22, 2017. In addition to reducing the U.S. corporate income tax rate from 35 percent to 21 percent, it fundamentally changed many elements of the pre-2017 Tax Act U.S. tax law and introduced several new concepts to tax multinational corporations such as us. Among the most notable new rules are the Base Erosion and Anti-Abuse Tax (commonly called BEAT), which may apply as a result of payments by U.S. taxpayers to non-U.S. affiliates, and the Global Intangible Low Taxed Income (GILTI) addition to Subpart F income, which for insurance groups potentially expands U.S. taxation on the earnings of foreign subsidiaries. The 2017 Tax Act also included a one-time reduced-rate transition tax in 2017 on previously untaxed post-1986 earnings of foreign subsidiaries of U.S. corporations. The 2017 Tax Act, which was generally effective in 2018, is a complex law with many significant new provisions. During 2018 and 2019, the IRS and U.S. Treasury Department issued notices, proposed, and final regulations to assist taxpayers in understanding and implementing the new provisions. There may be changes between this guidance and final regulations to be issued in 2020. Thus, there are many uncertainties relating to its ultimate application and effects on our company.

The Organization for Economic Cooperation and Development (OECD) and the European Union (EU) are considering measures that might change long standing tax principles that could increase our taxes.
The OECD has published a framework for taxation that in many respects is different than long standing international tax principles. This framework is a proposal that we expect to develop further in 2020 as it is designed by the OECD Secretariat. This framework is an alternative to digital services taxes that several countries have enacted or are considering. These changes could redefine what income is taxed in which country and institute a global minimum tax. These proposals may be completed

by the end of 2020 which could be adopted by OECD countries in 2021 or later years. As countries unilaterally amend their tax laws to adopt certain parts of the OECD framework, this may increase the company's income taxes and cause uncertainties related to our income taxes.

The OECD has also published an action plan to address base erosion and profit shifting (BEPS) impacting its member countries and other jurisdictions. It is possible that jurisdictions in which we do business could continue to react to the BEPS initiative or their own concerns by enacting tax legislation that could adversely affect us or our shareholders.

Several multilateral organizations, including the EU and the OECD have, in recent years, expressed concern about some countries not participating in adequate tax information exchange arrangements and have threatened those that do not agree to cooperate with punitive sanctions by member countries. It is still unclear what all these sanctions might be, which countries might adopt them, and when or if they might be imposed. We cannot assure, however, that the Tax Information Exchange Agreements (TIEAs) that have been entered into by Switzerland and Bermuda will be sufficient to preclude all of the sanctions described above, which, if ultimately adopted, could adversely affect us or our shareholders.

Shareholders

There are provisions in our charter documents that may reduce the voting rights and diminish the value of our Common Shares.
Our Articles of Association generally provide that shareholders have one vote for each Common Share held by them and are entitled to vote at all meetings of shareholders. However, the voting rights exercisable by a shareholder may be limited so that certain persons or groups are not deemed to hold 10 percent or more of the voting power conferred by our Common Shares. Moreover, these provisions could have the effect of reducing the voting power of some shareholders who would not otherwise be subject to the limitation by virtue of their direct share ownership. The Board of Directors may refuse to register holders of shares as shareholders with voting rights based on certain grounds, including if the holder would, directly or indirectly, formally, constructively or beneficially own (as described in Articles 8 and 14 of our Articles of Association) or otherwise control voting rights with respect to 10 percent or more of the registered share capital recorded in the commercial register. In addition, the Board of Directors shall reject entry of holders of registered shares as shareholders with voting rights in the share register or shall decide on their deregistration when the acquirer or shareholder upon request does not expressly state that she/he has acquired or holds the shares in her/his own name and for her/his account.

Applicable laws may make it difficult to effect a change of control of our company.
Before a person can acquire control of a U.S. insurance company, prior written approval must be obtained from the insurance commissioner of the state where the domestic insurer is domiciled. Prior to granting approval of an application to acquire control of a domestic insurer, the state insurance commissioner will consider such factors as the financial strength of the applicant, the integrity and management of the applicant's Board of Directors and executive officers, the acquirer's plans for the future operations of the domestic insurer, and any anti-competitive results that may arise from the consummation of the acquisition of control. Generally, state statutes provide that control over a domestic insurer is presumed to exist if any person, directly or indirectly, owns, controls, holds with the power to vote, or holds proxies representing 10 percent or more of the voting securities of the domestic insurer. Because a person acquiring 10 percent or more of our Common Shares would indirectly control the same percentage of the stock of our U.S. insurance subsidiaries, the insurance change of control laws of various U.S. jurisdictions would likely apply to such a transaction. Laws of other jurisdictions in which one or more of our existing subsidiaries are, or a future subsidiary may be, organized or domiciled may contain similar restrictions on the acquisition of control of Chubb.

While our Articles of Association limit the voting power of any shareholder to less than 10 percent, we cannot assure that the applicable regulatory body would agree that a shareholder who owned 10 percent or more of our Common Shares did not, because of the limitation on the voting power of such shares, control the applicable insurance subsidiary.

These laws may discourage potential acquisition proposals and may delay, deter, or prevent a change of control of Chubb, including transactions that some or all of our shareholders might consider to be desirable.

Shareholder voting requirements under Swiss law may limit our flexibility with respect to certain aspects of capital management.
Swiss law allows our shareholders to authorize share capital which can be issued by the Board of Directors without shareholder approval but this authorization must be renewed by the shareholders every two years. Swiss law also does not provide as much flexibility in the various terms that can attach to different classes of stock as permitted in other jurisdictions. Swiss law also reserves for approval by shareholders many corporate actions over which the Board of Directors had authority prior to our re-

domestication to Switzerland. For example, dividends must be approved by shareholders. While we do not believe that Swiss law requirements relating to our capital management will have an adverse effect on Chubb, we cannot assure that situations will not arise where such flexibility would have provided substantial benefits to our shareholders.

Chubb Limited is a Swiss company; it may be difficult to enforce judgments against it or its directors and executive officers.
Chubb Limited is incorporated pursuant to the laws of Switzerland. In addition, certain of our directors and officers reside outside the U.S. and all or a substantial portion of our assets and the assets of such persons are located in jurisdictions outside the U.S. As such, it may be difficult or impossible to effect service of process within the U.S. upon those persons or to recover against us or them on judgments of U.S. courts, including judgments predicated upon civil liability provisions of the U.S. federal securities laws.

Chubb has been advised by its Swiss counsel that there is doubt as to whether the courts in Switzerland would enforce:
- judgments of U.S. courts based upon the civil liability provisions of the U.S. federal securities laws obtained in actions against it or its directors and officers, who reside outside the U.S.; or
- original actions brought in Switzerland against these persons or Chubb predicated solely upon U.S. federal securities laws.

Chubb has also been advised by its Swiss counsel that there is no treaty in effect between the U.S. and Switzerland providing for this enforcement and there are grounds upon which Swiss courts may not enforce judgments of U.S. courts. Some remedies available under the laws of U.S. jurisdictions, including some remedies available under the U.S. federal securities laws, would not be allowed in Swiss courts as contrary to that nation's public policy.

Shareholders may be subject to Swiss withholding taxes on the payment of dividends.
Our dividends are generally subject to a Swiss withholding tax at a rate of 35 percent; however, payment of a dividend in the form of a par value reduction or qualifying capital contribution reserve reduction is not subject to Swiss withholding tax. We have previously obtained shareholder approval for dividends to be paid in such form. We currently intend to recommend to shareholders that they annually approve the payment of dividends in such form but we cannot assure that our shareholders will continue to approve a reduction in such form each year or that we will be able to meet the other legal requirements for a reduction in par value, or that Swiss withholding tax rules will not be changed in the future. We estimate we would be able to pay dividends in such form, and thus exempt from Swiss withholding tax until 2028–2033. This range may vary depending upon changes in annual dividends, special dividends, certain share repurchases, fluctuations in U.S. dollar/Swiss franc exchange rate, changes in par value or qualifying capital contribution reserves or changes or new interpretations to Swiss corporate or tax law or regulations.

Under certain circumstances, U.S. shareholders may be subject to adverse U.S. federal income tax consequences.
Under certain circumstances, a U.S. person who owns or is deemed to own 10 percent or more of the voting power or value of a foreign corporation that is a “controlled foreign corporation” (CFC) (a foreign corporation in which 10 percent U.S. shareholders own or are deemed to own more than 50 percent of the voting power or value of the stock of a foreign corporation or more than 25 percent of certain foreign insurance corporations) for any period during a taxable year must include in gross income for U.S. federal income tax purposes a pro rata share of the CFC's "subpart F income". We believe that because of the dispersion of our share ownership it is unlikely that any U.S. person who acquires shares of Chubb Limited directly or indirectly through one or more foreign entities should be required to include any subpart F income in income under the CFC rules of U.S. tax law.

Separately, any U.S. persons who hold shares may be subject to U.S. federal income taxation at ordinary income tax rates on their proportionate share of our Related Person Insurance Income (RPII). If the RPII of any of our non-U.S. insurance subsidiaries (each a "Non-U.S. Insurance Subsidiary") were to equal or exceed 20 percent of that company's gross insurance income in any taxable year and direct or indirect insureds (and persons related to those insureds) own directly or indirectly through foreign entities 20 percent or more of the voting power or value of Chubb Limited, then a U.S. person who owns any shares of Chubb Limited (directly or indirectly through foreign entities) on the last day of the taxable year would be required to include in his or her income for U.S. federal income tax purposes such person's pro rata share of such company's RPII for the taxable year. In addition, any RPII that is includible in the income of a U.S. tax-exempt organization may be treated as unrelated business taxable income. We believe that the gross RPII of each Non-U.S. Insurance Subsidiary did not in prior years of operation and is not expected in the foreseeable future to equal or exceed 20 percent of each such company's gross insurance income. Likewise, we do not expect the direct or indirect insureds of each Non-U.S. Insurance Subsidiary (and persons related to such insureds) to directly or indirectly own 20 percent or more of either the voting power or value of our shares. However, we cannot be certain that this will be the case because some of the factors which determine the extent of RPII may be beyond our control. If these thresholds are met or exceeded, any U.S. person’s investment in Chubb Limited could be adversely affected.

A U.S. tax-exempt organization may recognize unrelated business taxable income if a portion of our insurance income is allocated to the organization. This generally would be the case if either (i) Chubb Limited is considered a CFC and the tax-exempt shareholder is a 10 percent U.S. shareholder or (ii) there is RPII, certain exceptions do not apply, and the tax-exempt organization, directly (or indirectly through foreign entities) owns any shares of Chubb Limited. Although we do not believe that any U.S. tax-exempt organization should be allocated such insurance income, we cannot be certain that this will be the case. Potential U.S. tax-exempt investors are advised to consult their tax advisors.

U.S. persons who hold shares will be subject to adverse tax consequences if we are considered to be a Passive Foreign Investment Company (PFIC) for U.S. federal income tax purposes.
If Chubb Limited is considered a PFIC for U.S. federal income tax purposes, a U.S. person who holds Chubb Limited shares will be subject to adverse U.S. federal income tax consequences in which case their investment could be adversely affected. In addition, if Chubb Limited were considered a PFIC, upon the death of any U.S. individual owning shares, such individual's heirs or estate would not be entitled to a "step-up" in the basis of the shares which might otherwise be available under U.S. federal income tax laws. We believe that we are not, have not been, and currently do not expect to become, a PFIC for U.S. federal income tax purposes. We cannot assure, however, that we will not be deemed a PFIC by the IRS. Recently enacted U.S. federal tax law and recently proposed regulations issued by the IRS and U.S. Treasury Department contain new rules that may affect the application of the PFIC provisions to an insurance company. Final regulations or pronouncements interpreting or clarifying these rules may be forthcoming. We cannot predict what impact, if any, such guidance would have on an investor that is subject to U.S. federal income taxation. Any shareholder electing to apply the newly proposed PFIC regulations could be adversely affected by an investment in us. Shareholders are advised to consult their tax advisors.

ITEM 1B. Unresolved Staff Comments

There are currently no unresolved SEC staff comments regarding our periodic or current reports.

ITEM 2. Properties

We maintain office facilities around the world including in North America, Europe (including our principal executive offices in Switzerland), Bermuda, Latin America, Asia Pacific, and the Far East. Most of our office facilities are leased, although we own major facilities in Hamilton, Bermuda, and in the U.S., including in Philadelphia, Pennsylvania; Wilmington, Delaware; Whitehouse Station, New Jersey; and Simsbury, Connecticut. Management considers its office facilities suitable and adequate for the current level of operations.

ITEM 3. Legal Proceedings

The information required with respect to Item 3 is included in Note 10 h) to the Consolidated Financial Statements, which is hereby incorporated herein by reference.

ITEM 4. Mine Safety Disclosures

Item not applicable.

ITEM 5. Market for Registrant's Common Equity, Related Stockholder Matters and Issuer Purchases of Equity Securities

Our Common Shares have been listed on the New York Stock Exchange since March 25, 1993, with a current par value of CHF 24.15 per share. The trading symbol for our Common Shares is "CB."

We have paid dividends each quarter since we became a public company in 1993. In 2019 and 2018, our annual dividends were paid by way of a distribution from capital contribution reserves (Additional paid-in capital) through the transfer of dividends from Additional paid-in capital to Retained earnings (free reserves) as approved by our shareholders.

Chubb Limited is a holding company whose principal sources of income are dividends and investment income from its operating subsidiaries. The ability of the operating subsidiaries to pay dividends to us and our ability to pay dividends to our shareholders are each subject to legal and regulatory restrictions. The recommendation and payment of future dividends will be based on the determination of the Board of Directors (Board) and will be dependent upon shareholder approval, profits and financial requirements of Chubb and other factors, including legal restrictions on the payment of dividends and other such factors as the Board deems relevant. Refer to Part I, Item 1A and Part II, Item 7 for additional information.

The number of record holders of Common Shares as of February 13, 2020 was 6,902. This is not the actual number of beneficial owners of Chubb's Common Shares since most of our shareholders hold their shares through a stockbroker, bank or other nominee rather than directly in their own names.

Refer to Part III, Item 12 for information relating to compensation plans under which equity securities are authorized for issuance.

Issuer's Repurchases of Equity Securities for the Three Months Ended December 31, 2019

Period	Total Number of Shares Purchased [(1)]	Average Price Paid per Share	Total Number of Shares Purchased as Part of Publicly Announced Plans [(2)]	Approximate Dollar Value of Shares that May Yet be Purchased Under Publicly Announced Plans [(3)]
October 1 through October 31	703,138	$ 153.65	700,900	$ 151 million
November 1 through November 30	677,640	$ 151.41	670,000	$ 1.55 billion
December 1 through December 31	654,352	$ 153.84	653,500	$ 1.45 billion
Total	2,035,130	$ 152.97	2,024,400	

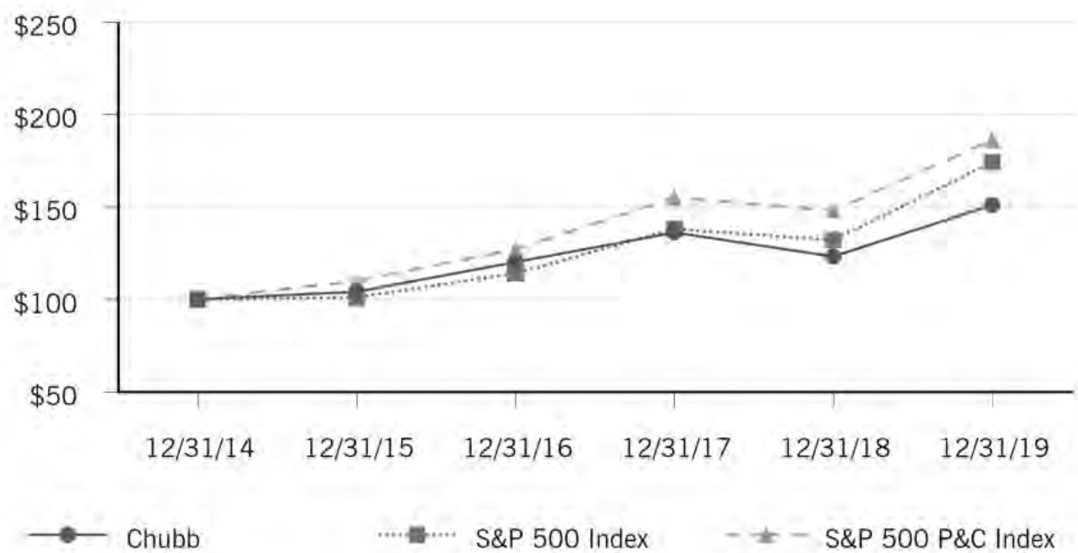
(1) This represents open market share repurchases and the surrender to Chubb of Common Shares to satisfy tax withholding obligations in connection with the vesting of restricted stock issued to employees and the exercise of options by employees.

(2) The aggregate value of shares purchased in the three months ended December 31, 2019 as part of the publicly announced plans was $310 million.

(3) Refer to Note 11 to the Consolidated Financial Statements for more information on the Chubb Limited securities repurchase authorizations. In November 2019, the Board authorized the repurchase of up to $1.5 billion of Chubb's Common Shares from November 21, 2019 through December 31, 2020. The $1.5 billion December 2018 Board authorization remained effective through December 31, 2019, and was used in advance of the $1.5 billion share repurchase authorized in November 2019. For the period January 1, 2020 through February 26, 2020, we repurchased 947,400 Common Shares for a total of $151 million in a series of open market transactions. As of February 26, 2020, $1.30 billion in share repurchase authorization remained through December 31, 2020.

Performance Graph

Set forth below is a line graph comparing the dollar change in the cumulative total shareholder return on Chubb's Common Shares from December 31, 2014, through December 31, 2019, as compared to the cumulative total return of the Standard & Poor's 500 Stock Index and the cumulative total return of the Standard & Poor's Property-Casualty Insurance Index. The cumulative total shareholder return is a concept used to compare the performance of a company's stock over time and is the ratio of the stock price change plus the cumulative amount of dividends over the specified time period (assuming dividend reinvestment), to the stock price at the beginning of the time period. The chart depicts the value on December 31, 2015, 2016, 2017, 2018, and 2019, of a $100 investment made on December 31, 2014, with all dividends reinvested.



	12/31/2014	12/31/2015	12/31/2016	12/31/2017	12/31/2018	12/31/2019
Chubb Limited	$100	$104	$120	$136	$123	$151
S&P 500 Index	$100	$101	$114	$138	$132	$174
S&P 500 P&C Index	$100	$110	$127	$155	$148	$186

ITEM 6. Selected Financial Data

On January 14, 2016, we completed the acquisition of The Chubb Corporation (Chubb Corp). The results of operations of Chubb Corp are included in our results from the acquisition date forward (i.e., after January 14, 2016 and only in the 2016, 2017, 2018 and 2019 columns) within the table below.

(in millions of U.S. dollars, except per share data and ratios)	2019	2018	2017	2016	2015
Operations data:					
Net premiums earned – excluding Life Insurance segment	**$ 28,947**	$ 27,846	$ 26,933	$ 26,694	$ 15,266
Net premiums earned – Life Insurance segment	**2,343**	2,218	2,101	2,055	1,947
Total net premiums earned	**31,290**	30,064	29,034	28,749	17,213
Net investment income	**3,426**	3,305	3,125	2,865	2,194
Losses and loss expenses	**18,730**	18,067	18,454	16,052	9,484
Policy benefits	**740**	590	676	588	543
Policy acquisition costs and administrative expenses	**9,183**	8,798	8,614	8,985	5,211
Net income	**4,454**	3,962	3,861	4,135	2,834
Weighted-average shares outstanding – diluted	**459**	467	471	466	329
Diluted earnings per share	**$ 9.71**	$ 8.49	$ 8.19	$ 8.87	$ 8.62
Balance sheet data (at end of period):					
Total investments	**$ 109,234**	$ 100,968	$ 102,444	$ 99,094	$ 66,251
Total assets	**176,943**	167,771	167,022	159,786	102,306
Net unpaid losses and loss expenses	**48,509**	48,271	49,165	47,832	26,562
Net future policy benefits	**5,617**	5,304	5,137	4,854	4,620
Long-term debt	**13,559**	12,087	11,556	12,610	9,389
Trust preferred securities	**308**	308	308	308	307
Total liabilities	**121,612**	117,459	115,850	111,511	73,171
Shareholders' equity	**55,331**	50,312	51,172	48,275	29,135
Book value per share	**$ 122.42**	$ 109.56	$ 110.32	$ 103.60	$ 89.77
Selected data:					
Loss and loss expense ratio (1)	**62.1%**	62.1%	65.8%	57.7%	58.1%
Underwriting and administrative expense ratio (2)	**28.5%**	28.5%	28.9%	30.6%	29.2%
Combined ratio (3)	**90.6%**	90.6%	94.7%	88.3%	87.3%
Cash dividends per share	**$ 2.98**	$ 2.90	$ 2.82	$ 2.74	$ 2.66

(1) The Loss and loss expense ratio is calculated by dividing losses and loss expenses, excluding the Life Insurance segment, by Net premiums earned – excluding Life Insurance segment. Losses and loss expenses for the Life Insurance segment were $757 million, $766 million, $739 million, $663 million, and $601 million for the years ended December 31, 2019, 2018, 2017, 2016, and 2015, respectively.

(2) The Underwriting and administrative expense ratio is calculated by dividing the policy acquisition costs and administrative expenses, excluding the Life Insurance segment, by Net premiums earned – excluding Life Insurance segment. Policy acquisition costs and administrative expenses for the Life Insurance segment were $943 million, $867 million, $833 million, $816 million, and $767 million for the years ended December 31, 2019, 2018, 2017, 2016, and 2015, respectively.

(3) The combined ratio is the sum of Loss and loss expense ratio and the Underwriting and administrative expense ratio.

ITEM 7. Management's Discussion and Analysis of Financial Condition and Results of Operations

The following is a discussion of our results of operations, financial condition, and liquidity and capital resources as of and for the year ended December 31, 2019. This discussion should be read in conjunction with the consolidated financial statements and related Notes, under Item 8 of this Form 10-K.

All comparisons in this discussion are to the corresponding prior year unless otherwise indicated. All dollar amounts are rounded. However, percent changes and ratios are calculated using whole dollars. Accordingly, calculations using rounded dollars may differ.

Forward-Looking Statements

The Private Securities Litigation Reform Act of 1995 provides a "safe harbor" for forward-looking statements. Any written or oral statements made by us or on our behalf may include forward-looking statements that reflect our current views with respect to future events and financial performance. These forward-looking statements are subject to certain risks, uncertainties, and other factors that could, should potential events occur, cause actual results to differ materially from such statements. These risks, uncertainties, and other factors, which are described in more detail under Part I, Item 1A, under Risk Factors, starting on page 19 and elsewhere herein and in other documents we file with the U.S. Securities and Exchange Commission (SEC), include but are not limited to:

- losses arising out of natural or man-made catastrophes such as hurricanes, typhoons, earthquakes, floods, climate change (including effects on weather patterns; greenhouse gases; sea, land and air temperatures; sea levels; and rain and snow), nuclear accidents, or terrorism which could be affected by:
    - the number of insureds and ceding companies affected;
    - the amount and timing of losses actually incurred and reported by insureds;
    - the impact of these losses on our reinsurers and the amount and timing of reinsurance recoverable actually received;
    - the cost of building materials and labor to reconstruct properties or to perform environmental remediation following a catastrophic event; and
    - complex coverage and regulatory issues such as whether losses occurred from storm surge or flooding and related lawsuits;
- actions that rating agencies may take from time to time, such as financial strength or credit ratings downgrades or placing these ratings on credit watch negative or the equivalent;
- the ability to collect reinsurance recoverable, credit developments of reinsurers, and any delays with respect thereto and changes in the cost, quality, or availability of reinsurance;
- actual loss experience from insured or reinsured events and the timing of claim payments;
- the uncertainties of the loss-reserving and claims-settlement processes, including the difficulties associated with assessing environmental damage and asbestos-related latent injuries, the impact of aggregate-policy-coverage limits, the impact of bankruptcy protection sought by various asbestos producers and other related businesses, and the timing of loss payments;
- changes to our assessment as to whether it is more likely than not that we will be required to sell, or have the intent to sell, available for sale fixed maturity investments before their anticipated recovery;
- infection rates and severity of pandemics and their effects on our business operations and claims activity;
- developments in global financial markets, including changes in interest rates, stock markets, and other financial markets, increased government involvement or intervention in the financial services industry, the cost and availability of financing, and foreign currency exchange rate fluctuations (which we refer to in this report as foreign exchange and foreign currency exchange), which could affect our statement of operations, investment portfolio, financial condition, and financing plans;
- general economic and business conditions resulting from volatility in the stock and credit markets and the depth and duration of potential recession;
- global political conditions, the occurrence of any terrorist attacks, including any nuclear, radiological, biological, or chemical events, or the outbreak and effects of war, and possible business disruption or economic contraction that may result from such events;
- the potential impact of the United Kingdom's vote to withdraw from the European Union, including political, regulatory, social, and economic uncertainty and market and exchange rate volatility;
- judicial decisions and rulings, new theories of liability, legal tactics, and settlement terms;

- the effects of public company bankruptcies and/or accounting restatements, as well as disclosures by and investigations of public companies relating to possible accounting irregularities, and other corporate governance issues, including the effects of such events on:
    - the capital markets;
    - the markets for directors and officers (D&O) and errors and omissions (E&O) insurance; and
    - claims and litigation arising out of such disclosures or practices by other companies;
- uncertainties relating to governmental, legislative and regulatory policies, developments, actions, investigations, and treaties, which, among other things, could subject us to insurance regulation or taxation in additional jurisdictions or affect our current operations;
- the effects of data privacy or cyber laws or regulation on our current or future business;
- the actual amount of new and renewal business, market acceptance of our products, and risks associated with the introduction of new products and services and entering new markets, including regulatory constraints on exit strategies;
- the competitive environment in which we operate, including trends in pricing or in policy terms and conditions, which may differ from our projections and changes in market conditions that could render our business strategies ineffective or obsolete;
- acquisitions made by us performing differently than expected, our failure to realize anticipated expense-related efficiencies or growth from acquisitions, the impact of acquisitions on our pre-existing organization, or announced acquisitions not closing;
- risks and uncertainties relating to our planned purchases of additional interests in Huatai Insurance Group Company Limited (Huatai Group), including our ability to receive Chinese insurance regulatory approval and complete the purchases;
- risks associated with being a Swiss corporation, including reduced flexibility with respect to certain aspects of capital management and the potential for additional regulatory burdens;
- the potential impact from government-mandated insurance coverage for acts of terrorism;
- the availability of borrowings and letters of credit under our credit facilities;
- the adequacy of collateral supporting funded high deductible programs;
- changes in the distribution or placement of risks due to increased consolidation of insurance and reinsurance brokers;
- material differences between actual and expected assessments for guaranty funds and mandatory pooling arrangements;
- the effects of investigations into market practices in the property and casualty (P&C) industry;
- changing rates of inflation and other economic conditions, for example, recession;
- the amount of dividends received from subsidiaries;
- loss of the services of any of our executive officers without suitable replacements being recruited in a reasonable time frame;
- the ability of our technology resources, including information systems and security, to perform as anticipated such as with respect to preventing material information technology failures or third-party infiltrations or hacking resulting in consequences adverse to Chubb or its customers or partners;
- the ability of our company to increase use of data analytics and technology as part of our business strategy and adapt to new technologies; and
- management's response to these factors and actual events (including, but not limited to, those described above).

The words "believe," "anticipate," "estimate," "project," "should," "plan," "expect," "intend," "hope," "feel," "foresee," "will likely result," or "will continue," and variations thereof and similar expressions, identify forward-looking statements. You are cautioned not to place undue reliance on these forward-looking statements, which speak only as of their dates. We undertake no obligation to publicly update or review any forward-looking statements, whether as a result of new information, future events or otherwise.

Overview

We operate through six business segments: North America Commercial P&C Insurance, North America Personal P&C Insurance, North America Agricultural Insurance, Overseas General Insurance, Global Reinsurance, and Life Insurance. For more information on our segments refer to "Segment Information" under Item 1.

We have grown our business through increased premium volume, expansion of product offerings and geographic reach, and acquisitions of other companies.

Our product and geographic diversification differentiates us from the vast majority of our competitors and has been a source of stability during periods of industry volatility. Our long-term business strategy focuses on sustained growth in book value achieved through a combination of underwriting and investment income. By doing so, we provide value to our clients and shareholders through use of our substantial capital base in the insurance and reinsurance markets.

We are organized along a profit center structure by line of business and territory that does not necessarily correspond to corporate legal entities. Profit centers can access various legal entities subject to licensing and other regulatory rules. Profit centers are expected to generate underwriting income and appropriate risk-adjusted returns. Our corporate structure has facilitated the development of management talent by giving each profit center's senior management team the necessary autonomy within underwriting authorities to make operating decisions and create products and coverages needed by its target customer base. We are focused on delivering underwriting profit by only writing policies which we believe adequately compensate us for the risk we accept.

Our insurance and reinsurance operations generate gross revenues from two principal sources: premiums and investment income. Cash flow is generated from premiums collected and investment income received less paid losses and loss expenses, policy acquisition costs, and administrative expenses. Invested assets are substantially held in liquid, investment grade fixed income securities of relatively short duration. Claims payments in any short-term period are highly unpredictable due to the random nature of loss events and the timing of claims awards or settlements. The value of investments held to pay future claims is subject to market forces such as the level of interest rates, stock market volatility, and credit events such as corporate defaults. The actual cost of claims is also volatile based on loss trends, inflation rates, court awards, and catastrophes. We believe that our cash balance, our highly liquid investments, credit facilities, and reinsurance protection provide sufficient liquidity to meet unforeseen claim demands that might occur in the year ahead. Refer to "Liquidity" and "Capital Resources" for additional information.

Financial Highlights for the Year Ended December 31, 2019

- Net income was $4,454 million compared with $3,962 million in 2018.
- Net premiums written were $32.3 billion, up 5.5 percent, or 7.0 percent on a constant-dollar basis.
- The North America Agricultural Insurance segment combined ratio was 95.1 percent compared with 75.5 percent in 2018, or a decline of $296 million in underwriting income, principally due to the downward revision in the 2019 crop year margin estimate reflecting preventive planting claims due to the impact of wet weather conditions and crop yield shortfalls resulting from poor growing conditions.
- P&C combined ratio was 90.6 percent in both 2019 and 2018. P&C current accident year combined ratio excluding catastrophe losses was 89.2 percent compared with 88.0 percent in 2018, reflecting the increase in the North America Agricultural Insurance segment combined ratio noted above.
- Total pre-tax and after-tax catastrophe losses, including reinstatement premiums, were $1,187 million (4.1 percentage points of the combined ratio) and $966 million, respectively, compared with $1,626 million (5.9 percentage points of the combined ratio) and $1,354 million, respectively, in 2018. Refer to the Consolidated Operating Results section for additional information on our catastrophe losses.
- Total pre-tax and after-tax favorable prior period development were $792 million (2.7 percentage points of the combined ratio) and $624 million, respectively, compared with $896 million (3.3 percentage points of the combined ratio) and $706 million, respectively, in 2018. Pre-tax favorable prior period development in 2018 included favorable reinsurance settlements of $205 million related to legacy run-off exposures.

- Operating cash flow was $6,342 million compared with $5,480 million in 2018, an increase of $862 million primarily due to higher underwriting cash flow. Refer to the Liquidity section for additional information on our cash flows.
- Net investment income was $3,426 million compared with $3,305 million in 2018.
- Share repurchases totaled $1,531 million, or approximately 10.4 million shares for the year, at an average purchase price of $146.61 per share.

Outlook

We completed 2019 with net premiums written growth of 5.5 percent, or 7.0 percent on a constant-dollar basis. Premium growth accelerated globally with the current pricing and underwriting environment, which has continued to improve in more lines of business and more territories. We plan to use our global presence to capitalize on these market conditions in the year ahead, while continuing to focus on our long-term strategic growth initiatives.

Our net investment income increased 3.6 percent in 2019, reflecting strong operating cash flow and a higher invested asset base. There are several factors that impact the variability in investment income, including interest rates and private equity distributions. Nevertheless, we expect our quarterly pre-tax net investment income in 2020 to be in the range of $852 million to $862 million, including the expected amortization of the fair value adjustment on acquired invested assets, at current exchange rates, of approximately $33 million per quarter. Excluding the amortization of the fair value adjustment on acquired invested assets, we expect quarterly pre-tax adjusted net investment income in 2020 to be in the range of $885 million to $895 million. The estimate of amortization expense of the fair value adjustment on acquired invested assets could vary materially based on current market conditions, bond calls, overall duration of the acquired investment portfolio, and foreign exchange.

During 2019, Chubb increased its ownership interest in Huatai Group and is committed to acquire additional interests with the goal of majority and beyond ownership. To that end, Chubb entered into agreements to purchase an additional 22.4 percent ownership in Huatai Group through separate purchases of 15.3 percent and 7.1 percent, respectively, each contingent upon regulatory approvals and other important conditions. At the completion of the 7.1 percent purchase, which is expected by the end of 2021, Chubb is expected to apply consolidation accounting.

Critical Accounting Estimates

Our consolidated financial statements include amounts that, either by their nature or due to requirements of generally accepted accounting principles in the U.S. (GAAP), are determined using best estimates and assumptions. While we believe that the amounts included in our consolidated financial statements reflect our best judgment, actual amounts could ultimately materially differ from those currently presented. We believe the items that require the most subjective and complex estimates are:

- unpaid loss and loss expense reserves, including long-tail asbestos and environmental (A&E) reserves and non-A&E casualty exposures;
- future policy benefits reserves;
- the valuation of value of business acquired (VOBA) and amortization of deferred policy acquisition costs and VOBA;
- the assessment of risk transfer for certain structured insurance and reinsurance contracts;
- reinsurance recoverable, including a provision for uncollectible reinsurance;
- the valuation of our investment portfolio and assessment of other-than-temporary impairments (OTTI);
- the valuation of deferred income taxes;
- the valuation of derivative instruments related to guaranteed living benefits (GLB); and
- the assessment of goodwill for impairment.

We believe our accounting policies for these items are of critical importance to our consolidated financial statements. The following discussion provides more information regarding the estimates and assumptions required to arrive at these amounts and should be read in conjunction with the sections entitled: Prior Period Development, Asbestos and Environmental (A&E), Reinsurance Recoverable on Ceded Reinsurance, Investments, Net Realized and Unrealized Gains (Losses), and Other Income and Expense Items.

Unpaid losses and loss expenses

As an insurance and reinsurance company, we are required by applicable laws and regulations and GAAP to establish loss and loss expense reserves for the estimated unpaid portion of the ultimate liability for losses and loss expenses under the terms of our policies and agreements with our insured and reinsured customers. At December 31, 2019, our gross unpaid loss and loss expense reserves were $62.7 billion and our net unpaid loss and loss expense reserves were $48.5 billion. With the exception of certain structured settlements, for which the timing and amount of future claim payments are reliably determinable, and certain reserves for unsettled claims, our loss reserves are not discounted for the time value of money. In connection with such structured settlements and certain reserves for unsettled claims, we carried net discounted reserves of $74 million and $73 million at December 31, 2019 and 2018, respectively.

The following table presents a roll-forward of our unpaid losses and loss expenses:

	December 31, 2019			December 31, 2018		
(in millions of U.S. dollars)	**Gross Losses**	**Reinsurance Recoverable[(1)]**	**Net Losses**	Gross Losses	Reinsurance Recoverable[(1)]	Net Losses
Balance, beginning of year	**$ 62,960**	**$ 14,689**	**$ 48,271**	$ 63,179	$ 14,014	$ 49,165
Losses and loss expenses incurred	**23,657**	**4,927**	**18,730**	23,645	5,578	18,067
Losses and loss expenses paid	**(23,911)**	**(5,438)**	**(18,473)**	(23,079)	(4,739)	(18,340)
Other (including foreign exchange translation)	**(16)**	**3**	**(19)**	(785)	(164)	(621)
Balance, end of year	**$ 62,690**	**$ 14,181**	**$ 48,509**	$ 62,960	$ 14,689	$ 48,271

(1) Net of provision for uncollectible reinsurance.

The estimate of the liabilities includes provisions for claims that have been reported but are unpaid at the balance sheet date (case reserves) and for obligations on claims that have been incurred but not reported (IBNR) at the balance sheet date. IBNR may also include provisions to account for the possibility that reported claims may settle for amounts that differ from the established case reserves. Loss reserves also include an estimate of expenses associated with processing and settling unpaid claims (loss expenses). Our loss reserves comprise approximately 80 percent casualty-related business, which typically encompasses long-tail risks, and other risks where a high degree of judgment is required.

The process of establishing loss reserves for property and casualty claims can be complex and is subject to considerable uncertainty as it requires the use of informed estimates and judgments based on circumstances underlying the insured losses known at the date of accrual. For example, the reserves established for high excess casualty claims, asbestos and environmental claims, claims from major catastrophic events, or for our various product lines each require different assumptions and judgments to be made. Necessary judgments are based on numerous factors and may be revised as additional experience and other data become available and are reviewed, as new or improved methods are developed, or as laws change. Hence, ultimate loss payments may differ from the estimate of the ultimate liabilities made at the balance sheet date. Changes to our previous estimates of prior period loss reserves impact the reported calendar year underwriting results adversely if our estimates increase or favorably if our estimates decrease. The potential for variation in loss reserve estimates is impacted by numerous factors. Reserve estimates for casualty lines are particularly uncertain given the lengthy reporting patterns and corresponding need for IBNR.

Case reserves for those claims reported by insureds or ceding companies to us prior to the balance sheet date and where we have sufficient information are determined by our claims personnel as appropriate based on the circumstances of the claim(s), standard claim handling practices, and professional judgment. Furthermore, for our Brandywine run-off operations and our assumed reinsurance operation, Global Reinsurance, we may adjust the case reserves as notified by the ceding company if the judgment of our respective claims department differs from that of the cedant.

With respect to IBNR reserves and those claims that have been incurred but not reported prior to the balance sheet date, there is, by definition, limited actual information to form the case reserve estimate and reliance is placed upon historical loss experience and actuarial methods to estimate the ultimate loss obligations and the corresponding amount of IBNR. IBNR reserve estimates are generally calculated by first projecting the ultimate amount of losses for a product line and subtracting paid losses and case reserves for reported claims. The judgments involved in projecting the ultimate losses may pertain to the use and interpretation of various standard actuarial reserving methods that place reliance on the extrapolation of actual historical data, loss development patterns, industry data, and other benchmarks as appropriate. The estimate of the required IBNR reserve also requires judgment by actuaries and management to reflect the impact of more contemporary and subjective factors, both qualitative and quantitative. Among some of these factors that might be considered are changes in business mix or volume, changes in ceded reinsurance structures, changes in claims handling practices, reported and projected loss trends, inflation, the legal environment, and the terms and conditions of the contracts sold to our insured parties.

Determining management's best estimate

Our recorded reserves represent management's best estimate of the provision for unpaid claims as of the balance sheet date, and establishing them involves a process that includes collaboration with various relevant parties in the company. For information on our reserving process, refer to Note 7 to the Consolidated Financial Statements.

Sensitivity to underlying assumptions

While we believe that our reserve for unpaid losses and loss expenses at December 31, 2019, is adequate, new information or emerging trends that differ from our assumptions may lead to future development of losses and loss expenses that is significantly greater or less than the recorded reserve, which could have a material effect on future operating results. As noted previously, our best estimate of required loss reserves for most portfolios is judgmentally selected for each origin year after considering the results from a number of reserving methods and is not a purely mechanical process. Therefore, it is difficult to convey, in a simple and quantitative manner, the impact that a change to a single assumption will have on our best estimate. In the examples below, we attempt to give an indication of the potential impact by isolating a single change for a specific reserving method that would be pertinent in establishing the best estimate for the product line described. We consider each of the following sensitivity analyses to represent a reasonably likely deviation in the underlying assumption.

North America Commercial P&C Insurance

Given the long reporting and paid development patterns for workers' compensation business, the development factors used to project actual current losses to ultimate losses for our current exposure require considerable judgment that could be material to consolidated loss and loss expense reserves. Specifically, adjusting ground up ultimate losses by a one percent change in the tail factor (i.e., 1.04 changed to either 1.05 or 1.03) would cause a change of approximately $823 million, either positive or negative, for the projected net loss and loss expense reserves. This represents an impact of about 8.8 percent relative to recorded net loss and loss expense reserves of approximately $9.4 billion.

The reserve portfolio for our Chubb Bermuda operations contains exposure to predominantly high excess liability coverage on an occurrence-first-reported basis (typically with attachment points in excess of $325 million and gross limits of up to $150 million) and D&O and other professional liability coverage on a claims-made basis (typically with attachment points in excess of $125 million and gross limits of up to $75 million). Due to the layer of exposure covered, the expected frequency for this book is very low. As a result of the low frequency/high severity nature of the book, a small difference in the actual vs. expected claim frequency, either positive or negative, could result in a material change to the projected ultimate loss if such change in claim frequency was related to a policy where close to maximum limits were deployed.

North America Personal P&C Insurance

Due to the relatively short-tailed nature of many of the coverages involved (e.g., homeowners property damage), most of the incurred losses in Personal Lines are resolved within a few years of occurrence. As shown in our loss triangle disclosure, the vast majority (over 95 percent) of Personal Lines net ultimate losses and allocated loss adjustment expenses are typically paid within five years of the accident date and over 80 percent within two years. Even though there are significant reserves associated with some liability exposures such as personal excess/umbrella liability, our incurred loss triangle also shows a roughly consistent pattern of only relatively minor movements in incurred estimates over time by accident year especially after twenty-four months of maturity. While the liability exposures are subject to additional uncertainties from more protracted resolution times, the main drivers of volatility in the Personal Lines business are relatively short-term in nature and relate to things like natural catastrophes, non-catastrophe weather events, man-made risks, and individual large loss volatility from other fortuitous claim events.

North America Agricultural Insurance

Approximately 66 percent of the reserves for this segment are from the crop related lines, which all have short payout patterns, with the majority of the liabilities expected to be resolved in the ensuing twelve months. Claim reserves for our Multiple Peril Crop Insurance (MPCI) product are set on a case-by-case basis and our aggregate exposure is subject to state level risk sharing formulae as well as third-party reinsurance. The majority of the development risk arises out of the accuracy of case reserve estimates and the time needed for final crop conditions to be assessed. We do not view our Agriculture reserves as substantially influenced by the general assumptions and risks underlying more typical P&C reserve estimates.

Overseas General Insurance
Certain long-tail lines, such as casualty and professional lines, are particularly susceptible to changes in loss trend and claim inflation. Heightened perceptions of tort and settlement awards around the world can increase the demand for these products as well as contributing to the uncertainty in the reserving estimates. Our reserving methods rely on loss development patterns estimated from historical data and while we attempt to adjust such factors for known changes in the current tort environment, it is possible that such factors may not entirely reflect all recent trends in tort environments. For example, when applying the reported loss development method, the lengthening of our selected loss development patterns by six months would increase reserve estimates on long-tail casualty and professional lines for accident years 2017 and prior by approximately $525 million. This represents an impact of 14.4 percent relative to recorded net loss and loss expense reserves of approximately $3.6 billion.

Global Reinsurance
Typically, there is inherent uncertainty around the length of paid and reported development patterns, especially for certain casualty lines such as excess workers' compensation or general liability, which may take decades to fully develop. This uncertainty is accentuated by the need to supplement client development patterns with industry development patterns due to the sometimes low statistical credibility of the data. The underlying source and selection of the final development patterns can thus have a significant impact on the selected ultimate net losses and loss expenses. For example, a 20 percent shortening or lengthening of the development patterns used for U.S. long-tail lines would cause the loss reserve estimate derived by the reported Bornhuetter-Ferguson method for these lines to change by approximately $285 million. This represents an impact of 43 percent relative to recorded net loss and loss expense reserves of approximately $670 million.

Assumed reinsurance
At December 31, 2019, net unpaid losses and loss expenses for the Global Reinsurance segment aggregated to $1.4 billion, consisting of $769 million of case reserves and $664 million of IBNR. In comparison, at December 31, 2018, net unpaid losses and loss expenses for the Global Reinsurance segment aggregated to $1.6 billion, consisting of $807 million of case reserves and $807 million of IBNR.

For our catastrophe business, we principally estimate unpaid losses and loss expenses on an event basis by considering various sources of information, including specific loss estimates reported by our cedants, ceding company and overall industry loss estimates reported by our brokers, and our internal data regarding reinsured exposures related to the geographical location of the event. Our internal data analysis enables us to establish catastrophe reserves for known events with more certainty at an earlier date than would be the case if we solely relied on reports from third parties to determine carried reserves.

For our casualty reinsurance business, we generally rely on ceding companies to report claims and then use that data as a key input to estimate unpaid losses and loss expenses. Due to the reliance on claims information reported by ceding companies, as well as other factors, the estimation of unpaid losses and loss expenses for assumed reinsurance includes certain risks and uncertainties that are unique relative to our direct insurance business. These include, but are not necessarily limited to, the following:

- The reported claims information could be inaccurate;
- Typically, a lag exists between the reporting of a loss event to a ceding company and its reporting to us as a reinsurance claim. The use of a broker to transmit financial information from a ceding company to us increases the reporting lag. Because most of our reinsurance business is produced by brokers, ceding companies generally first submit claim and other financial information to brokers, who then report the proportionate share of such information to each reinsurer of a particular treaty. The reporting lag generally results in a longer period of time between the date a claim is incurred and the date a claim is reported compared with direct insurance operations. Therefore, the risk of delayed recognition of loss reserve development is higher for assumed reinsurance than for direct insurance lines; and
- The historical claims data for a particular reinsurance contract can be limited relative to our insurance business in that there may be less historical information available. Further, for certain coverages or products, such as excess of loss contracts, there may be relatively few expected claims in a particular year so the actual number of claims may be susceptible to significant variability. In such cases, the actuary often relies on industry data from several recognized sources.

We mitigate the above risks in several ways. In addition to routine analytical reviews of ceding company reports to ensure reported claims information appears reasonable, we perform regular underwriting and claims audits of certain ceding companies to ensure reported claims information is accurate, complete, and timely. As appropriate, audit findings are used to adjust claims in the reserving process. We also use our knowledge of the historical development of losses from individual ceding companies to adjust the level of adequacy we believe exists in the reported ceded losses.

On occasion, there will be differences between our carried loss reserves and unearned premium reserves and the amount of loss reserves and unearned premium reserves reported by the ceding companies. This is due to the fact that we receive consistent and timely information from ceding companies only with respect to case reserves. For IBNR, we use historical experience and other statistical information, depending on the type of business, to estimate the ultimate loss. We estimate our unearned premium reserve by applying estimated earning patterns to net premiums written for each treaty based upon that treaty's coverage basis (i.e., risks attaching or losses occurring). At December 31, 2019, the case reserves reported to us by our ceding companies were $758 million, compared with the $769 million we recorded. Our policy is to post additional case reserves in addition to the amounts reported by our cedants when our evaluation of the ultimate value of a reported claim is different than the evaluation of that claim by our cedant.

Within Corporate, we also have exposure to certain liability reinsurance lines that have been in run-off since 1994. Unpaid losses and loss expenses relating to this run-off reinsurance business resides within the Brandywine Division reported within Corporate. Most of the remaining unpaid loss and loss expense reserves for the run-off reinsurance business relate to A&E claims. Refer to the “Asbestos and Environmental (A&E)” section for additional information.

Asbestos and environmental reserves
Included in our liabilities for losses and loss expenses are amounts for A&E (A&E liabilities). The A&E liabilities principally relate to claims arising from bodily-injury claims related to asbestos products and remediation costs associated with hazardous waste sites. The estimation of our A&E liabilities is particularly sensitive to future changes in the legal, social, and economic environment. We have not assumed any such future changes in setting the value of our A&E liabilities, which include provisions for both reported and IBNR claims.

There are many complex variables that we consider when estimating the reserves for our inventory of asbestos accounts and these variables may directly impact the predicted outcome. We believe the most significant variables relating to our A&E liabilities include the current legal environment; specific settlements that may be used as precedents to settle future claims; assumptions regarding trends with respect to claim severity and the frequency of higher severity claims; assumptions regarding the ability to allocate liability among defendants (including bankruptcy trusts) and other insurers; the ability of a claimant to bring a claim in a state in which they have no residency or exposure; the ability of a policyholder to claim the right to unaggregated coverage; whether high-level excess policies have the potential to be accessed given the policyholder's claim trends and liability situation; payments to unimpaired claimants; and, the potential liability of peripheral defendants. Based on the policies, the facts, the law, and a careful analysis of the impact that these factors will likely have on any given account, we estimate the potential liability for indemnity, policyholder defense costs, and coverage litigation expense.

The results in asbestos cases announced by other carriers or defendants may well have little or no relevance to us because coverage exposures are highly dependent upon the specific facts of individual coverage and resolution status of disputes among carriers, policyholders, and claimants.

For additional information refer to the “Asbestos and Environmental (A&E)” section and to Note 7 to the Consolidated Financial Statements.

Future policy benefits reserves
We issue contracts in our Overseas General Insurance and Life Insurance segments that are classified as long-duration. These contracts generally include accident and supplemental health products, term and whole life products, endowment products, and annuities. In accordance with GAAP, we establish reserves for contracts determined to be long-duration based on approved actuarial methods that include assumptions related to expenses, mortality, morbidity, persistency, and investment yields with a factor for adverse deviation. These assumptions are “locked in” at the inception of the contract, meaning we use our original assumptions throughout the life of the policy and do not subsequently modify them unless we deem the reserves to be inadequate. The future policy benefits reserves balance is regularly evaluated for a premium deficiency. If experience is less favorable than assumptions, additional liabilities may be required, resulting in a charge to policyholder benefits and claims.

Valuation of value of business acquired (VOBA), and amortization of deferred policy acquisition costs and VOBA
As part of the acquisition of businesses that sell long-duration contracts, such as life products, we established an intangible asset related to VOBA, which represented the fair value of the future profits of the in-force contracts. The valuation of VOBA at the time of acquisition is derived from similar assumptions to those used to establish the associated future policy benefits

reserves. The most significant input in this calculation is the discount rate used to arrive at the present value of the net cash flows. We amortize deferred policy acquisition costs associated with long-duration contracts and VOBA (collectively policy acquisition costs) over the estimated life of the contracts, generally in proportion to premium revenue recognized based upon the same assumptions used in estimating the liability for future policy benefits. For non-traditional long-duration contracts, we amortize policy acquisition costs over the expected life of the contracts in proportion to estimates of expected gross profits. The estimated life is established at the inception of the contracts or upon acquisition and is based on current persistency assumptions. Policy acquisition costs, which consist of commissions, premium taxes, and certain underwriting costs related directly to the successful acquisition of a new or renewal insurance contract, are reviewed to determine if they are recoverable from future income, including investment income. Unrecoverable costs are expensed in the period identified.

Risk transfer

In the ordinary course of business, we both purchase (or cede) and sell (or assume) reinsurance protection. We discontinued the purchase of all finite risk reinsurance contracts, as a matter of policy, in 2002. For both ceded and assumed reinsurance, risk transfer requirements must be met in order to use reinsurance accounting, principally resulting in the recognition of cash flows under the contract as premiums and losses. If risk transfer requirements are not met, a contract is to be accounted for as a deposit, typically resulting in the recognition of cash flows under the contract through a deposit asset or liability and not as revenue or expense. To meet risk transfer requirements, a reinsurance contract must include both insurance risk, consisting of underwriting and timing risk, and a reasonable possibility of a significant loss for the assuming entity. We also apply similar risk transfer requirements to determine whether certain commercial insurance contracts should be accounted for as insurance or a deposit. Contracts that include fixed premium (i.e., premium not subject to adjustment based on loss experience under the contract) for fixed coverage generally transfer risk and do not require judgment.

Reinsurance and insurance contracts that include both significant risk sharing provisions, such as adjustments to premiums or loss coverage based on loss experience, and relatively low policy limits, as evidenced by a high proportion of maximum premium assessments to loss limits, can require considerable judgment to determine whether or not risk transfer requirements are met. For such contracts, often referred to as finite or structured products, we require that risk transfer be specifically assessed for each contract by developing expected cash flow analyses at contract inception. To support risk transfer, the cash flow analyses must demonstrate that a significant loss is reasonably possible, such as a scenario in which the ratio of the net present value of losses divided by the net present value of premiums equals or exceeds 110 percent. For purposes of cash flow analyses, we generally use a risk-free rate of return consistent with the expected average duration of loss payments. In addition, to support insurance risk, we must prove the reinsurer's risk of loss varies with that of the reinsured and/or support various scenarios under which the assuming entity can recognize a significant loss.

To ensure risk transfer requirements are routinely assessed, qualitative and quantitative risk transfer analyses and memoranda supporting risk transfer are developed by underwriters for all structured products. We have established protocols for structured products that include criteria triggering an accounting review of the contract prior to quoting. If any criterion is triggered, a contract must be reviewed by a committee established by each of our segments with reporting oversight, including peer review, from our global Structured Transaction Review Committee.

With respect to ceded reinsurance, we entered into a few multi-year excess of loss retrospectively-rated contracts, principally in 2002. These contracts primarily provided severity protection for specific product divisions. Because traditional one-year reinsurance coverage had become relatively costly, these contracts were generally entered into in order to secure a more cost-effective reinsurance program. All of these contracts transferred risk and were accounted for as reinsurance. In addition, we maintain a few aggregate excess of loss reinsurance contracts that were principally entered into prior to 2003, such as the National Indemnity Company (NICO) contracts referred to in the section entitled, “Asbestos and Environmental (A&E)”. We have not purchased any other retroactive ceded reinsurance contracts since 1999.

With respect to assumed reinsurance and insurance contracts, products giving rise to judgments regarding risk transfer were primarily sold by our financial solutions business. Although we have significantly curtailed writing financial solutions business, several contracts remain in-force and principally include multi-year retrospectively-rated contracts and loss portfolio transfers. Because transfer of insurance risk is generally a primary client motivation for purchasing these products, relatively few insurance and reinsurance contracts have historically been written for which we concluded that risk transfer criteria had not been met. For certain insurance contracts that have been reported as deposits, the insured desired to self-insure a risk but was required, legally or otherwise, to purchase insurance so that claimants would be protected by a licensed insurance company in the event of non-payment from the insured.

Reinsurance recoverable
Reinsurance recoverable includes balances due to us from reinsurance companies for paid and unpaid losses and loss expenses and is presented net of a provision for uncollectible reinsurance. The provision for uncollectible reinsurance is determined based upon a review of the financial condition of the reinsurers and other factors. Ceded reinsurance contracts do not relieve our primary obligation to our policyholders. Consequently, an exposure exists with respect to reinsurance recoverable to the extent that any reinsurer is unable or unwilling to meet its obligations or disputes the liabilities assumed under the reinsurance contracts. We determine the reinsurance recoverable on unpaid losses and loss expenses using actuarial estimates as well as a determination of our ability to cede unpaid losses and loss expenses under existing reinsurance contracts.

The recognition of a reinsurance recoverable asset requires two key judgments. The first judgment involves our estimation based on the amount of gross reserves and the percentage of that amount which may be ceded to reinsurers. Ceded IBNR, which is a major component of the reinsurance recoverable on unpaid losses and loss expenses, is generally developed as part of our loss reserving process and, consequently, its estimation is subject to similar risks and uncertainties as the estimation of gross IBNR (refer to "Critical Accounting Estimates – Unpaid losses and loss expenses"). The second judgment involves our estimate of the amount of the reinsurance recoverable balance that we may ultimately be unable to recover from reinsurers due to insolvency, contractual dispute, or for other reasons. Estimated uncollectible amounts are reflected in a provision that reduces the reinsurance recoverable asset and, in turn, shareholders' equity. Changes in the provision for uncollectible reinsurance are reflected in net income.

Although the obligation of individual reinsurers to pay their reinsurance obligations is based on specific contract provisions, the collectability of such amounts requires estimation by management. The majority of the recoverable balance will not be due for collection until sometime in the future, and the duration of our recoverables may be longer than the duration of our direct exposures. Over this period of time, economic conditions and operational performance of a particular reinsurer may impact their ability to meet these obligations and while they may continue to acknowledge their contractual obligation to do so, they may not have the financial resources or willingness to fully meet their obligation to us.

To estimate the provision for uncollectible reinsurance, the reinsurance recoverable must first be determined for each reinsurer. This determination is based on a process rather than an estimate, although an element of judgment must be applied. As part of the process, ceded IBNR is allocated to reinsurance contracts because ceded IBNR is not generally calculated on a contract by contract basis. The allocations are generally based on premiums ceded under reinsurance contracts, adjusted for actual loss experience and historical relationships between gross and ceded losses. If actual premium and loss experience vary materially from historical experience, the allocation of reinsurance recoverable by reinsurer will be reviewed and may change. While such change is unlikely to result in a large percentage change in the provision for uncollectible reinsurance, it could, nevertheless, have a material effect on our net income in the period recorded.

Generally, we use a default analysis to estimate uncollectible reinsurance. The primary components of the default analysis are reinsurance recoverable balances by reinsurer, net of collateral, and default factors used to estimate the probability that the reinsurer may be unable to meet its future obligations in full. The definition of collateral for this purpose requires some judgment and is generally limited to assets held in a Chubb-only beneficiary trust, letters of credit, and liabilities held by us with the same legal entity for which we believe there is a right of offset. We do not currently include multi-beneficiary trusts. However, we have several reinsurers that have established multi-beneficiary trusts for which certain of our companies are beneficiaries. The determination of the default factor is principally based on the financial strength rating of the reinsurer and a corresponding default factor applicable to the financial strength rating. Default factors require considerable judgment and are determined using the current financial strength rating, or rating equivalent, of each reinsurer as well as other key considerations and assumptions. Significant considerations and assumptions include, but are not necessarily limited to, the following:

- For reinsurers that maintain a financial strength rating from a major rating agency, and for which recoverable balances are considered representative of the larger population (i.e., default probabilities are consistent with similarly rated reinsurers and payment durations conform to averages), the judgment exercised by management to determine the provision for uncollectible reinsurance of each reinsurer is typically limited because the financial rating is based on a published source and the default factor we apply is based on a historical default factor of a major rating agency applicable to the particular rating class. Default factors applied for financial ratings of AAA, AA, A, BBB, BB, B, and CCC, are 0.8 percent, 1.2 percent, 1.7 percent, 4.9 percent, 19.6 percent, 34.0 percent, and 62.2 percent, respectively. Because our model is predicated on the historical default factors of a major rating agency, we do not generally consider alternative factors. However, when a recoverable is expected to be paid in a brief period of time by a highly-rated reinsurer, such as certain property catastrophe claims, a default factor may not be applied;

- For balances recoverable from reinsurers that are both unrated by a major rating agency and for which management is unable to determine a credible rating equivalent based on a parent or affiliated company, we may determine a rating equivalent based on our analysis of the reinsurer that considers an assessment of the creditworthiness of the particular entity, industry benchmarks, or other factors as considered appropriate. We then apply the applicable default factor for that rating class. For balances recoverable from unrated reinsurers for which our ceded reserve is below a certain threshold, we generally apply a default factor of 34.0 percent;
- For balances recoverable from reinsurers that are either insolvent or under regulatory supervision, we establish a default factor and resulting provision for uncollectible reinsurance based on specific facts and circumstances surrounding each company. Upon initial notification of an insolvency, we generally recognize expense for a substantial portion of all balances outstanding, net of collateral, through a combination of write-offs of recoverable balances and increases to the provision for uncollectible reinsurance. When regulatory action is taken on a reinsurer, we generally recognize a default factor by estimating an expected recovery on all balances outstanding, net of collateral. When sufficient credible information becomes available, we adjust the provision for uncollectible reinsurance by establishing a default factor pursuant to information received; and
- For captives and other recoverables, management determines the provision for uncollectible reinsurance based on the specific facts and circumstances.

The following table summarizes reinsurance recoverables and the provision for uncollectible reinsurance for each type of recoverable balance at December 31, 2019:

(in millions of U.S. dollars)	Gross Reinsurance Recoverables on Losses and Loss Expenses	Recoverables (net of Usable Collateral)	Provision for Uncollectible Reinsurance [1]
Type			
Reinsurers with credit ratings	$ 11,460	$ 10,043	$ 156
Reinsurers not rated	321	190	66
Reinsurers under supervision and insolvent reinsurers	81	79	37
Captives	2,647	378	20
Other - structured settlements and pools	988	978	37
Total	$ 15,497	$ 11,668	$ 316

[1] The provision for uncollectible reinsurance is based on a default analysis applied to gross reinsurance recoverables, net of approximately $3.8 billion of collateral at December 31, 2019.

At December 31, 2019, the use of different assumptions within our approach could have a material effect on the provision for uncollectible reinsurance. To the extent the creditworthiness of our reinsurers were to deteriorate due to an adverse event affecting the reinsurance industry, such as a large number of major catastrophes, actual uncollectible amounts could be significantly greater than our provision for uncollectible reinsurance. Such an event could have a material adverse effect on our financial condition, results of operations, and our liquidity. Given the various considerations used to estimate our uncollectible provision, we cannot precisely quantify the effect a specific industry event may have on the provision for uncollectible reinsurance. However, based on the composition (particularly the average credit quality) of the reinsurance recoverable balance at December 31, 2019, we estimate that a ratings downgrade of one notch for all rated reinsurers (e.g., from A to A- or A- to BBB+) could increase our provision for uncollectible reinsurance by approximately $66 million or approximately 0.4 percent of the gross reinsurance recoverable balance, assuming no other changes relevant to the calculation. While a ratings downgrade would result in an increase in our provision for uncollectible reinsurance and a charge to earnings in that period, a downgrade in and of itself does not imply that we will be unable to collect all of the ceded reinsurance recoverable from the reinsurers in question. Refer to Note 5 to the Consolidated Financial Statements for additional information.

Fair value measurements

Accounting guidance defines fair value as the price to sell an asset or transfer a liability (an exit price) in an orderly transaction between market participants and establishes a three-level valuation hierarchy based on the reliability of the inputs. The fair value hierarchy gives the highest priority to quoted prices in active markets (Level 1 inputs) and the lowest priority to unobservable data (Level 3 inputs). Level 2 includes inputs, other than quoted prices within Level 1, that are observable for assets or liabilities either directly or indirectly. Refer to Note 4 and Note 13 to the Consolidated Financial Statements for information on our fair value measurements.

Other-than-temporary impairments (OTTI)
Each quarter, we review securities in an unrealized loss position (impaired securities), including fixed maturities and securities lending collateral to identify impaired securities to be specifically evaluated for a potential OTTI. Because our investment portfolio is the largest component of consolidated assets, OTTI could be material to our financial condition and results of operations. Refer to Note 3 c) to the Consolidated Financial Statements for a description of the OTTI process.

Deferred income taxes
At December 31, 2019, our net deferred tax liability was $804 million. Our deferred tax assets and liabilities primarily result from temporary differences between the amounts recorded in our consolidated financial statements and the tax basis of our assets and liabilities. We determine deferred tax assets and liabilities separately for each tax-paying component (an individual entity or group of entities that is consolidated for tax purposes) in each tax jurisdiction. The realization of deferred tax assets depends upon the existence of sufficient taxable income within the carryback or carryforward periods under the tax law in the applicable tax jurisdiction. There may be changes in tax laws in a number of countries where we transact business that impact our deferred tax assets and liabilities.

At each balance sheet date, management assesses the need to establish a valuation allowance that reduces deferred tax assets when it is more likely than not that all, or some portion, of the deferred tax assets will not be realized. The determination of the need for a valuation allowance is based on all available information including projections of future taxable income, principally derived from business plans and where appropriate available tax planning strategies. Projections of future taxable income incorporate assumptions of future business and operations that are apt to differ from actual experience. If our assumptions and estimates that resulted in our forecast of future taxable income prove to be incorrect, an additional valuation allowance could become necessary, which could have a material adverse effect on our financial condition, results of operations, and liquidity. At December 31, 2019, the valuation allowance of $114 million reflects management's assessment that it is more likely than not that a portion of the deferred tax assets will not be realized due to the inability of certain foreign subsidiaries to generate sufficient taxable income.

Assumed reinsurance programs involving minimum benefit guarantees under variable annuity contracts
Chubb reinsures various death and living benefit guarantees associated with variable annuities issued primarily in the United States. We ceased writing this business in 2007. Guarantees which are payable on death are referred to as guaranteed minimum death benefits (GMDB). Guarantees on living benefits (GLB) consist mainly of guaranteed minimum income benefits (GMIB). For further description of this product and related accounting treatment, refer to Note 1 j) to the Consolidated Financial Statements.

Guaranteed living benefits (GLB) derivatives
Our GLB reinsurance is classified as a derivative for accounting purposes and therefore carried at fair value. We believe that the most meaningful presentation of these GLB derivatives is as follows:

- Estimates of the average modeled value of future cash outflows is recorded as incurred losses (i.e., benefit reserves). Cash inflows or revenue are reported as net premiums earned and changes in the benefit reserves are reflected as Policy benefits expense in the Consolidated statements of operations, which is included in underwriting income.
- The incremental difference between the fair value of GLB reinsurance contracts and benefit reserves is reflected in Accounts payable, accrued expenses, and other liabilities in the Consolidated balance sheets and related changes in fair value are reflected in Net realized gains (losses) in the Consolidated statements of operations.

Determination of GLB fair value
The fair value of GLB reinsurance is estimated using an internal valuation model, which includes current market information and estimates of policyholder behavior from the perspective of a theoretical market participant that would assume these liabilities. All of our treaties contain claim limits, which are factored into the valuation model. The fair value depends on a number of factors, including interest rates, equity markets, credit risk, current account value, market volatility, expected annuitization rates and other policyholder behavior, and changes in policyholder mortality. The model and related assumptions are regularly re-evaluated by management and enhanced, as appropriate, based upon additional experience obtained related to policyholder behavior and availability of more timely market information. Due to the inherent uncertainties of the assumptions used in the valuation models to determine the fair value of these derivative products, actual experience may differ materially from the estimates reflected in our Consolidated Financial Statements.

We intend to hold these derivative contracts to maturity (i.e., the expiration of the underlying liabilities through lapse, annuitization, death, or expiration of the reinsurance contract). To partially offset the risk of changes in the fair value of GLB reinsurance contracts, we invest in derivative hedge instruments. At maturity, the cumulative realized gains and losses (excluding cumulative hedge gains or losses) from fair value changes of GLB reinsurance contracts will net to zero because, over time, the insurance liability will be increased or decreased to equal our obligation.

Determination of GLB and GMDB benefit reserves

Management established benefit reserves based on a long-term benefit ratio (or loss ratio) calculated using assumptions reflecting management's best estimate of the future short-term and long-term performance of the variable annuity line of business. Despite the long-term nature of the risk, the benefit ratio calculation is impacted by short-term market movements that may be judged by management to be transient. Management regularly examines both qualitative and quantitative analysis, including a review of the differential between the benefit ratio used at the most recent valuation date and the benefit ratio calculated on subsequent dates. Management regularly evaluates its estimates and uses judgment to determine the extent to which assumptions underlying the benefit ratio calculation should be adjusted. For the year ended December 31, 2019, management determined that no change to the benefit ratio was warranted.

For further information on the estimates and assumptions used in determining the fair value of GLB reinsurance, refer to Note 4 to the Consolidated Financial Statements. For a sensitivity discussion of the effect of changes in interest rates, equity indices, and other assumptions on the fair value of GLBs, and the estimated resulting impact on our net income, refer to Item 7A.

Risk Management

We employ a strategy to manage the financial market and policyholder behavior risks embedded in the reinsurance of variable annuity (VA) guarantees. Risk management begins with underwriting a prospective client and guarantee design, with particular focus on protecting our position from policyholder options that, because of anti-selective behavior, could adversely impact our obligation.

A second layer of risk management is the structure of the reinsurance contracts. All VA guarantee reinsurance contracts include some form of annual or aggregate claim limit(s) primarily designed to reduce our exposure to severe equity market and/or interest rate declines (which would cause an increase in expected claims).

A third layer of risk management is the hedging strategy which looks to mitigate both long-term economic loss over time as well as dampen income statement volatility. We owned financial market instruments as part of the hedging strategy with a fair value asset (liability) of $(13) million and $23 million at December 31, 2019 and 2018, respectively. The instruments are substantially collateralized on a daily basis.

We also limit the aggregate amount of variable annuity reinsurance guarantee risk we are willing to assume. The last substantive transactions were quoted in late 2007. The aggregate number of policyholders is currently decreasing through policyholder withdrawals, annuitizations, and deaths at a rate of 5 percent to 15 percent per annum.

Note that GLB claims cannot occur for any reinsured policy until it has reached the end of its "waiting period". As shown in the table below, 92 percent of the policies we reinsure reached the end of their "waiting periods" in 2019 and prior.

Year of first payment eligibility	Percent of living benefit account values
2019 and prior	92%
2020	1%
2021	2%
2022	—%
2023	1%
2024 and after	4%
Total	100%

The following table presents the historical cash flows under these policies for the periods indicated. The amounts represent accrued past premium received and claims paid, split by benefit type.

	2019			2018			2017		
(in millions of U.S. dollars)	**GMDB**	**GLB**	**Total**	GMDB	GLB	Total	GMDB	GLB	Total
Premium received	**$ 40**	**$ 91**	**$ 131**	$ 47	$ 96	$ 143	$ 49	$ 110	$ 159
Less paid claims	**34**	**91**	**125**	32	49	81	31	54	85
Net cash received	**$ 6**	**$ —**	**$ 6**	$ 15	$ 47	$ 62	$ 18	$ 56	$ 74

Collateral

Chubb holds collateral on behalf of most of its clients in the form of qualified assets in trust or letters of credit, typically in an amount sufficient for the client to obtain statutory reserve credit for the reinsurance. The timing of the calculation and amount of the collateral varies by client according to the particulars of the reinsurance treaty and the statutory reserve guidelines of the client's domicile.

Goodwill impairment assessment

Goodwill, which represents the excess of acquisition cost over the estimated fair value of net assets acquired, was $15.3 billion at both December 31, 2019 and 2018. Goodwill is assigned to applicable reporting units of acquired entities at the time of acquisition. Our reporting units are the same as our reportable segments. For goodwill balances by reporting units, refer to Note 6 to the Consolidated Financial Statements.

Goodwill is not amortized but is subject to a periodic evaluation for impairment at least annually, or earlier if there are any indications of possible impairment. Impairment is tested at the reporting unit level. The impairment evaluation first uses a qualitative assessment to determine whether it is more likely than not (i.e., more than a 50 percent probability) that the fair value of a reporting unit is greater than its carrying amount. If a reporting unit fails this qualitative assessment, a single quantitative analysis is used to measure and record the amount of the impairment.

In assessing the fair value of a reporting unit, we make assumptions and estimates about the profitability attributable to our reporting units, including:

- short-term and long-term growth rates; and
- estimated cost of equity and changes in long-term risk-free interest rates.

If our assumptions and estimates made in assessing the fair value of acquired entities change, we could be required to write-down the carrying value of goodwill which could be material to our results of operations in the period the charge is taken. Based on our impairment testing for 2019, we determined no impairment was required and none of our reporting units was at risk for impairment.

Consolidated Operating Results – Years Ended December 31, 2019, 2018, and 2017

(in millions of U.S. dollars, except for percentages)	2019	2018	2017	% Change 2019 vs. 2018	% Change 2018 vs. 2017
Net premiums written	**$ 32,275**	$ 30,579	$ 29,244	5.5 %	4.6 %
Net premiums earned	**31,290**	30,064	29,034	4.1 %	3.5 %
Net investment income	**3,426**	3,305	3,125	3.6 %	5.8 %
Net realized gains (losses)	**(530)**	(652)	84	(18.8)%	NM
Total revenues	**34,186**	32,717	32,243	4.5 %	1.5 %
Losses and loss expenses	**18,730**	18,067	18,454	3.7 %	(2.1)%
Policy benefits	**740**	590	676	25.5 %	(12.7)%
Policy acquisition costs	**6,153**	5,912	5,781	4.1 %	2.3 %
Administrative expenses	**3,030**	2,886	2,833	5.0 %	1.9 %
Interest expense	**552**	641	607	(13.9)%	5.6 %
Other (income) expense	**(596)**	(434)	(400)	37.2 %	8.5 %
Amortization of purchased intangibles	**305**	339	260	(10.2)%	30.4 %
Chubb integration expenses	**23**	59	310	(61.7)%	(81.0)%
Total expenses	**28,937**	28,060	28,521	3.1 %	(1.6)%
Income before income tax	**5,249**	4,657	3,722	12.7 %	25.1 %
Income tax expense (benefit)	**795**	695	(139)	14.3 %	NM
Net income	**$ 4,454**	$ 3,962	$ 3,861	12.4 %	2.6 %
Net premiums written - constant dollars [(1)]				7.0 %	4.1 %
Net premiums earned - constant dollars [(1)]				5.5 %	3.1 %

NM – not meaningful

[(1)] On a constant-dollar basis. Amounts are calculated by translating prior period results using the same local currency rates as the comparable current period.

Net Premiums Written

2019 vs. 2018

Net premiums written reflect the premiums we retain after purchasing reinsurance protection. Consolidated net premiums written increased $1.7 billion in 2019, or $2.1 billion on a constant-dollar basis, reflecting growth across most segments.

- Net premiums written in our North America Commercial P&C Insurance segment increased $890 million (7.1 percent) in 2019, reflecting positive rate increases, new business written and strong retention across most retail lines, including property, financial lines, excess casualty, risk management, and commercial package, as well as in our wholesale and high excess Bermuda lines, and in our small commercial businesses.
- Net premiums written in our North America Personal P&C Insurance segment increased $113 million (2.4 percent) in 2019, primarily due to strong retention and rate and exposure increases across most lines, partially offset by a $44 million benefit in 2018 related to the harmonization of our legacy premium registration systems, which unfavorably impacted growth by approximately 0.9 percentage points.
- Net premiums written in our North America Agricultural Insurance segment increased $233 million (14.8 percent) in 2019, primarily due to growth in our MPCI business and growth in our Chubb Agribusiness. Growth in our MPCI premium was driven primarily by higher retention as a result of the premium sharing formulas under the U.S. government, as well as the non-renewal of a quota-share treaty effective with the current crop year and an increase in current year production. Under the MPCI premium sharing formula under the U.S. government, we cede additional premiums to the government during profitable years. In 2018, the program was more profitable which resulted in higher cessions compared to 2019.
- Net premiums written in our Overseas General Insurance segment increased $360 million (4.0 percent) in 2019, or $722 million (8.4 percent) on a constant-dollar basis, reflecting growth across all regions and most lines of business. P&C lines growth was across all regions and was principally due to positive rate increases and new business in property, casualty, and financial lines. Personal lines growth was driven by new business principally in Latin America and Europe. Accident and health (A&H) lines growth was principally in Asia and Latin America driven by new business.

- Net premiums written in our Global Reinsurance segment decreased $22 million (3.2 percent) in 2019, or $12 million (1.7 percent) on a constant-dollar basis, as an increase in new business written in property and marine lines was more than offset by an increase in ceded retrocessions, reductions in the international motor line, and higher reinstatement premiums collected in the prior year.
- Net premiums written in our Life Insurance segment increased $122 million (5.3 percent) in 2019, or $143 million (6.4 percent) on a constant-dollar basis, primarily reflecting growth in our Asian and Latin American international life operations and North American Combined Insurance supplemental A&H program, partially offset by our life reinsurance business, which continues to decline as no new life reinsurance business is being written.

2018 vs. 2017

Consolidated net premiums written increased $1.3 billion in 2018, or $1.2 billion (4.1 percent) on a constant-dollar basis, reflecting growth across most segments.

- Net premiums written in our North America Commercial P&C Insurance segment increased $466 million (3.9 percent) in 2018 reflecting positive rate increases, new business written, and strong renewals across a number of lines. Retail casualty and risk management, A&H, retail property, and continued growth in our small commercial business represented $339 million of the $466 million increase. In addition, the year-over-year increase in large structured transactions was $195 million. This growth was partially offset by merger-related underwriting actions of $123 million and premium reductions from planned portfolio management in our retail and wholesale brokerage financial lines ($62 million).
- Net premiums written in our North America Personal P&C Insurance segment increased $141 million (3.1 percent) for 2018, primarily due to strong retention and new business growth in homeowners and complementary products such as automobiles and valuables. In addition, the non-renewal of a quota share treaty in the second quarter of 2017 covering the acquired Fireman's Fund homeowners and automobile businesses added $47 million of additional net premiums written in 2018. These increases were partially offset by the addition of California to the homeowners quota share reinsurance treaty, effective October 1, 2018 ($47 million), which included a non-recurring unearned premium reserves (UPR) transfer of $32 million.
- Net premiums written in our North America Agricultural Insurance segment increased $61 million (4.0 percent) in 2018, primarily due to growth in our MPCI business and growth in our Chubb Agribusiness. The growth in MPCI premium was driven by policy count growth and the year-over-year impact of the premium sharing formulas under the U.S. government. In 2017, the program was more profitable which resulted in higher cessions compared to 2018. The increase was partially offset by lower volatility factors, which are a component of the policy pricing that measures the likelihood the commodity price will fluctuate over the crop year and reduces the premium we charge.
- Net premiums written in our Overseas General Insurance segment increased $552 million (6.6 percent) in 2018, or $448 million (5.3 percent) on a constant-dollar basis, reflecting growth across most regions and lines of business. P&C lines growth was across all regions, principally in small commercial property and general casualty lines reflecting new business, and in middle market driven by new business and rate increases. Personal lines growth was principally in our automobile line in Mexico driven by new business, as well as in our specialty lines in Asia. A&H lines growth was principally in Asia driven by new business.
- Net premiums written in our Global Reinsurance segment decreased $14 million (2.1 percent) in 2018, or $22 million (3.3 percent) on a constant-dollar basis, primarily due to higher reinstatement premiums collected in the prior year principally relating to the 2017 natural catastrophes ($15 million year-over-year decrease) and lower renewals, which is reflective of competitive market conditions primarily in catastrophe and catastrophe exposed lines of business, partially offset by new business written in the casualty line of business.
- Net premiums written in our Life Insurance segment increased $129 million (6.1 percent) in 2018, or $123 million (5.7 percent) on a constant-dollar basis, primarily due to growth in our North American Combined Insurance supplemental A&H program business, and Asian and Latin American international life operations, partially offset by our life reinsurance business, which continues to decline as no new life reinsurance business is being written.

Net Premiums Written By Line of Business

(in millions of U.S. dollars, except for percentages)	2019	2018	2017	C$ [(1)] 2018	% Change C$ [(1)] 2019 vs. 2018
Commercial casualty	**$ 5,654**	$ 5,204	$ 4,721	$ 5,154	9.7 %
Workers' compensation	**2,098**	2,094	2,067	2,094	0.1 %
Professional liability	**3,697**	3,527	3,547	3,479	6.3 %
Surety	**639**	635	627	622	2.7 %
Commercial multiple peril [(2)]	**983**	910	879	910	8.0 %
Property and other short-tail lines	**4,468**	4,016	3,819	3,930	13.7 %
Total Commercial P&C [(3)]	**17,539**	16,386	15,660	16,189	8.3 %
Agriculture	**1,810**	1,577	1,516	1,577	14.8 %
Personal automobile	**1,786**	1,695	1,563	1,685	6.0 %
Personal homeowners	**3,513**	3,391	3,302	3,383	3.9 %
Personal other	**1,514**	1,508	1,441	1,454	4.0 %
Total Personal lines	**6,813**	6,594	6,306	6,522	4.4 %
Total Property and Casualty lines	**26,162**	24,557	23,482	24,288	7.7 %
Global A&H lines [(4)]	**4,315**	4,277	4,056	4,157	3.8 %
Reinsurance lines	**649**	671	685	661	(1.7)%
Life	**1,149**	1,074	1,021	1,059	8.5 %
Total consolidated	**$ 32,275**	$ 30,579	$ 29,244	$ 30,165	7.0 %

(1) On a constant-dollar basis. Amounts are calculated by translating prior period results using the same local currency rates as the comparable current period.

(2) Commercial multiple peril represents retail package business (property and general liability).

(3) 2018 included a reclassification of $56 million from Workers' compensation and $1 million from Commercial multiple peril to Commercial casualty ($48 million) and Property and other short-tail lines ($9 million) to better align the reporting with current year. There is no impact to total Commercial P&C.

(4) For purposes of this schedule only, A&H results from our Combined North America and International businesses, normally included in the Life Insurance and Overseas General Insurance segments, respectively, as well as the A&H results of our North America Commercial P&C segment, are included in Global A&H lines above.

The increase in net premiums written in 2019 reflects growth across most lines of business.

- The growth in commercial casualty was due to new business and rate improvement in North America. In addition, commercial casualty grew internationally due to positive rate increases and new business across Europe, as well as growth in Australia.
- Growth in workers' compensation was adversely impacted by competitive market conditions in North America.
- The increase in professional liability was due to growth in North America and new business in Australia and Europe. Professional liability also had positive rate increases and retention in Australia.
- Surety increased due to new business in North America.
- Commercial multiple peril increased due to new business and higher renewal business in North America.
- Property and other short-tail lines increased due to growth in North America. In addition, property and other short-tail lines increased internationally, primarily due to new business in Australia and across Europe, as well as positive rate increases internationally.
- Our personal lines increased due to strong retention and rate and exposure increases in North America. Personal lines also increased due to growth in Latin America and Europe.
- Global A&H lines increased due to growth in our North American Combined Insurance supplemental A&H program, along with new business in Asia and Latin America.
- The increase in Life was primarily driven by growth in our Asian and Latin American international life operations.

For additional information on net premiums written, refer to the segment results discussions.

Net Premiums Earned

2019 vs. 2018

Net premiums earned for short-duration contracts, typically P&C contracts, generally reflect the portion of net premiums written that were recorded as revenues for the period as the exposure periods expire. Net premiums earned for long-duration contracts, typically traditional life contracts, generally are recognized as earned when due from policyholders. Net premiums earned increased $1.2 billion, or $1.6 billion on a constant-dollar basis in 2019, reflecting the growth in net premiums written described above, including the impact of premiums that were fully earned when written (e.g., large structured transactions and audit and retrospective premium adjustments).

2018 vs. 2017

Net premiums earned increased $1.0 billion, or $912 million on a constant-dollar basis in 2018, primarily due to the same factors driving the increase in net premiums written as described above. Net premiums earned were favorably impacted by the year-over-year increase in large structured transactions ($163 million), a number of which were earned immediately when written. These retroactive transactions did not impact premiums earned in 2019 as they were fully earned in 2018.

P&C Combined Ratio

In evaluating our segments excluding Life Insurance financial performance, we use the P&C combined ratio, the loss and loss expense ratio, the policy acquisition cost ratio, and the administrative expense ratio. We calculate these ratios by dividing the respective expense amounts by net premiums earned. We do not calculate these ratios for the Life Insurance segment as we do not use these measures to monitor or manage that segment. The P&C combined ratio is determined by adding the loss and loss expense ratio, the policy acquisition cost ratio, and the administrative expense ratio. A P&C combined ratio under 100 percent indicates underwriting income, and a combined ratio exceeding 100 percent indicates underwriting loss.

	2019	2018	2017
Loss and loss expense ratio	**62.1%**	62.1%	65.8%
Policy acquisition cost ratio	**19.1%**	19.2%	19.5%
Administrative expense ratio	**9.4%**	9.3%	9.4%
P&C Combined ratio	**90.6%**	90.6%	94.7%

The loss and loss expense ratio decreased 3.7 percentage points in 2018 principally due to the following:

- Lower catastrophe losses;
- Integration-related claims handling expense savings;
- Partially offset by increased frequency and severity of homeowners losses in our North America Personal P&C Insurance segment, primarily non-catastrophe water related events and large fire losses which are trending above our expectations, and higher non-catastrophe large losses in our North America Commercial P&C Insurance segment.

Policy acquisition costs consist of commissions, premium taxes, and certain underwriting costs directly related to the successful acquisition of a new or renewal insurance contract. Our policy acquisition cost ratio decreased 0.3 percentage points in 2018 principally due to increased cessions under certain reinsurance agreements that resulted in higher ceded acquisition costs benefits than in the prior year.

Catastrophe Losses and Prior Period Development

Catastrophe losses exclude reinstatement premiums which are additional premiums paid on certain reinsurance agreements in order to reinstate coverage that had been exhausted by loss occurrences. The reinstatement premium amount is typically a pro rata portion of the original ceded premium paid based on how much of the reinsurance limit had been exhausted. Prior period development is net of related adjustments which typically relate to either profit commission reserves or policyholder dividend reserves based on actual claim experience that develops after the policy period ends. The expense adjustments correlate to the prior period loss development on these same policies. Refer to the Non-GAAP Reconciliation section for further information on reinstatement premiums on catastrophe losses and adjustments to prior period development.

(in millions of U.S dollars)	**2019**	2018	2017
Catastrophe losses (excludes reinstatement premiums)	**$ 1,175**	$ 1,622	$ 2,753
Favorable prior period development	**$ 792**	$ 896	$ 829

We generally define catastrophe loss events consistent with the definition of the Property Claims Service (PCS) for events in the U.S. and Canada. PCS defines a catastrophe as an event that causes damage of $25 million or more in insured property losses and affects a significant number of insureds. For events outside of the U.S. and Canada, we generally use a similar definition. The tables below represent catastrophe loss estimates for events that occurred in the related calendar year only. Changes in catastrophe loss estimates in the current calendar year that relate to loss events that occurred in previous calendar years are considered prior period development and are excluded from the tables below.

The following table presents catastrophe losses and reinstatement premiums (RIPs) collected (expensed) in 2019:

	Catastrophe Loss Charge by Event							
(in millions of U.S. dollars)	North America Commercial P&C Insurance	North America Personal P&C Insurance	North America Agricultural Insurance	Overseas General Insurance	Global Reinsurance	Total excluding RIPs	RIPs collected (expensed)	Total including RIPs
Net losses								
U.S. flooding, hail, tornadoes, and wind events	**$ 220**	**$ 202**	**$ 7**	**$ —**	**$ 9**	**$ 438**	**$ —**	**$ 438**
Tornado in Dallas, Texas	**55**	**145**	**—**	**—**	**2**	**202**	**(11)**	**213**
Winter-related storms	**74**	**110**	**1**	**6**	**2**	**193**	**—**	**193**
Hurricane Dorian	**26**	**30**	**—**	**10**	**8**	**74**	**1**	**73**
California wildfires	**11**	**45**	**—**	**—**	**—**	**56**	**—**	**56**
Typhoon Hagibis	**—**	**—**	**—**	**20**	**17**	**37**	**1**	**36**
Civil unrest in Hong Kong and Chile	**—**	**—**	**—**	**33**	**—**	**33**	**(4)**	**37**
International weather-related events	**1**	**2**	**—**	**30**	**—**	**33**	**—**	**33**
Tropical Storm Imelda	**26**	**4**	**—**	**—**	**1**	**31**	**—**	**31**
Australia storms	**—**	**—**	**—**	**27**	**1**	**28**	**—**	**28**
Typhoon Faxai	**—**	**—**	**—**	**15**	**10**	**25**	**1**	**24**
Hurricane Barry	**3**	**4**	**—**	**—**	**—**	**7**	**—**	**7**
Australia wildfires	**—**	**—**	**—**	**5**	**—**	**5**	**—**	**5**
Other	**5**	**1**	**—**	**6**	**1**	**13**	**—**	**13**
Total	**$ 421**	**$ 543**	**$ 8**	**$ 152**	**$ 51**	**$ 1,175**		
RIPs collected (expensed)	**—**	**(11)**	**—**	**(4)**	**3**		**(12)**	
Total before income tax	**$ 421**	**$ 554**	**$ 8**	**$ 156**	**$ 48**			**$ 1,187**
Income tax benefit								**221**
Total after income tax								**$ 966**

The following table presents catastrophe losses and reinstatement premiums (RIPs) collected (expensed) in 2018:

(in millions of U.S. dollars)	North America Commercial P&C Insurance	North America Personal P&C Insurance	North America Agricultural Insurance	Overseas General Insurance	Global Reinsurance	Total excluding RIPs	RIPs collected (expensed)	Total including RIPs
	Catastrophe Loss Charge by Event							
Net losses								
Hurricane Michael	$ 187	$ 16	$ 6	$ 6	$ 85	$ 300	$ 15	$ 285
U.S. flooding, hail, tornadoes, and wind events [1]	162	157	7	—	6	332	—	332
Northeast winter storms	43	117	—	—	5	165	—	165
California wildfires	51	61	1	1	58	172	(23)	195
Hurricane Florence	109	29	7	15	14	174	1	173
California mudslides	4	120	—	1	—	125	—	125
Colorado rain and hail storm	7	65	—	1	—	73	—	73
International weather-related events	—	—	—	182	31	213	2	211
Other	16	46	—	—	6	68	1	67
Total	$ 579	$ 611	$ 21	$ 206	$ 205	$ 1,622		
RIPs collected (expensed)	—	(26)	—	—	22		(4)	
Total before income tax	$ 579	$ 637	$ 21	$ 206	$ 183			$ 1,626
Income tax benefit								272
Total after income tax								$ 1,354

[1] This grouping comprised of 34 separate events, principally impacting the southern and northeastern regions of the U.S.

The following table presents catastrophe losses and reinstatement premiums (RIPs) collected (expensed) in 2017:

(in millions of U.S. dollars)	North America Commercial P&C Insurance	North America Personal P&C Insurance	North America Agricultural Insurance	Overseas General Insurance	Global Reinsurance	Total excluding RIPs	RIPs collected (expensed)	Total including RIPs
	Catastrophe Loss Charge by Event							
Net losses								
N. California wildfires	$ 61	$ 151	$ —	$ 2	$ 42	$ 256	$ (21)	$ 277
S. California wildfires	23	134	—	—	—	157	—	157
Hurricane Harvey	391	175	1	40	48	655	5	650
Hurricane Irma	464	206	2	79	159	910	30	880
Hurricane Maria	50	—	—	89	55	194	(7)	201
Mexico Earthquakes	—	—	—	25	—	25	—	25
Other	231	205	15	96	9	556	—	556
Total	$ 1,220	$ 871	$ 18	$ 331	$ 313	$ 2,753		
RIPs collected (expensed)	(4)	(22)	—	(4)	37		7	
Total before income tax	$ 1,224	$ 893	$ 18	$ 335	$ 276			$ 2,746
Income tax benefit								575
Total after income tax								$ 2,171

Prior period development (PPD) arises from changes to loss estimates recognized in the current year that relate to loss events that occurred in previous calendar years and excludes the effect of losses from the development of earned premium from previous accident years.

Pre-tax net favorable prior period development for the year ended 2019 was $792 million, which included favorable development of $80 million in our crop insurance business and adverse development of $116 million related to legacy run-off exposures, principally asbestos and environmental liabilities. The remaining favorable development of $828 million comprised 92 percent long-tail lines, principally from accident years 2015 and prior, and 8 percent short-tail lines.

Net favorable prior period development for the year ended 2018 was $896 million, which included favorable reinsurance settlements of $205 million related to legacy run-off exposures, $197 million favorable development related to the 2017 catastrophe events, and favorable development of $110 million in our crop insurance business. There were $216 million of adverse development related to legacy run-off exposures, principally asbestos and environmental liabilities. The remaining favorable development of $600 million comprised 82 percent long-tail lines, principally for the 2014 and prior accident years, and 18 percent short-tail lines.

Refer to the Prior Period Development section in Note 7 to the Consolidated Financial Statements for additional information.

Current Accident Year (CAY) Loss Ratio excluding Catastrophe Losses (CATs)

The following table presents the impact of catastrophe losses and prior period development on our loss and loss expense ratio. Refer to the Non-GAAP Reconciliation section for additional information.

	2019	2018	2017
Loss and loss expense ratio	**62.1 %**	62.1 %	65.8 %
Catastrophe losses	**(4.1)%**	(5.8)%	(10.2)%
Favorable prior period development	**2.8 %**	3.3 %	3.2 %
CAY loss ratio excluding catastrophe losses	**60.8 %**	59.6 %	58.8 %

2019 vs. 2018

The CAY loss ratio excluding catastrophe losses increased 1.2 percentage points in 2019 principally due to the following:

- Downward revision in the 2019 crop year margin estimate reflecting preventive planting claims due to the impact of wet weather conditions and crop yield shortfalls resulting from poor growing conditions;
- Change in mix of business and earned price changes modestly below loss trends in certain classes of our business;
- Partially offset by the adverse impact of elevated homeowners losses in the prior year.

2018 vs. 2017

The CAY loss ratio excluding catastrophe losses increased 0.8 percentage points in 2018 principally due to the following:

- Increased frequency and severity of homeowners losses in our North America Personal P&C Insurance segment, primarily non-catastrophe water related events and large fire losses;
- Higher non-catastrophe large losses in our North America Commercial P&C Insurance segment;
- Partially offset by integration-related claims handling expense savings realized.

CAY P&C Combined Ratio excluding CATs

	2019	2018	2017
CAY Loss and loss expense ratio ex CATs	**60.8%**	59.6%	58.8%
CAY Policy acquisition cost ratio ex CATs	**19.1%**	19.2%	19.4%
CAY Administrative expense ratio ex CATs	**9.3%**	9.2%	9.4%
CAY P&C combined ratio ex CATs	**89.2%**	88.0%	87.6%

Policy benefits
Policy benefits represent losses on contracts classified as long-duration and generally include accident and supplemental health products, term and whole life products, endowment products, and annuities. Refer to the Life Insurance segment operating results section for further discussion.

Policy benefits were $740 million, $590 million and $676 million in 2019, 2018 and 2017, respectively, which included separate account liabilities (gains) losses of $44 million, $(38) million and $97 million, respectively. The offsetting movements of these liabilities are recorded in Other (income) expense on the Consolidated statements of operations. Excluding the separate account gains and losses, Policy benefits were $696 million in 2019, compared with $628 million and $579 million in 2018 and 2017, respectively.

Refer to the respective sections that follow for a discussion of Net investment income, Interest expense, Other (income) expense, Net realized gains and losses, Amortization of purchased intangibles, and Income tax expense.

Segment Operating Results – Years Ended December 31, 2019, 2018, and 2017

We operate through six business segments: North America Commercial P&C Insurance, North America Personal P&C Insurance, North America Agricultural Insurance, Overseas General Insurance, Global Reinsurance, and Life Insurance. In addition, the results of our run-off Brandywine business, including all run-off asbestos and environmental (A&E) exposures, and the results of Westchester specialty operations for 1996 and prior years are presented within Corporate.

North America Commercial P&C Insurance

The North America Commercial P&C Insurance segment comprises operations that provide property and casualty (P&C) insurance and services to large, middle market, and small commercial businesses in the U.S., Canada, and Bermuda. This segment includes our North America Major Accounts and Specialty Insurance division (large corporate accounts and wholesale business), and the North America Commercial Insurance division (principally middle market and small commercial accounts).

(in millions of U.S. dollars, except for percentages)	**2019**	2018	2017	% Change 2019 vs. 2018	% Change 2018 vs. 2017
Net premiums written	**$ 13,375**	$ 12,485	$ 12,019	7.1 %	3.9 %
Net premiums earned	**12,922**	12,402	12,191	4.2 %	1.7 %
Losses and loss expenses	**8,206**	8,000	8,287	2.6 %	(3.5)%
Policy acquisition costs	**1,831**	1,829	1,873	0.2 %	(2.3)%
Administrative expenses	**1,028**	966	981	6.4 %	(1.5)%
Underwriting income	**1,857**	1,607	1,050	15.5 %	53.0 %
Net investment income	**2,082**	2,033	1,961	2.4 %	3.7 %
Other (income) expense	**(3)**	(25)	1	(86.5)%	NM
Segment income	**$ 3,942**	$ 3,665	$ 3,010	7.5 %	21.8 %
Loss and loss expense ratio	**63.5%**	64.5%	68.0%	(1.0) pt	(3.5) pts
Policy acquisition cost ratio	**14.2%**	14.7%	15.4%	(0.5) pts	(0.7) pts
Administrative expense ratio	**7.9%**	7.8%	8.0%	0.1 pts	(0.2) pts
Combined ratio	**85.6%**	87.0%	91.4%	(1.4) pts	(4.4) pts

NM – not meaningful

Premiums
The table below shows the impact of large structured transactions as well as other transactions that are fully earned when written (e.g., audit and retrospective premium adjustments).

(in millions of U.S. dollars)	**2019**	2018	2017
Net premiums fully earned when written	**$ 391**	$ 342	$ 160

2019 vs. 2018
Net premiums written increased $890 million, or 7.1 percent in 2019, reflecting positive rate increases, new business written and strong retention across most retail lines, including property, financial lines, excess casualty, risk management, and commercial package, as well as in our wholesale and high excess Bermuda lines, and in our small commercial businesses.

Net premiums earned increased $520 million, or 4.2 percent in 2019, due to the growth in net premiums written described above.

2018 vs. 2017
Net premiums written increased $466 million, or 3.9 percent in 2018 reflecting positive rate increases, new business written, and strong renewals across a number of lines. Retail casualty and risk management, A&H, retail property, and continued growth in our small commercial business represented $339 million of the $466 million increase. In addition, the year-over-year increase in large structured transactions was $195 million. This growth was partially offset by merger-related underwriting actions of $123 million and premium reductions from planned portfolio management in our retail and wholesale brokerage financial lines ($62 million).

Net premiums earned increased $211 million, or 1.7 percent in 2018 principally reflecting the net premiums written increases described above and the year-over-year increase in large structured transactions ($163 million), a number of which were earned immediately when written as they were retroactive covers.

Combined Ratio
2019 vs. 2018
The loss and loss expense ratio decreased 1.0 percentage point in 2019, primarily due to lower catastrophe losses, partially offset by a change in mix of business and earned price changes modestly below loss trends in certain classes of our business.

The policy acquisition cost ratio decreased 0.5 percentage points in 2019, due to a change in mix of business towards lower acquisition cost ratio lines and increased cessions under certain reinsurance agreements that resulted in higher ceded acquisition cost benefits than in the prior year.

2018 vs. 2017
The loss and loss expense ratio decreased 3.5 percentage points in 2018, primarily due to lower catastrophe losses and integration-related claims handling expense savings realized, partially offset by lower favorable prior period development, higher non-catastrophe losses (0.4 percentage points), and a less favorable adjustment to our claims handling reserve in the current year relative to 2017.

The policy acquisition cost ratio decreased 0.7 percentage points in 2018, due to increased cessions under certain reinsurance agreements that resulted in higher ceded acquisition costs benefits than in the prior year.

The administrative expense ratio decreased 0.2 percentage points in 2018, primarily due to integration-related expense savings realized, higher net profit from our third-party claims administration business, ESIS, and the net favorable impact of one-time expense accrual releases.

Catastrophe Losses and Prior Period Development

(in millions of U.S. dollars)	**2019**	2018	2017
Catastrophe losses (excludes reinstatement premiums)	**$ 421**	$ 579	$ 1,220
Favorable prior period development	**$ 649**	$ 610	$ 746

Catastrophe losses were primarily from the following events (refer to the table on page 54):
- 2019: Winter-related storms and other severe weather-related events in the U.S., including tornadoes in Texas, Hurricane Dorian, and Tropical Storm Imelda
- 2018: Hurricanes Florence and Michael, and severe weather-related events in the U.S., including California wildfires
- 2017: Hurricanes Harvey, Irma and Maria and severe weather-related events in the U.S., including California wildfires

CAY Loss Ratio excluding Catastrophe Losses

	2019	2018	2017
Loss and loss expense ratio	**63.5 %**	64.5 %	68.0 %
Catastrophe losses	**(3.3)%**	(4.7)%	(10.0)%
Favorable prior period development	**5.1 %**	5.1 %	6.3 %
CAY loss ratio excluding catastrophe losses	**65.3 %**	64.9 %	64.3 %

2019 vs. 2018

The CAY loss ratio excluding catastrophe losses increased 0.4 percentage points for 2019 due to a change in mix of business and earned price changes modestly below loss trends in certain classes of our business.

2018 vs. 2017

The CAY loss ratio excluding catastrophe losses increased 0.6 percentage points for 2018, due to higher year-over-year large loss activity and a less favorable adjustment to our claims handling reserve in the current year relative to 2017, partially offset by integration-related claims handling expense savings realized.

North America Personal P&C Insurance

The North America Personal P&C Insurance segment comprises operations that provide high net worth personal lines products, including homeowners and complementary products such as valuable articles, excess liability, automobile, and recreational marine insurance and services in the U.S. and Canada.

				% Change	
(in millions of U.S. dollars, except for percentages)	**2019**	2018	2017	2019 vs. 2018	2018 vs. 2017
Net premiums written	**$ 4,787**	$ 4,674	$ 4,533	2.4 %	3.1 %
Net premiums earned	**4,694**	4,593	4,399	2.2 %	4.4 %
Losses and loss expenses	**3,043**	3,229	3,265	(5.8)%	(1.1)%
Policy acquisition costs	**948**	939	899	1.0 %	4.4 %
Administrative expenses	**286**	269	264	6.0 %	1.9 %
Underwriting income (loss)	**417**	156	(29)	167.2 %	NM
Net investment income	**258**	236	226	9.2 %	4.4 %
Other (income) expense	**3**	1	4	117.1 %	(75.0)%
Amortization of purchased intangibles	**12**	13	16	(11.1)%	(18.8)%
Segment income	**$ 660**	$ 378	$ 177	74.7 %	113.6 %
Loss and loss expense ratio	**64.8%**	70.3%	74.2%	(5.5) pts	(3.9) pts
Policy acquisition cost ratio	**20.2%**	20.4%	20.4%	(0.2) pts	—
Administrative expense ratio	**6.1%**	5.9%	6.1%	0.2 pts	(0.2) pts
Combined ratio	**91.1%**	96.6%	100.7%	(5.5) pts	(4.1) pts

NM – not meaningful

Premiums

2019 vs. 2018

Net premiums written increased $113 million, or 2.4 percent for 2019, primarily due to strong retention and rate and exposure increases across most lines, partially offset by a $44 million benefit in 2018 related to the harmonization of our legacy premium registration systems, which unfavorably impacted growth by approximately 0.9 percentage points.

Net premiums earned increased $101 million, or 2.2 percent for 2019, reflecting the growth in net premiums written described above.

2018 vs. 2017
Net premiums written increased $141 million, or 3.1 percent for 2018, primarily due to strong retention and new business growth in homeowners and complementary products such as automobiles and valuables. In addition, the non-renewal of a quota share treaty in the second quarter of 2017 covering the acquired Fireman's Fund homeowners and automobile businesses added $47 million of additional net premiums written in 2018. These increases were partially offset by the addition of California to the homeowners quota share reinsurance treaty, effective October 1, 2018 ($47 million), which included a non-recurring unearned premium reserves (UPR) transfer of $32 million.

Net premiums earned increased $194 million, or 4.4 percent for 2018, primarily due to the factors described above.

Combined Ratio
2019 vs. 2018
The loss and loss expense ratio decreased 5.5 percentage points in 2019, primarily due to lower catastrophe losses and favorable prior period development in the current year compared to unfavorable prior period development in the prior year. Additionally, the prior year underlying loss ratio was elevated principally due to increased frequency and severity, primarily non-catastrophe water and fire losses in our homeowners business.

The policy acquisition cost ratio decreased 0.2 percentage points in 2019, primarily due to higher ceded commission benefits.

2018 vs. 2017
The loss and loss expense ratio decreased 3.9 percentage points in 2018, primarily due to lower catastrophe losses (6.5 percentage points), lower unfavorable prior period development (0.6 percentage points), and integration-related claims handling expense savings realized. These decreases were offset by increased frequency and severity of homeowners losses primarily non-catastrophe water related events and large fire losses which are trending above our expectations (3.3 percentage points).

The policy acquisition cost ratio remained flat in 2018. The administrative expense ratio decreased 0.2 percentage points in 2018, primarily due to integration-related expense savings realized that exceeded normal merit and inflation.

Catastrophe Losses and Prior Period Development

(in millions of U.S. dollars)	**2019**	2018	2017
Catastrophe losses (excludes reinstatement premiums)	**$ 543**	$ 611	$ 871
Favorable (unfavorable) prior period development	**$ 95**	$ (41)	$ (69)

Catastrophe losses were primarily from the following events (refer to the table on page 54):
- 2019: Winter-related storms and other severe weather-related events in the U.S., including tornadoes in Texas, California wildfires and Hurricane Dorian
- 2018: Colorado rain and hailstorms, Hurricanes Florence and Michael, California mudslides, and other severe weather-related events in the U.S., including California wildfires
- 2017: Hurricanes Harvey and Irma and severe weather-related events in the U.S., including California wildfires

CAY Loss Ratio excluding Catastrophe Losses

	2019	2018	2017
Loss and loss expense ratio	**64.8 %**	70.3 %	74.2 %
Catastrophe losses	**(11.6)%**	(13.6)%	(20.1)%
Favorable (unfavorable) prior period development	**1.9 %**	(0.9)%	(1.5)%
CAY loss ratio excluding catastrophe losses	**55.1 %**	55.8 %	52.6 %

2019 vs. 2018
The CAY loss ratio excluding catastrophe losses decreased 0.7 percentage points in 2019. The prior year underlying loss ratio was elevated, principally due to increased frequency and severity, primarily non-catastrophe water and fire losses in our homeowners business.

2018 vs. 2017
The CAY loss ratio excluding catastrophe losses increased 3.2 percentage points in 2018, due to increased frequency and severity of homeowners losses primarily non-catastrophe water related events and large fire losses.

North America Agricultural Insurance

The North America Agricultural Insurance segment comprises our North American based businesses that provide a variety of coverages in the U.S. and Canada including crop insurance, primarily Multiple Peril Crop Insurance (MPCI) and crop-hail through Rain and Hail Insurance Service, Inc. (Rain and Hail) as well as farm and ranch and specialty P&C commercial insurance products and services through our Chubb Agribusiness unit.

(in millions of U.S. dollars, except for percentages)	**2019**	2018	2017	% Change 2019 vs. 2018	% Change 2018 vs. 2017
Net premiums written	**$ 1,810**	$ 1,577	$ 1,516	14.8 %	4.0 %
Net premiums earned	**1,795**	1,569	1,508	14.4 %	4.1 %
Adjusted losses and loss expenses	**1,616**	1,114	1,043	45.1 %	6.8 %
Policy acquisition costs	**84**	79	81	6.8 %	(2.5)%
Administrative expenses	**6**	(9)	(8)	NM	12.5 %
Underwriting income	**89**	385	392	(77.0)%	(1.8)%
Net investment income	**30**	28	25	5.0 %	12.0 %
Other (income) expense	**1**	2	2	(33.6)%	—
Amortization of purchased intangibles	**28**	28	29	(2.0)%	(3.4)%
Segment income	**$ 90**	$ 383	$ 386	(76.6)%	(0.8)%
Loss and loss expense ratio	**90.1%**	71.0 %	69.2 %	19.1 pts	1.8 pts
Policy acquisition cost ratio	**4.7%**	5.0 %	5.4 %	(0.3) pts	(0.4) pts
Administrative expense ratio	**0.3%**	(0.5)%	(0.6)%	0.8 pts	0.1 pts
Combined ratio	**95.1%**	75.5 %	74.0 %	19.6 pts	1.5 pts

NM – not meaningful

Premiums
2019 vs. 2018
Net premiums written increased $233 million, or 14.8 percent in 2019, primarily due to growth in our MPCI business and growth in our Chubb Agribusiness. Growth in our MPCI premium was driven primarily by higher retention as a result of the premium sharing formulas under the U.S. government, as well as the non-renewal of a quota-share treaty effective with the current crop year and an increase in current year production. Under the MPCI premium sharing formula under the U.S. government, we cede additional premiums to the government during profitable years. In 2018, the program was more profitable which resulted in higher cessions compared to 2019.

Net premiums earned increased $226 million, or 14.4 percent in 2019, reflecting the growth in net premiums written described above.

2018 vs. 2017
Net premiums written increased $61 million, or 4.0 percent in 2018, primarily due to growth in our MPCI business and growth in our Chubb Agribusiness. The growth in MPCI premium was driven by policy count growth and the year-over-year impact of the premium sharing formulas under the U.S. government. In 2017, the program was more profitable which resulted in higher cessions compared to 2018. The increase was partially offset by lower volatility factors, which are a component of the policy pricing that measures the likelihood the commodity price will fluctuate over the crop year and reduces the premium we charge.

Net premiums earned increased $61 million, or 4.1 percent in 2018, due to the factors described above.

Combined Ratio

2019 vs. 2018

The loss and loss expense ratio increased 19.1 percentage points in 2019, principally due to lower favorable prior period development and the downward revision in the 2019 crop year margin estimate reflecting preventive planting claims due to the impact of wet weather conditions and crop yield shortfalls resulting from poor growing conditions. The increase in the loss ratio was partially offset by lower catastrophe losses.

The policy acquisition cost ratio decreased 0.3 percentage points in 2019, primarily due to lower agent profit sharing commission.

The administrative expense ratio increased 0.8 percentage points in 2019, primarily due to a reduction in the current year Administrative and Operating (A&O) reimbursements on the MPCI business we received under the government program and normal operating expense and inflationary increases.

2018 vs. 2017

The loss and loss expense ratio increased 1.8 percentage points in 2018 due to higher catastrophe losses and lower favorable prior period development.

The policy acquisition cost ratio decreased 0.4 percentage points in 2018 due to lower MPCI reinsurance cessions in the current year.

Catastrophe Losses and Prior Period Development

(in millions of U.S. dollars)	**2019**	2018	2017
Catastrophe losses (excludes reinstatement premiums)	**$ 8**	$ 21	$ 18
Favorable prior period development	**$ 80**	$ 110	$ 119

Catastrophe losses in 2019, 2018, and 2017 were primarily from severe weather-related events in the U.S. in our farm, ranch and specialty P&C businesses. Refer to the table on page 54.

Net favorable prior period development was $80 million, $110 million, and $119 million in 2019, 2018, and 2017, respectively. For 2019, the prior period development amount included $103 million of favorable incurred losses and $13 million of lower acquisition costs due to lower than expected MPCI losses for the 2018 crop year, partially offset by a $36 million decrease in net premiums earned related to the MPCI profit and loss calculation formula. For 2018, the prior period development amount included $140 million of favorable incurred losses and $10 million of lower acquisition costs due to lower than expected MPCI losses for the 2017 crop year, partially offset by a $40 million decrease in net premiums earned related to the MPCI profit and loss calculation formula.

CAY Loss Ratio excluding Catastrophe Losses

	2019	2018	2017
Loss and loss expense ratio	**90.1 %**	71.0 %	69.2 %
Catastrophe losses	**(0.5)%**	(1.3)%	(1.2)%
Favorable prior period development	**3.9 %**	7.0 %	8.2 %
CAY loss ratio excluding catastrophe losses	**93.5 %**	76.7 %	76.2 %

2019 vs. 2018

The CAY loss ratio excluding catastrophe losses increased 16.8 percentage points in 2019, principally due to the downward revision in the 2019 crop year margin estimate reflecting preventive planting claims due to the impact of wet weather conditions and crop yield shortfalls resulting from poor growing conditions.

2018 vs. 2017

The CAY loss ratio excluding catastrophe losses increased 0.5 percentage points in 2018, primarily due to a less favorable crop margin in the current year versus 2017, partially offset by lower underlying losses in our Chubb Agribusiness unit.

Overseas General Insurance

Overseas General Insurance segment comprises Chubb International and Chubb Global Markets (CGM). Chubb International comprises our international commercial P&C traditional and specialty lines serving large corporations, middle market and small customers; A&H and traditional and specialty personal lines business serving local territories outside the U.S., Bermuda, and Canada. CGM, our London-based international commercial P&C excess and surplus lines business, includes Lloyd's of London (Lloyd's) Syndicate 2488. Chubb provides funds at Lloyd's to support underwriting by Syndicate 2488 which is managed by Chubb Underwriting Agencies Limited.

				% Change	
(in millions of U.S. dollars, except for percentages)	**2019**	2018	2017	2019 vs. 2018	2018 vs. 2017
Net premiums written	**$ 9,262**	$ 8,902	$ 8,350	4.0 %	6.6 %
Net premiums earned	**8,882**	8,612	8,131	3.1 %	5.9 %
Losses and loss expenses	**4,606**	4,429	4,281	4.0 %	3.5 %
Policy acquisition costs	**2,501**	2,346	2,221	6.6 %	5.6 %
Administrative expenses	**1,033**	1,014	982	1.9 %	3.3 %
Underwriting income	**742**	823	647	(9.8)%	27.2 %
Net investment income	**588**	619	610	(5.1)%	1.5 %
Other (income) expense	**12**	—	(4)	NM	NM
Amortization of purchased intangibles	**45**	41	45	8.3 %	(8.9)%
Segment income	**$ 1,273**	$ 1,401	$ 1,216	(9.2)%	15.2 %
Net premiums written - constant dollars [1]				8.4 %	5.3 %
Net premiums earned - constant dollars [1]				7.6 %	4.7 %
Underwriting income - constant dollars [1]				(3.7)%	24.1 %
Loss and loss expense ratio	**51.9%**	51.4%	52.6%	0.5 pts	(1.2) pts
Policy acquisition cost ratio	**28.1%**	27.2%	27.3%	0.9 pts	(0.1) pts
Administrative expense ratio	**11.6%**	11.8%	12.1%	(0.2) pts	(0.3) pts
Combined ratio	**91.6%**	90.4%	92.0%	1.2 pts	(1.6) pts

NM – not meaningful

Net Premiums Written by Region

					% Change		
(in millions of U.S. dollars, except for percentages)	**2019**	2018	2017	C$ [1] 2018	2019 vs. 2018	C$ [1] 2019 vs. 2018	2018 vs. 2017
Region							
Europe	**$ 3,631**	$ 3,508	$ 3,281	$ 3,357	3.5%	8.2%	6.9 %
Latin America	**2,277**	2,181	2,108	2,059	4.4%	10.6%	3.5 %
Asia	**3,021**	2,884	2,596	2,806	4.7%	7.6%	11.1 %
Other [2]	**333**	329	365	318	1.1%	4.8%	(9.9)%
Net premiums written	**$ 9,262**	$ 8,902	$ 8,350	$ 8,540	4.0%	8.4%	6.6 %

	2019 % of Total	2018 % of Total	2017 % of Total
Region			
Europe	**38%**	39%	40%
Latin America	**25%**	25%	25%
Asia	**33%**	32%	31%
Other [2]	**4%**	4%	4%
Net premiums written	**100%**	100%	100%

(1) On a constant-dollar basis. Amounts are calculated by translating prior period results using the same local currency rates as the comparable current period.

(2) Comprises Combined International, Eurasia and Africa region, and other international.

Premiums

2019 vs. 2018

Net premiums written increased $360 million in 2019, or $722 million on a constant-dollar basis, reflecting growth across all regions and most lines of business. P&C lines growth was across all regions and was principally due to positive rate increases and new business in property, casualty, and financial lines. Personal lines growth was driven by new business principally in Latin America and Europe. Accident and health (A&H) lines growth was principally in Asia and Latin America driven by new business.

Net premiums earned increased $270 million in 2019, or $629 million on a constant-dollar basis, reflecting the increase in net premiums written.

2018 vs. 2017

Net premiums written increased $552 million in 2018, or $448 million on a constant-dollar basis, reflecting growth across most regions and lines of business. P&C lines growth was across all regions, principally in small commercial property and general casualty lines reflecting new business, and in middle market driven by new business and rate increases. Personal lines growth was principally in our automobile line in Mexico driven by new business, as well as in our specialty lines in Asia. A&H lines growth was principally in Asia driven by new business.

Net premiums earned increased $481 million in 2018, or $384 million on a constant-dollar basis, due to the factors described above.

Combined Ratio

2019 vs. 2018

The loss and loss expense ratio increased 0.5 percentage points in 2019 due to lower favorable prior period development, partially offset by lower catastrophe losses, earned price changes modestly above loss trends, favorable loss experience in certain personal lines, and a change in mix of business towards products and regions that have a lower loss and loss expense ratio and a higher policy acquisition cost ratio.

The policy acquisition cost ratio increased 0.9 percentage points in 2019 due to a change in mix of business towards products and regions that have a higher policy acquisition cost ratio and lower loss and loss expense ratio as noted above, higher underwriting costs resulting from the successful acquisition of business, and higher commissions paid on certain personal lines due to favorable loss experience.

2018 vs. 2017

The loss and loss expense ratio decreased 1.2 percentage points in 2018, reflecting lower catastrophe losses (1.6 percentage points) and a change in the mix of business towards consumer and property and casualty lines in countries that have a lower loss ratio and a higher acquisition cost ratio (0.3 percentage points), partially offset by lower favorable prior period development in 2018 (0.6 percentage points).

The policy acquisition cost ratio was relatively flat in 2018.

The administrative expense ratio decreased 0.3 percentage points in 2018, primarily driven by integration-expense savings realized (0.3 percentage points).

Catastrophe Losses and Prior Period Development

(in millions of U.S. dollars)		**2019**		2018		2017
Catastrophe losses (excludes reinstatement premiums)	**$**	**152**	$	206	$	331
Favorable prior period development	**$**	**92**	$	212	$	252

Catastrophe losses were primarily from the following events (refer to the table on page 54):

- 2019: Typhoons Faxai and Hagibis; Hurricane Dorian; storms in Australia; civil unrest in Hong Kong and Chile; and other international weather-related events
- 2018: Typhoons Jebi, Mangkhut and Trami; Hurricane Florence and storms in Australia
- 2017: Hurricanes Harvey, Irma and Maria; Earthquakes in Mexico, Cyclone Debbie in Australia, and flooding in Latin America

CAY Loss Ratio excluding Catastrophe Losses

	2019	2018	2017
Loss and loss expense ratio	**51.9 %**	51.4 %	52.6 %
Catastrophe losses	**(1.8)%**	(2.4)%	(4.0)%
Favorable prior period development	**1.1 %**	2.5 %	3.1 %
CAY loss ratio excluding catastrophe losses	**51.2 %**	51.5 %	51.7 %

2019 vs. 2018

The CAY loss ratio excluding catastrophe losses decreased 0.3 percentage points in 2019 primarily due to earned price changes modestly above loss trends, favorable loss experience in certain personal lines, and a change in mix of business towards products and regions that have a lower loss and loss expense ratio and a higher policy acquisition cost ratio.

2018 vs. 2017

The CAY loss ratio excluding catastrophe losses decreased 0.2 percentage points in 2018 primarily due to a change in the mix of business towards consumer and property and casualty lines in countries that have a lower loss ratio and a higher acquisition cost ratio.

Global Reinsurance

The Global Reinsurance segment represents our reinsurance operations comprising Chubb Tempest Re Bermuda, Chubb Tempest Re USA, Chubb Tempest Re International, and Chubb Tempest Re Canada. Global Reinsurance markets its reinsurance products worldwide primarily through reinsurance brokers under the Chubb Tempest Re brand name and provides a broad range of traditional and non-traditional reinsurance coverage to a diverse array of primary P&C companies.

				% Change	
(in millions of U.S. dollars, except for percentages)	**2019**	2018	2017	2019 vs. 2018	2018 vs. 2017
Net premiums written	**$ 649**	$ 671	$ 685	(3.2)%	(2.1)%
Net premiums earned	**654**	670	704	(2.3)%	(4.9)%
Losses and loss expenses	**352**	479	561	(26.5)%	(14.7)%
Policy acquisition costs	**169**	162	177	4.2 %	(8.4)%
Administrative expenses	**35**	41	44	(12.7)%	(8.4)%
Underwriting income (loss)	**98**	(12)	(78)	NM	84.8 %
Net investment income	**220**	257	273	(14.4)%	(6.1)%
Other (income) expense	**(58)**	(32)	(1)	80.6 %	NM
Segment income	**$ 376**	$ 277	$ 196	35.7 %	41.3 %
Net premiums written - constant dollars [(1)]				(1.7)%	(3.3)%
Net premiums earned - constant dollars [(1)]				(0.8)%	(6.0)%
Underwriting income - constant dollars [(1)]				NM	84.0 %
Loss and loss expense ratio	**53.9%**	71.6%	79.8%	(17.7) pts	(8.2) pts
Policy acquisition cost ratio	**25.7%**	24.2%	25.1%	1.5 pts	(0.9) pts
Administrative expense ratio	**5.4%**	6.0%	6.3%	(0.6) pts	(0.3) pts
Combined ratio	**85.0%**	101.8%	111.2%	(16.8) pts	(9.4) pts

NM – not meaningful

(1) On a constant-dollar basis. Amounts are calculated by translating prior period results using the same local currency rates as the comparable current period.

Premiums

2019 vs. 2018

Net premiums written decreased $22 million in 2019, or $12 million on a constant-dollar basis, as an increase in new business written in property and marine lines was more than offset by an increase in ceded retrocessions, reductions in the international motor line, and higher reinstatement premiums collected in the prior year.

Net premiums earned decreased $16 million in 2019, or $5 million on a constant-dollar basis, reflecting the decrease in net premiums written described above.

2018 vs. 2017

Net premiums written decreased $14 million in 2018, or $22 million on a constant-dollar basis, primarily due to higher reinstatement premiums collected in the prior year principally relating to the 2017 natural catastrophes ($15 million year-over-year decrease) and lower renewals, which is reflective of competitive market conditions primarily in catastrophe and catastrophe exposed lines of business, partially offset by new business written in the casualty line of business.

Net premiums earned decreased $34 million in 2018, or $42 million on a constant-dollar basis, reflecting the decrease in net premiums written. The decrease was also due to $14 million of short-term treaties (less than one year in duration) earned in the prior year that were written in 2016 and 2017.

Combined Ratio

2019 vs. 2018

The loss and loss expense ratio decreased 17.7 percentage points in 2019 primarily due to lower catastrophe losses, partially offset by lower favorable prior period development.

The policy acquisition cost ratio increased 1.5 percentage points in 2019 primarily due to higher commissions paid on property and motor lines treaties with adjustable commission features, and higher reinstatement premiums collected in the prior year which have a lower acquisition cost.

The administrative expense ratio decreased 0.6 percentage points in 2019 primarily driven by lower variable costs.

2018 vs. 2017

The loss and loss expense ratio decreased 8.2 percentage points in 2018 principally due to lower catastrophe losses partially offset by lower favorable prior period development and a shift in the mix of business from property catastrophe business towards casualty business, which generally has a higher loss ratio.

The policy acquisition cost ratio decreased 0.9 percentage points in 2018 primarily due to lower acquisition expenses from proportional business sold.

The administrative expense ratio decreased 0.3 percentage points in 2018 primarily due to continued expense management.

Catastrophe Losses and Prior Period Development

(in millions of U.S dollars)	**2019**	2018	2017
Catastrophe losses (excludes reinstatement premiums)	**$ 51**	$ 205	$ 313
Favorable prior period development	**$ 29**	$ 50	$ 59

Catastrophe losses were primarily from the following events (refer to the table on page 54):

- 2019: Typhoons Hagibis and Faxai; Hurricane Dorian, and other severe weather-related events primarily in the U.S.
- 2018: Hurricanes Florence and Michael; Typhoons Jebi and Trami; Windstorm Friederike, California Wildfires, and severe weather-related events in the U.S., Canada and Japan
- 2017: Hurricanes Harvey, Irma and Maria; Northern California Wildfires, and severe weather-related events in the U.S.

CAY Loss Ratio excluding Catastrophe Losses

	2019	2018	2017
Loss and loss expense ratio	**53.9 %**	71.6 %	79.8 %
Catastrophe losses	**(7.6)%**	(29.2)%	(42.4)%
Favorable prior period development	**4.3 %**	8.1 %	8.6 %
CAY loss ratio excluding catastrophe losses	**50.6 %**	50.5 %	46.0 %

The CAY loss ratio excluding catastrophe losses remained relatively flat in 2019. The CAY loss ratio excluding catastrophe losses increased 4.5 percentage points in 2018 primarily due to a shift in the mix of business from property catastrophe business towards casualty business which generally has a higher loss ratio and higher losses in our U.S. property lines.

Life Insurance

The Life Insurance segment comprises Chubb's international life operations, Chubb Tempest Life Re (Chubb Life Re), and the North American supplemental A&H and life business of Combined Insurance.

				% Change	
(in millions of U.S. dollars, except for percentages)	**2019**	2018	2017	2019 vs. 2018	2018 vs. 2017
Net premiums written	**$ 2,392**	$ 2,270	$ 2,141	5.3 %	6.1%
Net premiums earned	**2,343**	2,218	2,101	5.6 %	5.6%
Losses and loss expenses	**757**	766	739	(1.1)%	3.7%
Adjusted policy benefits	**696**	628	579	10.8 %	8.5%
Policy acquisition costs	**620**	557	530	11.2 %	5.1%
Administrative expenses	**323**	310	303	4.5 %	2.3%
Net investment income	**373**	341	313	9.2 %	8.9%
Life Insurance underwriting income	**320**	298	263	6.9 %	13.3%
Other (income) expense	**(48)**	(12)	13	NM	NM
Amortization of purchased intangibles	**2**	2	2	—	—
Segment income	**$ 366**	$ 308	$ 248	18.6 %	24.2%
Net premiums written - constant dollars [(1)]				6.4 %	5.7%
Net premiums earned - constant dollars [(1)]				6.6 %	5.3%
Life Insurance underwriting income - constant dollars [(1)]				8.1 %	13.9%

NM – not meaningful

(1) On a constant-dollar basis. Amounts are calculated by translating prior period results using the same local currency rates as the comparable current period.

Premiums

2019 vs. 2018

Net premiums written increased $122 million in 2019, or $143 million on a constant-dollar basis, primarily reflecting growth in our Asian and Latin American international life operations and North American Combined Insurance supplemental A&H program, partially offset by our life reinsurance business, which continues to decline as no new life reinsurance business is being written.

2018 vs. 2017

Net premiums written increased $129 million in 2018, or $123 million on a constant-dollar basis, primarily due to growth in our North American Combined Insurance supplemental A&H program business, and Asian and Latin American international life operations, partially offset by our life reinsurance business, which continues to decline as no new life reinsurance business is being written.

Deposits

The following table presents deposits collected on universal life and investment contracts:

(in millions of U.S. dollars, except for percentages)	**2019**	2018	2017	% Change 2019 vs. 2018	C$ [1] 2019 vs. 2018	2018 vs. 2017
Deposits collected on universal life and investment contracts	**$ 1,463**	$ 1,538	$ 1,436	(4.9)%	(2.3)%	7.1%

(1) On a constant-dollar basis. Amounts are calculated by translating prior period results using the same local currency rates as the comparable current period.

Deposits collected on universal life and investment contracts (life deposits) are not reflected as revenues in our Consolidated statements of operations in accordance with GAAP. New life deposits are an important component of production, and although they do not significantly affect current period income from operations they are key to our efforts to grow our business. Life deposits collected decreased in 2019 due to declines in Taiwan, driven by competitive market conditions, and Hong Kong, due to the civil unrest negatively impacting growth in the second half of the year, partially offset by growth in Vietnam. Foreign exchange unfavorably impacted growth by $40 million in 2019.

Life deposits collected increased in 2018 due to growth in Korea, Taiwan, and Vietnam. Foreign exchange favorably impacted growth by $14 million in 2018.

Life Insurance underwriting income and Segment income

2019 vs. 2018

Life Insurance underwriting income increased $22 million in 2019 compared to 2018, principally reflecting an increase in net investment income, partially offset by a favorable reserve development in the prior year. Additionally, segment income benefited from other income of $48 million in 2019 compared to $12 million in 2018, principally due to our share of net income from Huatai Life, our partially-owned life insurance entity in China.

2018 vs. 2017

Life Insurance underwriting income increased $35 million in 2018 compared to 2017 primarily due to an increase in net investment income as well as growth as described above.

Corporate

Corporate results primarily include the results of our non-insurance companies, income and expenses not attributable to reportable segments and loss and loss expenses of asbestos and environmental (A&E) liabilities and certain other non-A&E run-off exposures.

Our exposure to A&E claims principally arises out of liabilities acquired when we purchased Westchester Specialty in 1998, CIGNA's P&C business in 1999, and legacy Chubb Corp A&E claims in 2016. Corporate staff expenses and net investment income of Chubb Limited, including the amortization of the fair value adjustment on acquired invested assets and debt, interest expense, amortization of purchased intangibles related to the Chubb Corp acquisition, and Chubb integration expenses are reported within Corporate.

							% Change	
(in millions of U.S. dollars, except for percentages)		**2019**		2018		2017	2019 vs. 2018	2018 vs. 2017
Losses and loss expenses	**$**	**158**	$	53	$	285	203.0 %	(81.4)%
Administrative expenses		**319**		295		267	8.1 %	10.5 %
Underwriting loss		**477**		348		552	36.6 %	(37.0)%
Net investment income (loss)		**(125)**		(209)		(283)	(40.5)%	(26.1)%
Interest expense		**552**		641		607	(13.9)%	5.6 %
Adjusted net realized gains (losses)		**(522)**		(649)		91	(19.7)%	NM
Other (income) expense		**(459)**		(406)		(318)	12.6 %	27.7 %
Amortization of purchased intangibles		**218**		255		168	(14.3)%	51.8 %
Chubb integration expenses		**23**		59		310	(61.7)%	(81.0)%
Income tax expense (benefit)		**795**		695		(139)	14.4 %	NM
Net loss	**$**	**(2,253)**	$	(2,450)	$	(1,372)	(8.1)%	78.6 %

NM – not meaningful

Losses and loss expenses in 2019, 2018, and 2017 were primarily from adverse development relating to our Brandywine asbestos and environmental exposures, non-A&E run-off casualty exposure, including workers' compensation, and unallocated loss adjustment expenses of the A&E claims operations. In addition, 2018 included favorable reinsurance settlements of $205 million. Refer to Note 7 of the Consolidated Financial Statements for further information.

Administrative expenses increased $24 million and $28 million in 2019 and 2018, respectively, primarily due to higher global advertising expenses.

Chubb integration expenses are one-time in nature and are not related to the on-going business activities of the segments. The Chief Executive Officer does not manage segment results or allocate resources to segments when considering these costs and they are therefore excluded from our definition of segment income. Chubb integration expenses in 2019 principally consisted of small residual items related to the Chubb acquisition. Chubb integration expenses for 2018 were $59 million and principally consisted of personnel-related expenses ($18 million) and rebranding ($14 million).

Refer to the respective sections that follow for a discussion of Net investment income, Interest expense, Other (income) expense, Net realized gains and losses, Amortization of purchased intangibles, and Income tax expense.

Effective income tax rate

Our effective income tax rate reflects a mix of income or losses in jurisdictions with a wide range of tax rates, permanent differences between US GAAP and local tax laws, and the timing of recording discrete items. A change in the geographic mix of earnings could impact our effective tax rate.

In 2019, 2018, and 2017, our effective income tax rate was 15.1 percent, 14.9 percent, and (3.7) percent, respectively. The effective income tax rate in 2018 was favorably impacted by an increase to the provisional benefit recorded related to the impact of the 2017 Tax Act. The effective income tax rate in 2017 included the favorable income tax benefit of $450 million, which represented our best estimate of the impact of the 2017 Tax Act. In addition, the income tax benefit in 2017 reflected the significant catastrophe losses in the year.

The 2017 Tax Act included provisions for Global Intangible Low-Taxed Income (GILTI) under which taxes may be imposed on income of foreign subsidiaries and for a Base Erosion and Anti-Abuse Tax (BEAT) under which taxes may be imposed on certain payments to affiliated foreign companies. There remain substantial uncertainties in the interpretation of GILTI and BEAT and portions of the formal guidance issued to date are still in part in proposed form. Finalization of the proposed guidance, and changes to the interpretations and assumptions related to these provisions may impact amounts recorded with respect to the international provisions of the 2017 Tax Act, which may be material in the period the adjustment is recorded. Refer to Note 8 to the Consolidated Financial Statements for additional information on the 2017 Tax Act.

Our effective income tax rate reflects the lower corporate tax rates that prevailed outside the United States on income attributed to certain foreign operations, including 7.83 percent in Switzerland and 0.0 percent in Bermuda. During 2019, approximately 42 percent of our total pre-tax income was tax effected based on these lower rates compared with 49 percent and 62 percent in 2018 and 2017, respectively.

Non-GAAP Reconciliation

In presenting our results, we included and discussed certain non-GAAP measures. These non-GAAP measures, which may be defined differently by other companies, are important for an understanding of our overall results of operations and financial condition. However, they should not be viewed as a substitute for measures determined in accordance with generally accepted accounting principles (GAAP).

Adjusted interest expense and adjusted net investment income are non-GAAP financial measures which exclude amortization of the fair value adjustment on assumed long-term debt and acquired invested assets, respectively, related to the Chubb Corp acquisition due to the size and complexity of this acquisition. Refer to the Interest Expense section for a reconciliation of interest expense to adjusted interest expense.

We provide financial measures, including net premiums written, net premiums earned, and underwriting income on a constant-dollar basis. We believe it is useful to evaluate the trends in our results exclusive of the effect of fluctuations in exchange rates between the U.S. dollar and the currencies in which our international business is transacted, as these exchange rates could fluctuate significantly between periods and distort the analysis of trends. The impact is determined by assuming constant foreign exchange rates between periods by translating prior period results using the same local currency exchange rates as the comparable current period.

Adjusted policy benefits include gains and losses from fair value changes in separate account assets, as well as the offsetting movement in separate account liabilities, for purposes of reporting Life Insurance underwriting income. The gains and losses from fair value changes in separate account assets that do not qualify for separate account reporting under GAAP have been reclassified from Other (income) expense. We view gains and losses from fair value changes in both separate account assets and liabilities as part of the results of our underwriting operations, and therefore these gains and losses are reclassified to adjusted policy benefits.

The following table presents a reconciliation of Policy benefits to Adjusted policy benefits:

	Year Ended December 31		
(in millions of U.S. dollars)	**2019**	2018	2017
Policy benefits	**$ 740**	$ 590	$ 676
Add: (Gains) losses from fair value changes in separate account assets	**(44)**	38	(97)
Adjusted policy benefits	**$ 696**	$ 628	$ 579

P&C performance metrics comprise consolidated operating results (including Corporate) and exclude the operating results of the Life Insurance segment. We believe that these measures are useful and meaningful to investors as they are used by management to assess the company's P&C operations which are the most economically similar. We exclude the Life Insurance segment because the results of this business do not always correlate with the results of our P&C operations.

P&C combined ratio is the sum of the loss and loss expense ratio, acquisition cost ratio and the administrative expense ratio excluding the life business and including the realized gains and losses on the crop derivatives. These derivatives were purchased to provide economic benefit, in a manner similar to reinsurance protection, in the event that a significant decline in commodity pricing impacts underwriting results. We view gains and losses on these derivatives as part of the results of our underwriting operations.

CAY P&C combined ratio excluding catastrophe losses (CATs) excludes CATs and prior period development (PPD) from the P&C combined ratio. We exclude CATs as they are not predictable as to timing and amount and PPD as these unexpected loss developments on historical reserves are not indicative of our current underwriting performance. The combined ratio numerator is adjusted to exclude CATs, net premiums earned adjustments on PPD, prior period expense adjustments and reinstatement premiums on PPD, and the denominator is adjusted to exclude net premiums earned adjustments on PPD and reinstatement premiums on CATs and PPD. In periods where there are adjustments on loss sensitive policies, these adjustments are excluded from PPD and net premiums earned when calculating the ratios. We believe this measure provides a better evaluation of our underwriting performance and enhances the understanding of the trends in our P&C business that may be obscured by these items. This measure is commonly reported among our peer companies and allows for a better comparison.

Reinstatement premiums are additional premiums paid on certain reinsurance agreements in order to reinstate coverage that had been exhausted by loss occurrences. The reinstatement premium amount is typically a pro rata portion of the original ceded premium paid based on how much of the reinsurance limit had been exhausted.

Net premiums earned adjustments within PPD are adjustments to the initial premium earned on retrospectively rated policies based on actual claim experience that develops after the policy period ends. The premium adjustments correlate to the prior period loss development on these same policies and are fully earned in the period the adjustments are recorded.

Prior period expense adjustments typically relate to adjustable commission reserves or policyholder dividend reserves based on actual claim experience that develops after the policy period ends. The expense adjustments correlate to the prior period loss development on these same policies.

For this disclosure purpose, the normalized level of CATs, or expected level of CATs, is not intended to represent a probability weighted expectation for the company but rather to represent management's view of what might be more typical for a given period based on various factors, including historical experience, seasonal patterns, and consideration of both modeled CATs (e.g., windstorm and earthquake) as well as non-modeled CATs (e.g., wildfires, floods and freeze).

The following table presents CATs above (below) expected level and the impact on the combined ratio:

	Year Ended December 31		
(in millions of U.S. dollars, except for percentage points)	**2019**	2018	2017
Actual level of CATs - pre-tax	**$ 1,187**	$ 1,626	$ 2,746
Less: Expected level of CATs - pre-tax	**969**	937	908
CATs above expected level - pre-tax	**$ 218**	$ 689	$ 1,838
Adverse impact of CATs above an expected level on combined ratio	**0.7%**	2.5%	6.8%

The following tables present the calculation of combined ratio, as reported for each segment to P&C combined ratio, adjusted for catastrophe losses (CATs) and PPD:

For the Year Ended December 31, 2019 (in millions of U.S. dollars except for ratios)		North America Commercial P&C Insurance	North America Personal P&C Insurance	North America Agricultural Insurance	Overseas General Insurance	Global Reinsurance	Corporate	Total P&C
Numerator								
Losses and loss expenses								
Losses and loss expenses		$ 8,206	$ 3,043	$ 1,608	$ 4,606	$ 352	$ 158	$ 17,973
Realized (gains) losses on crop derivatives		—	—	8	—	—	—	8
Adjusted losses and loss expenses	A	$ 8,206	$ 3,043	$ 1,616	$ 4,606	$ 352	$ 158	$ 17,981
Catastrophe losses and related adjustments								
Catastrophe losses, net of related adjustments		(421)	(554)	(8)	(156)	(48)	—	(1,187)
Reinstatement premiums collected (expensed) on catastrophe losses		—	(11)	—	(4)	3	—	(12)
Catastrophe losses, gross of related adjustments		(421)	(543)	(8)	(152)	(51)	—	(1,175)
PPD and related adjustments								
PPD, net of related adjustments - favorable (unfavorable)		649	95	80	92	29	(153)	792
Net premiums earned adjustments on PPD - unfavorable (favorable)		38	—	36	—	1	—	75
Expense adjustments - unfavorable (favorable)		(3)	—	(13)	—	(1)	—	(17)
PPD reinstatement premiums - unfavorable (favorable)		(1)	(4)	—	1	(1)	—	(5)
PPD, gross of related adjustments - favorable (unfavorable)		683	91	103	93	28	(153)	845
CAY loss and loss expense ex CATs	B	$ 8,468	$ 2,591	$ 1,711	$ 4,547	$ 329	$ 5	$ 17,651
Policy acquisition costs and administrative expenses								
Policy acquisition costs and administrative expenses	C	$ 2,859	$ 1,234	$ 90	$ 3,534	$ 204	$ 319	$ 8,240
Expense adjustments - favorable (unfavorable)		3	—	13	—	1	—	17
Policy acquisition costs and administrative expenses, adjusted	D	$ 2,862	$ 1,234	$ 103	$ 3,534	$ 205	$ 319	$ 8,257
Denominator								
Net premiums earned	E	$ 12,922	$ 4,694	$ 1,795	$ 8,882	$ 654		$ 28,947
Reinstatement premiums (collected) expensed on catastrophe losses		—	11	—	4	(3)		12
Net premiums earned adjustments on PPD - unfavorable (favorable)		38	—	36	—	1		75
PPD reinstatement premiums - unfavorable (favorable)		(1)	(4)	—	1	(1)		(5)
Net premiums earned excluding adjustments	F	$ 12,959	$ 4,701	$ 1,831	$ 8,887	$ 651		$ 29,029
P&C Combined ratio								
Loss and loss expense ratio	A/E	63.5%	64.8%	90.1%	51.9%	53.9%		62.1%
Policy acquisition cost and administrative expense ratio	C/E	22.1%	26.3%	5.0%	39.7%	31.1%		28.5%
P&C Combined ratio		85.6%	91.1%	95.1%	91.6%	85.0%		90.6%
CAY P&C Combined ratio ex CATs								
Loss and loss expense ratio, adjusted	B/F	65.3%	55.1%	93.5%	51.2%	50.6%		60.8%
Policy acquisition cost and administrative expense ratio, adjusted	D/F	22.1%	26.3%	5.6%	39.7%	31.5%		28.4%
CAY P&C Combined ratio ex CATs		87.4%	81.4%	99.1%	90.9%	82.1%		89.2%
Combined ratio								
Combined ratio								90.6%
Add: impact of gains and losses on crop derivatives								—
P&C Combined ratio								90.6%

Note: The ratios above are calculated using whole U.S. dollars. Accordingly, calculations using rounded amounts may differ. Letters A, B, C, D, E and F included in the table are references for calculating the ratios above.

For the Year Ended December 31, 2018 (in millions of U.S. dollars except for ratios)		North America Commercial P&C Insurance	North America Personal P&C Insurance	North America Agricultural Insurance	Overseas General Insurance	Global Reinsurance	Corporate	Total P&C
Numerator								
Losses and loss expenses								
Losses and loss expenses		$ 8,000	$ 3,229	$ 1,111	$ 4,429	$ 479	$ 53	$ 17,301
Realized (gains) losses on crop derivatives		—	—	3	—	—	—	3
Adjusted losses and loss expenses	A	$ 8,000	$ 3,229	$ 1,114	$ 4,429	$ 479	$ 53	$ 17,304
Catastrophe losses and related adjustments								
Catastrophe losses, net of related adjustments		(579)	(637)	(21)	(206)	(183)	—	(1,626)
Reinstatement premiums collected (expensed) on catastrophe losses		—	(26)	—	—	22	—	(4)
Catastrophe losses, gross of related adjustments		(579)	(611)	(21)	(206)	(205)	—	(1,622)
PPD and related adjustments								
PPD, net of related adjustments - favorable (unfavorable)		610	(41)	110	212	50	(45)	896
Net premiums earned adjustments on PPD - unfavorable (favorable)		29	—	40	—	8	—	77
Expense adjustments - unfavorable (favorable)		7	—	(10)	—	(1)	—	(4)
PPD reinstatement premiums - unfavorable (favorable)		7	1	—	4	—	—	12
PPD, gross of related adjustments - favorable (unfavorable)		653	(40)	140	216	57	(45)	981
CAY loss and loss expense ex CATs	**B**	$ 8,074	$ 2,578	$ 1,233	$ 4,439	$ 331	$ 8	$ 16,663
Policy acquisition costs and administrative expenses								
Policy acquisition costs and administrative expenses	C	$ 2,795	$ 1,208	$ 70	$ 3,360	$ 203	$ 295	$ 7,931
Expense adjustments - favorable (unfavorable)		(7)	—	10	—	1	—	4
Policy acquisition costs and administrative expenses, adjusted	D	$ 2,788	$ 1,208	$ 80	$ 3,360	$ 204	$ 295	$ 7,935
Denominator								
Net premiums earned	E	$ 12,402	$ 4,593	$ 1,569	$ 8,612	$ 670		$ 27,846
Reinstatement premiums (collected) expensed on catastrophe losses		—	26	—	—	(22)		4
Net premiums earned adjustments on PPD - unfavorable (favorable)		29	—	40	—	8		77
PPD reinstatement premiums - unfavorable (favorable)		7	1	—	4	—		12
Net premiums earned excluding adjustments	F	$ 12,438	$ 4,620	$ 1,609	$ 8,616	$ 656		$ 27,939
P&C Combined ratio								
Loss and loss expense ratio	A/E	64.5%	70.3%	71.0%	51.4%	71.6%		62.1%
Policy acquisition cost and administrative expense ratio	C/E	22.5%	26.3%	4.5%	39.0%	30.2%		28.5%
P&C Combined ratio		87.0%	96.6%	75.5%	90.4%	101.8%		90.6%
CAY P&C Combined ratio ex CATs								
Loss and loss expense ratio, adjusted	B/F	64.9%	55.8%	76.7%	51.5%	50.5%		59.6%
Policy acquisition cost and administrative expense ratio, adjusted	D/F	22.4%	26.1%	4.9%	39.0%	31.1%		28.4%
CAY P&C Combined ratio ex CATs		87.3%	81.9%	81.6%	90.5%	81.6%		88.0%
Combined ratio								
Combined ratio								90.6%
Add: impact of gains and losses on crop derivatives								—
P&C Combined ratio								90.6%

Note: The ratios above are calculated using whole U.S. dollars. Accordingly, calculations using rounded amounts may differ. Letters A, B, C, D, E and F included in the table are references for calculating the ratios above.

Net Investment Income

(in millions of U.S. dollars, except for percentages)	**2019**	2018	2017
Average invested assets	**$ 104,074**	$ 101,453	$ 99,675
Net investment income [1]	**$ 3,426**	$ 3,305	$ 3,125
Yield on average invested assets	**3.3%**	3.3%	3.1%
Market yield on fixed maturities	**2.7%**	3.7%	2.9%

(1) Includes $161 million, $248 million and $332 million of amortization expense related to the fair value adjustment of acquired invested assets related to the Chubb Corp acquisition in 2019, 2018 and 2017, respectively.

Net investment income is influenced by a number of factors including the amounts and timing of inward and outward cash flows, the level of interest rates, and changes in overall asset allocation. Net investment income increased 3.6 percent in 2019 compared with 2018, primarily due to higher average invested assets, partially offset by a reduction in the usage of notional cash pooling programs and unfavorable foreign exchange. Net investment income increased 5.8 percent in 2018 compared with 2017, primarily due to higher reinvestment rates offset by lower private equity distributions. Refer to Note 3 g) to the Consolidated Financial Statements for additional information.

For private equities where we own less than three percent, investment income is included within Net investment income in the table above. For private equities where we own more than three percent, investment income is included within Other income (expense) in the Consolidated statements of operations. Excluded from Net investment income is the mark-to-market movement for private equities, which is recorded within either Other income (expense) or Net realized gains (losses) based on our percentage of ownership. The total mark-to-market movement for private equities excluded from Net investment income was as follows:

(in millions of U.S. dollars)	**2019**	2018
Total mark-to-market gain on private equity, pre-tax	**$ 449**	$ 298

Interest Expense

The following table presents our pre-tax interest expense for the years ended December 31, 2019 and 2018. Also presented below is our estimated pre-tax interest expense for the year ended December 31, 2020 based on our existing debt obligations as well as fees based on our expected usage of certain facilities, including letters of credit, collateral fees, and repurchase agreements.

	Estimated Interest Expense					Actual Interest Expense	
	First Quarter	Second Quarter	Third Quarter	Fourth Quarter	Full Year	**Full Year**	Full Year
(in millions of U.S. dollars)	2020	2020	2020	2020	2020	**2019**	2018
Fixed interest expense based on outstanding debt	$ 123	$ 123	$ 122	$ 118	$ 486	**$ 488**	$ 520
Variable interest expense based on expected usage	18	18	18	18	72	**85**	154
Adjusted interest expense	$ 141	$ 141	$ 140	$ 136	$ 558	**$ 573**	$ 674
Amortization of the fair value of debt assumed in the Chubb Corp acquisition	(5)	(5)	(5)	(6)	(21)	**(21)**	(33)
Total interest expense, including amortization of the fair value of debt	$ 136	$ 136	$ 135	$ 130	$ 537	**$ 552**	$ 641

Estimated 2020 fixed interest expense assumes that the $1.3 billion 2.3 percent senior notes is fully paid in November 2020 at the maturity date. Estimated variable interest expense is based on expected usage and current interest rates and may fluctuate.

Net Realized and Unrealized Gains (Losses)

We take a long-term view with our investment strategy, and our investment managers manage our investment portfolio to maximize total return within certain specific guidelines designed to minimize risk. The majority of our investment portfolio is available for sale and reported at fair value. Our held to maturity investment portfolio is reported at amortized cost.

The effect of market movements on our fixed maturities portfolio impacts Net income (through Net realized gains (losses)) when securities are sold or when we record an Other-than-temporary impairment (OTTI) charge. For a further discussion related to how we assess OTTI for our fixed maturities, including credit-related OTTI, and the related impact on Net income, refer to Note 3 c) to the Consolidated Financial Statements. Additionally, Net income is impacted through the reporting of changes in the fair value of equity securities and private equity securities where we own less than three percent, and derivatives, including financial futures, options, swaps, and GLB reinsurance. Changes in unrealized appreciation and depreciation on available for sale securities resulting from the revaluation of securities held, changes in cumulative foreign currency translation adjustment, and unrealized postretirement benefit obligations liability adjustment, are reported as separate components of Accumulated other comprehensive income (loss) in Shareholders' equity in the Consolidated balance sheets. The following table presents our net realized and unrealized gains (losses):

	Year Ended December 31						
	2019			2018			2017
(in millions of U.S. dollars)	**Net Realized Gains (Losses)**	**Net Unrealized Gains (Losses)**	**Net Impact**	Net Realized Gains (Losses)	Net Unrealized Gains (Losses)	Net Impact	Net Realized Gains (Losses)
Fixed maturities	**$ (31)**	**$ 3,738**	**$ 3,707**	$ (302)	$ (1,996)	$ (2,298)	$ (31)
Fixed income and equity derivatives	**(435)**	**—**	**(435)**	(75)	—	(75)	(11)
Public equity							
Sales	**58**	**—**	**58**	70	—	70	16
Mark-to-market	**46**	**—**	**46**	(129)	—	(129)	—
Private equity (less than 3 percent ownership)							
Sales	**(5)**	**—**	**(5)**	121	—	121	(11)
Mark-to-market	**(15)**	**—**	**(15)**	(126)	—	(126)	—
Total investment portfolio	**(382)**	**3,738**	**3,356**	(441)	(1,996)	(2,437)	(37)
Variable annuity reinsurance derivative transactions, net of applicable hedges	**(142)**	**—**	**(142)**	(252)	—	(252)	103
Other derivatives	**(8)**	**—**	**(8)**	(3)	—	(3)	(5)
Foreign exchange	**7**	**13**	**20**	131	(802)	(671)	36
Other [(1)]	**(5)**	**(79)**	**(84)**	(87)	(321)	(408)	(13)
Net gains (losses), pre-tax	**$ (530)**	**$ 3,672**	**$ 3,142**	$ (652)	$ (3,119)	$ (3,771)	$ 84

(1) Net unrealized gains (losses) includes our postretirement programs of $(76) million, $(321) million, and $(16) million for the years ended December 31, 2019, 2018, and 2017, respectively.

For the years ended December 31, 2019 and 2018, other-than-temporary impairments in Net realized gains (losses) include $58 million and $49 million, respectively, for fixed maturities.

The variable annuity reinsurance derivative transactions resulted in realized gains (losses), due to the (increase) decrease in the fair value of GLB liabilities of $(4) million, $(248) million, and $364 million for the years ended December 31, 2019, 2018, and 2017, respectively. The realized losses in 2019 reflected an increase in the fair value of GLB liabilities due to lower interest rates and changes made to our valuation model relating to policyholder behavior which was partially offset by higher global equity market levels. The realized losses in 2018 reflected an increase in the fair value of GLB liabilities due to lower global equity market levels, the impact of discounting future claims for one less year and changes made to our valuation model relating to policyholder behavior. In addition, we maintain positions in derivative instruments that decrease in fair value when the S&P 500 index increases. During the years ended December 31, 2019, 2018, and 2017, we experienced realized losses of $138 million, $4 million, and $261 million, respectively, related to these derivative instruments.

Amortization of Purchased Intangibles and Other Amortization

Amortization expense related to purchased intangibles were $305 million, $339 million, and $260 million for the years ended December 31, 2019, 2018, and 2017, respectively, and principally relates to the Chubb Corp acquisition. The decrease in amortization expense of purchased intangibles in 2019 compared to 2018 primarily reflects lower intangible amortization expense related to agency distribution relationships and renewal rights. The increase in 2018 compared to 2017 primarily reflects a lower amortization benefit from the fair value adjustment on unpaid losses and loss expenses. The amortization of purchased intangibles expense in 2020 is expected to be $290 million, or approximately $73 million each quarter.

Reduction of deferred tax liability associated with intangible assets related to Other intangible assets (excluding the fair value adjustment on Unpaid losses and loss expense)

At December 31, 2019, the deferred tax liability associated with the Other intangible assets (excluding the fair value adjustment on Unpaid losses and loss expenses) was $1,347 million.

The following table presents at December 31, 2019, the expected reduction to the deferred tax liability associated with Other intangible assets (which reduces as agency distribution relationships and renewal rights, and other intangible assets amortize), at current foreign currency exchange rates for the next five years:

For the Years Ending December 31 (in millions of U.S. dollars)	Reduction to deferred tax liability associated with intangible assets
2020	$ 72
2021	67
2022	64
2023	60
2024	55
Total	$ 318

Amortization of the fair value adjustment on acquired invested assets and assumed long-term debt

The following table presents at December 31, 2019, the expected amortization expense of the fair value adjustment on acquired invested assets, at current foreign currency exchange rates, and the expected amortization benefit from the amortization of the fair value adjustment on assumed long-term debt for the next five years as follows:

	Amortization (expense) benefit of the fair value adjustment on	
For the Years Ending December 31 (in millions of U.S. dollars)	Acquired invested assets (1)	Assumed long-term debt (2)
2020	$ (130)	$ 21
2021	(110)	21
2022	(92)	21
2023	—	21
2024	—	21
Total	$ (332)	$ 105

(1) Recorded as a reduction to Net investment income in the Consolidated statements of operations.

(2) Recorded as a reduction to Interest expense in the Consolidated statements of operations.

The estimate of amortization expense of the fair value adjustment on acquired invested assets could vary materially based on current market conditions, bond calls, overall duration of the acquired investment portfolio, and foreign exchange.

Investments

Our investment portfolio is invested primarily in publicly traded, investment grade, fixed income securities with an average credit quality of A/Aa as rated by the independent investment rating services Standard and Poor's (S&P)/ Moody's Investors Service (Moody's). The portfolio is externally managed by independent, professional investment managers and is broadly diversified across geographies, sectors, and issuers. Other investments principally comprise direct investments, investment funds, and limited partnerships. We hold no collateralized debt obligations in our investment portfolio, and we provide no credit default protection. We have long-standing global credit limits for our entire portfolio across the organization. Exposures are aggregated, monitored, and actively managed by our Global Credit Committee, comprising senior executives, including our Chief Financial Officer, our Chief Risk Officer, our Chief Investment Officer, and our Treasurer. We also have well-established, strict contractual investment rules requiring managers to maintain highly diversified exposures to individual issuers and closely monitor investment manager compliance with portfolio guidelines. The average duration of our fixed income securities, including the effect of options and swaps, was 3.8 years and 3.7 years at December 31, 2019 and 2018, respectively. We estimate that a 100 basis point (bps) increase in interest rates would reduce the valuation of our fixed income portfolio by approximately $3.9 billion at December 31, 2019.

	December 31, 2019		December 31, 2018	
(in millions of U.S. dollars)	**Fair Value**	**Cost/ Amortized Cost**	Fair Value	Cost/ Amortized Cost
Fixed maturities available for sale	**$ 85,488**	**$ 82,580**	$ 78,470	$ 79,323
Fixed maturities held to maturity	**13,005**	**12,581**	13,259	13,435
Short-term investments	**4,291**	**4,291**	3,016	3,016
	102,784	**99,452**	94,745	95,774
Equity securities	**812**	**812**	770	770
Other investments	**6,062**	**6,062**	5,277	5,277
Total investments	**$ 109,658**	**$ 106,326**	$ 100,792	$ 101,821

The fair value of our total investments increased $8.9 billion during the year ended December 31, 2019, primarily due to unrealized appreciation driven by declining interest rates and the investing of both operating cash flows and net proceeds from debt issuance. This increase was partially offset by the payment of dividends on our Common Shares and share repurchases.

The following tables present the market value of our fixed maturities and short-term investments at December 31, 2019 and 2018. The first table lists investments according to type and the second according to S&P credit rating:

	December 31, 2019		December 31, 2018	
(in millions of U.S. dollars, except for percentages)	**Market Value**	**% of Total**	Market Value	% of Total
Treasury / Agency	**$ 4,630**	**5%**	$ 5,327	6%
Corporate and asset-backed	**34,259**	**33%**	29,091	31%
Mortgage-backed	**21,588**	**21%**	18,026	19%
Municipal	**12,824**	**12%**	16,327	17%
Non-U.S.	**25,192**	**25%**	22,958	24%
Short-term investments	**4,291**	**4%**	3,016	3%
Total	**$ 102,784**	**100%**	$ 94,745	100%
AAA	**$ 15,714**	**15%**	$ 14,571	15%
AA	**37,504**	**37%**	36,715	39%
A	**19,236**	**19%**	17,253	18%
BBB	**13,650**	**13%**	12,035	13%
BB	**9,474**	**9%**	8,363	9%
B	**6,897**	**7%**	5,596	6%
Other	**309**	**—**	212	—
Total	**$ 102,784**	**100%**	$ 94,745	100%

Corporate and asset-backed securities

The following table presents our 10 largest global exposures to corporate bonds by market value at December 31, 2019:

(in millions of U.S. dollars)	Market Value
Wells Fargo & Co	$ 637
Bank of America Corp	575
JP Morgan Chase & Co	568
Comcast Corp	461
HSBC Holdings Plc	396
AT&T Inc	392
Citigroup Inc	392
Verizon Communications Inc	381
Goldman Sachs Group Inc	369
Morgan Stanley	358

Mortgage-backed securities

	S&P Credit Rating					Market Value	Amortized Cost
December 31, 2019 (in millions of U.S. dollars)	AAA	AA	A	BBB	BB and below	Total	Total
Agency residential mortgage-backed (RMBS)	$ 187	$ 17,722	$ —	$ —	$ —	$ 17,909	$ 17,436
Non-agency RMBS	184	32	75	18	10	319	317
Commercial mortgage-backed	2,946	272	136	6	—	3,360	3,290
Total mortgage-backed securities	$ 3,317	$ 18,026	$ 211	$ 24	$ 10	$ 21,588	$ 21,043

Municipal

As part of our overall investment strategy, we may invest in states, municipalities, and other political subdivisions fixed maturity securities (Municipal). We apply the same investment selection process described previously to our Municipal investments. The portfolio is highly diversified primarily in state general obligation bonds and essential service revenue bonds including education and utilities (water, power, and sewers).

Non-U.S.

Our exposure to the Euro results primarily from Chubb European Group SE which is headquartered in France and offers a broad range of coverages throughout the European Union, Central, and Eastern Europe. Chubb primarily invests in Euro denominated investments to support its local currency insurance obligations and required capital levels. Chubb's local currency investment portfolios have strict contractual investment guidelines requiring managers to maintain a high quality and diversified portfolio to both sector and individual issuers. Investment portfolios are monitored daily to ensure investment manager compliance with portfolio guidelines.

Our non-U.S. investment grade fixed income portfolios are currency-matched with the insurance liabilities of our non-U.S. operations. The average credit quality of our non-U.S. fixed income securities is A and 49 percent of our holdings are rated AAA or guaranteed by governments or quasi-government agencies. Within the context of these investment portfolios, our government and corporate bond holdings are highly diversified across industries and geographies. Issuer limits are based on credit rating (AA—two percent, A—one percent, BBB—0.5 percent of the total portfolio) and are monitored daily via an internal compliance system. We manage our indirect exposure using the same credit rating based investment approach. Accordingly, we do not believe our indirect exposure is material.

The following table summarizes the market value and amortized cost of our non-U.S. fixed income portfolio by country/sovereign for non-U.S. government securities at December 31, 2019:

(in millions of U.S. dollars)	Market Value	Amortized Cost
Republic of Korea	$ 1,032	$ 920
United Kingdom	924	903
Canada	835	830
Federative Republic of Brazil	688	669
Kingdom of Thailand	652	558
Province of Ontario	644	634
United Mexican States	567	554
Province of Quebec	496	484
Commonwealth of Australia	365	324
Socialist Republic of Vietnam	362	277
Other Non-U.S. Government Securities	4,890	4,706
Total	$ 11,455	$ 10,859

The following table summarizes the market value and amortized cost of our non-U.S. fixed income portfolio by country/sovereign for non-U.S. corporate securities at December 31, 2019:

(in millions of U.S. dollars)	Market Value	Amortized Cost
United Kingdom	$ 2,316	$ 2,224
Canada	1,781	1,735
United States (1)	1,156	1,111
France	1,136	1,088
Australia	813	781
Netherlands	685	656
Japan	587	576
Germany	560	538
Switzerland	511	490
China	371	362
Other Non-U.S. Corporate Securities	3,821	3,673
Total	$ 13,737	$ 13,234

(1) The countries that are listed in the non-U.S. corporate fixed income portfolio above represent the ultimate parent company's country of risk. Non-U.S. corporate securities could be issued by foreign subsidiaries of U.S. corporations.

Below-investment grade corporate fixed income portfolio
Below-investment grade securities have different characteristics than investment grade corporate debt securities. Risk of loss from default by the borrower is greater with below-investment grade securities. Below-investment grade securities are generally unsecured and are often subordinated to other creditors of the issuer. Also, issuers of below-investment grade securities usually have higher levels of debt and are more sensitive to adverse economic conditions, such as recession or increasing interest rates, than investment grade issuers. At December 31, 2019, our corporate fixed income investment portfolio included below-investment grade and non-rated securities which, in total, comprised approximately 14 percent of our fixed income portfolio. Our below-investment grade and non-rated portfolio includes over 1,300 issuers, with the greatest single exposure being $149 million.

We manage high-yield bonds as a distinct and separate asset class from investment grade bonds. The allocation to high-yield bonds is explicitly set by internal management and is targeted to securities in the upper tier of credit quality (BB/B). Our minimum rating for initial purchase is BB/B. Twelve external investment managers are responsible for high-yield security selection and portfolio construction. Our high-yield managers have a conservative approach to credit selection and very low historical default experience. Holdings are highly diversified across industries and generally subject to a 1.5 percent issuer limit as a percentage of high-yield allocation. We monitor position limits daily through an internal compliance system. Derivative and structured securities (e.g., credit default swaps and collateralized loan obligations) are not permitted in the high-yield portfolio.

Asbestos and Environmental (A&E)

Asbestos and environmental (A&E) reserving considerations
For asbestos, Chubb faces claims relating to policies issued to manufacturers, distributors, installers, and other parties in the chain of commerce for asbestos and products containing asbestos. Claimants will generally allege damages across an extended time period which may coincide with multiple policies covering a wide range of time periods for a single insured.

Environmental claims present exposure for remediation and defense costs associated with the contamination of property as a result of pollution.

The following table presents count information for asbestos claims by causative agent and environmental claims by account, for direct policies only:

	Asbestos (by causative agent)		Environmental (by account)	
	2019	2018	**2019**	2018
Open at beginning of year	**1,838**	1,789	**1,361**	1,349
Newly reported/reopened	**173**	188	**140**	149
Closed or otherwise disposed	**287**	139	**284**	137
Open at end of year	**1,724**	1,838	**1,217**	1,361

Survival ratios are calculated by dividing the asbestos or environmental loss and allocated loss adjustment expense (ALAE) reserves by the average asbestos or environmental loss and ALAE payments for the three most recent calendar years (3-year survival ratio). The 3-year survival ratios for gross and net Asbestos loss and ALAE reserves were 5.8 years and 6.0 years, respectively. The 3-year survival ratios for gross and net Environmental loss and ALAE reserves were 4.0 years and 12.1 years, respectively. The net 3-year survival ratios were impacted by favorable reinsurance settlements in 2018. Excluding the settlements, the 3-year survival ratio for net Asbestos loss and ALAE reserves and net Environmental loss and ALAE reserves were 5.7 years and 4.5 years, respectively. Refer to the PPD section in Note 7 to the consolidated financial statements for additional information on the settlements. The survival ratios provide only a very rough depiction of reserves and are significantly impacted by a number of factors such as aggressive settlement practices, variations in gross to ceded relationships within the asbestos or environmental claims, and levels of coverage provided. Therefore, we urge caution in using these very simplistic ratios to gauge reserve adequacy.

Catastrophe Management

We actively monitor and manage our catastrophe risk accumulation around the world such as setting risk limits based on probable maximum loss (PML) and purchasing catastrophe reinsurance. The table below presents our modeled pre-tax estimates of natural catastrophe PML, net of reinsurance, at December 31, 2019, for Worldwide, U.S. hurricane and California earthquake events, based on our in-force portfolio at October 1, 2019 and reflecting the April 1, 2019 reinsurance program (see Natural Catastrophe Property Reinsurance Program section) as well as inuring reinsurance protection coverages. According to the model, for the 1-in-100 return period scenario, there is a one percent chance that our pre-tax annual aggregate losses incurred in any year from U.S. hurricane events could be in excess of $2,685 million (or 4.9 percent of our total shareholders' equity at December 31, 2019). These estimates assume that reinsurance recoverable is fully collectible.

	Modeled Net Probable Maximum Loss (PML) Pre-tax					
	Worldwide (1) Annual Aggregate		U.S. Hurricane (2) Annual Aggregate		California Earthquake (3) Single Occurrence	
(in millions of U.S. dollars, except for percentages)	Chubb	% of Total Shareholders' Equity	Chubb	% of Total Shareholders' Equity	Chubb	% of Total Shareholders' Equity
1-in-10	$ 1,873	3.4%	$ 1,089	2.0%	$ 129	0.2%
1-in-100	$ 3,804	6.9%	$ 2,685	4.9%	$ 1,338	2.4%
1-in-250	$ 6,227	11.3%	$ 4,698	8.5%	$ 1,513	2.7%

(1) Worldwide losses are comprised of losses arising only from hurricanes, typhoons, convective storms and earthquakes and do not include "non-modeled" perils such as wildfire and flood.

(2) U.S. Hurricane losses include losses from wind and storm-surge and exclude rainfall.

(3) California earthquakes include fire-following perils.

The above estimates of Chubb's loss profile are inherently uncertain for many reasons, including the following:

- While the use of third-party catastrophe modeling packages to simulate potential hurricane and earthquake losses is prevalent within the insurance industry, the models are reliant upon significant meteorology, seismology, and engineering assumptions to estimate catastrophe losses. In particular, modeled catastrophe events are not always a representation of actual events and ensuing additional loss potential;
- There is no universal standard in the preparation of insured data for use in the models, the running of the modeling software and interpretation of loss output. These loss estimates do not represent our potential maximum exposures and it is highly likely that our actual incurred losses would vary materially from the modeled estimates; and
- The potential effects of climate change add to modeling complexity.

Natural Catastrophe Property Reinsurance Program

Chubb's core property catastrophe reinsurance program provides protection against natural catastrophes impacting its primary property operations (i.e., excluding our Global Reinsurance and Life Insurance segments).

We regularly review our reinsurance protection and corresponding property catastrophe exposures. This may or may not lead to the purchase of additional reinsurance prior to a program's renewal date. In addition, prior to each renewal date, we consider how much, if any, coverage we intend to buy and we may make material changes to the current structure in light of various factors, including modeled PML assessment at various return periods, reinsurance pricing, our risk tolerance and exposures, and various other structuring considerations.

Chubb renewed its Global Property Catastrophe Reinsurance Program for our North American and International operations effective April 1, 2019 through March 31, 2020, with modest enhancements in coverage from the expiring program. The program consists of three layers in excess of losses retained by Chubb on a per occurrence basis. In addition, Chubb also renewed its terrorism coverage (excluding nuclear, biological, chemical and radiation coverage, with an inclusion of coverage for biological and chemical coverage for personal lines) for the United States from April 1, 2019 through March 31, 2020 with the same limits and retention and percentage placed except that the majority of terrorism coverage is on an aggregate basis above our retentions without a reinstatement.

Natural Catastrophe Property Reinsurance Program

Loss Location	Layer of Loss	Comments	Notes
United States (excluding Alaska and Hawaii)	$0 million – $1.0 billion	Losses retained by Chubb	(a)
United States (excluding Alaska and Hawaii)	$1.0 billion – $1.2 billion	All natural perils and terrorism	(b)
United States (excluding Alaska and Hawaii)	$1.2 billion – $2.2 billion	All natural perils and terrorism	(c)
United States (excluding Alaska and Hawaii)	$2.2 billion – $3.5 billion	All natural perils and terrorism	(d)
International (including Alaska and Hawaii)	$0 million – $175 million	Losses retained by Chubb	(a)
International (including Alaska and Hawaii)	$175 million – $1.175 billion	All natural perils and terrorism	(c)
Alaska, Hawaii, and Canada	$1.175 billion– $2.475 billion	All natural perils and terrorism	(d)

(a) Ultimate retention will depend upon the nature of the loss and the interplay between the underlying per risk programs and certain other catastrophe programs purchased by individual business units. These other catastrophe programs have the potential to reduce our effective retention below the stated levels.

(b) These coverages are partially placed with Reinsurers.

(c) These coverages are both part of the same Second layer within the Global Catastrophe Program and are fully placed with Reinsurers.

(d) These coverages are both part of the same Third layer within the Global Catastrophe Program and are fully placed with Reinsurers.

Chubb also has a property catastrophe bond in place that offers additional natural catastrophe protection for certain parts of the portfolio. The geographic scope of this coverage is from Virginia through Maine. The East Lane VI 2015 bond currently provides $250 million of coverage as part of a $427 million layer in excess of $2.0 billion retention through March 13, 2020.

Political Risk and Credit Insurance

Political risk insurance is a specialized coverage that provides clients with protection against unexpected, catastrophic political or macroeconomic events, primarily in emerging markets. We participate in this market through our wholly-owned subsidiary Sovereign Risk Insurance Ltd. (Sovereign), and through a unit of our London-based CGM operation. Chubb is one of the world's leading underwriters of political risk and credit insurance, has a global portfolio spread across more than 150 countries and is also a member of the Berne Union. Our clients include financial institutions, national export credit agencies, leading multilateral agencies, private equity firms and multinational corporations. CGM writes political risk and credit insurance business out of underwriting offices in London, United Kingdom; Hamburg, Germany; Sao Paulo, Brazil; Singapore; Tokyo, Japan; and in the U.S. in the following locations: Chicago, Illinois; New York, New York; Los Angeles, California; and Washington, D.C.

Our political risk insurance provides protection to commercial lenders against defaults on cross border loans, insulates investors against equity losses, and protects exporters against defaults on contracts. Commercial lenders, our largest client segment, are covered for missed scheduled loan repayments due to acts of confiscation, expropriation or nationalization by the host government, currency inconvertibility or exchange transfer restrictions, or war or other acts of political violence. In addition, in the case of loans to government-owned entities or loans that have a government guarantee, political risk policies cover scheduled payments against risks of non-payment or non-honoring of government guarantees. Private equity investors and corporations receive similar coverage to that of lenders, except their equity is protected against financial losses, inability to repatriate dividends, and physical damage to their operations caused by covered events. Our export contracts protection provides coverage for both exporters and their financing banks against the risk of contract frustration due to government actions, including non-payment by governmental entities.

CGM's credit insurance businesses cover losses due to insolvency, protracted default, and political risk perils including export and license cancellation. Our credit insurance product provides coverage to larger companies that have sophisticated credit risk management systems, with exposure to multiple customers and that have the ability to self-insure losses up to a certain level through excess of loss coverage. It also provides coverage to trade finance banks, exporters, and trading companies, with exposure to trade-related financing instruments. CGM also has limited capacity for Specialist Credit insurance products which provide coverage for project finance and working capital loans for large corporations and banks.

We have implemented structural features in our policies in order to control potential losses within the political risk and credit insurance businesses. These include basic loss sharing features that include co-insurance and deductibles, and in the case of trade credit, the use of non-qualifying losses that drop smaller exposures deemed too difficult to assess. Ultimate loss severity is also limited by using waiting periods to enable the insurer and insured to agree on recovery strategies, and the subrogation of the rights of the lender/exporter to the insurer following a claim. We have the option to pay claims over the original loan payment schedule, rather than in a lump sum in order to provide insureds and the insurer additional time to remedy problems and work towards full recoveries. It is important to note that political risk and credit policies are named peril conditional contracts, not financial guarantees, and claims are only paid after conditions and warranties are fulfilled. Political risk and credit insurance do not cover currency devaluations, bond defaults, movements in overseas equity markets, transactions deemed illegal, situations where corruption or misrepresentation has occurred, or debt that is not legally enforceable. In addition to assessing and mitigating potential exposure on a policy-by-policy basis, we also have specific risk management measures in place to manage overall exposure and risk. These measures include placing country, credit, and individual transaction limits based on country risk and credit ratings, combined single loss limits on multi-country policies, the use of reinsurance protection as well as quarterly modeling and stress-testing of the portfolio. We have a dedicated Country and Credit Risk management team that are responsible for the portfolio.

Crop Insurance

We are, and have been since the 1980s, one of the leading writers of crop insurance in the U.S. and have conducted that business through a managing general agent subsidiary of Rain and Hail. We provide protection throughout the U.S. on a variety of crops and are therefore geographically diversified, which reduces the risk of exposure to a single event or a heavy accumulation of losses in any one region. Our crop insurance business comprises two components - Multiple Peril Crop Insurance (MPCI) and crop-hail insurance.

The MPCI program, offered in conjunction with the U.S. Department of Agriculture’s Risk Management Agency (RMA), is a federal subsidized insurance program that covers revenue shortfalls or production losses due to natural causes such as drought, excessive moisture, hail, wind, freeze, insects, and disease. These Revenue Products are defined as providing both commodity price and yield coverages. Policies are available for various crops in different areas of the U.S. and generally have deductibles generally ranging from 10 percent to 50 percent of the insured's risk. The USDA's Risk Management Agency (RMA) sets the policy terms and conditions, rates and forms, and is also responsible for setting compliance standards. As a participant in the MPCI program, we report all details of policies to the RMA and are party to a Standard Reinsurance Agreement (SRA). The SRA sets out the relationship between private insurance companies and the Federal Crop Insurance Corporation (FCIC) concerning the terms and conditions regarding the risks each will bear including the pro-rata and state stop-loss provisions, which allows companies to limit the exposure of any one state or group of states on their underwriting results. In addition to the pro-rata and excess of loss reinsurance protections inherent in the SRA, we also purchase third-party proportional and stop-loss reinsurance for our MPCI business to reduce our exposure. We may also enter into crop derivative contracts to further manage our risk exposure.

Each year the RMA issues a final SRA for the subsequent reinsurance year (i.e., the 2020 SRA covers the 2020 reinsurance year from July 1, 2019 through June 30, 2020). There were no significant changes in the terms and conditions from the 2019 SRA and therefore, the new SRA does not impact Chubb's outlook on the crop program relative to 2020.

We recognize net premiums written as soon as estimable on our MPCI business, which is generally when we receive acreage reports from the policyholders on the various crops throughout the U.S. This allows us to best determine the premium associated with the liability that is being planted. The MPCI program has specific timeframes as to when producers must report acreage to us and in certain cases, the reporting occurs after the close of the respective reinsurance year. Once the net premium written has been recorded, the premium is then earned over the growing season for the crops. A majority of the crops that are covered in the program are typically subject to the SRA in effect at the beginning of the year. Given the major crops covered in the program, we typically see a substantial written and earned premium impact in the second and third quarters.

The pricing of MPCI premium is determined using a number of factors including commodity prices and related volatility (i.e., both impact the amount of premium we can charge to the policyholder). For example, in most states, the pricing for the MPCI Revenue Product for corn (i.e., insurance coverage for lower than expected crop revenue in a given season) includes a factor based on the average commodity price in February. If corn commodity prices are higher in February, compared to the February price in the prior year, and all other factors are the same, the increase in price will increase the corn premium year-over-year.

Pricing is also impacted by volatility factors, which measure the likelihood commodity prices will fluctuate over the crop year. For example, if volatility is set at a higher rate compared to the prior year, and all other factors are the same, the premium charged to the policyholder will be higher year-over-year for the same level of coverage.

Losses incurred on the MPCI business are determined using both commodity price and crop yield. With respect to commodity price, there are two important periods on a large portion of the business: The month of February when the initial premium base is set, and the month of October when the final harvest price is set. If the price declines from February to October, with yield remaining at normal levels, the policyholder may be eligible to recover on the policy. However, in most cases there are deductibles on these policies, therefore, the impact of a decline in price would have to exceed the deductible before a policyholder would be eligible to recover.

We evaluate our MPCI business at an aggregate level and the combination of all of our insured crops (both winter and summer) go into our underwriting gain or loss estimate in any given year. Typically, we do not have enough information on the harvest prices or crop yield outputs to quantify the preliminary estimated impact to our underwriting results until the fourth quarter.

Our crop-hail program is a private offering. Premium is earned on the crop-hail program over the coverage period of the policy. Given the very short nature of the growing season, most crop-hail business is typically written in the second and third quarters and the recognition of earned premium is also more heavily concentrated during this timeframe. We use industry data to develop our own rates and forms for the coverage offered. The policy primarily protects farmers against yield reduction caused by hail and/or fire, and related costs such as transit to storage. We offer various deductibles to allow the grower to partially self-insure for a reduced premium cost. We limit our crop-hail exposures through the use of township liability limits and third-party reinsurance on our net retained hail business.

Liquidity

Liquidity is a measure of a company's ability to generate cash flows sufficient to meet short-term and long-term cash requirements. As a holding company, Chubb Limited possesses assets that consist primarily of the stock of its subsidiaries and other investments. In addition to net investment income, Chubb Limited's cash flows depend primarily on dividends and other statutorily permissible payments. Historically, dividends and other statutorily permitted payments have come primarily from Chubb's Bermuda-based operating subsidiaries, which we refer to as our Bermuda subsidiaries. Our consolidated sources of funds consist primarily of net premiums written, fees, net investment income, and proceeds from sales and maturities of investments. Funds are used at our various companies primarily to pay claims, operating expenses, and dividends; to service debt; to purchase investments; and to fund acquisitions.

We anticipate that positive cash flows from operations (underwriting activities and investment income) should be sufficient to cover cash outflows under most loss scenarios for the near term. Should the need arise, we generally have access to capital markets and available credit facilities. Refer to “Credit Facilities” below for additional information. Our access to funds under the existing credit facility is dependent on the ability of the bank that is a party to the facility to meet its funding commitments. Should our existing credit provider experience financial difficulty, we may be required to replace credit sources, possibly in a difficult market. If we cannot obtain adequate capital or sources of credit on favorable terms, on a timely basis, or at all, our business, operating results, and financial condition could be adversely affected. To date, we have not experienced difficulty accessing our credit facility.

To further ensure the sufficiency of funds to settle unforeseen claims, we hold certain invested assets in cash and short-term investments. In addition, for certain insurance, reinsurance, or deposit contracts that tend to have relatively large and reasonably predictable cash outflows, we attempt to establish dedicated portfolios of assets that are duration-matched with the related liabilities. With respect to the duration of our overall investment portfolio, we manage asset durations to both maximize return given current market conditions and provide sufficient liquidity to cover future loss payments. At December 31, 2019, the average duration of our fixed maturities (3.8 years) is less than the average expected duration of our insurance liabilities (4.3 years).

Despite our safeguards, if paid losses accelerate beyond our ability to fund such paid losses from current operating cash flows, we might need to either liquidate a portion of our investment portfolio or arrange for financing. Potential events causing such a liquidity strain could include several significant catastrophes occurring in a relatively short period of time, large uncollectible reinsurance recoverables on paid losses (as a result of coverage disputes, reinsurers' credit problems, or decreases in the value of collateral supporting reinsurance recoverables) or increases in collateral postings under our variable annuity reinsurance business. Because each subsidiary focuses on a more limited number of specific product lines than is collectively available from the Chubb Group of Companies, the mix of business tends to be less diverse at the subsidiary level. As a result, the probability of a liquidity strain, as described above, may be greater for individual subsidiaries than when liquidity is assessed on a consolidated basis. If such a liquidity strain were to occur in a subsidiary, we could be required to liquidate a portion of our investments, potentially at distressed prices, as well as be required to contribute capital to the particular subsidiary and/or curtail dividends from the subsidiary to support holding company operations.

The payment of dividends or other statutorily permissible distributions from our operating companies are subject to the laws and regulations applicable to each jurisdiction, as well as the need to maintain capital levels adequate to support the insurance and reinsurance operations, including financial strength ratings issued by independent rating agencies. During 2019, we were able to meet all our obligations, including the payments of dividends on our Common Shares, with our net cash flows.

We assess which subsidiaries to draw dividends from based on a number of factors. Considerations such as regulatory and legal restrictions as well as the subsidiary's financial condition are paramount to the dividend decision. Chubb Limited received dividends of $200 million and $75 million from its Bermuda subsidiaries in 2019 and 2018, respectively.

The payment of any dividends from CGM or its subsidiaries is subject to applicable U.K. insurance laws and regulations. In addition, the release of funds by Syndicate 2488 to subsidiaries of CGM is subject to regulations promulgated by the Society of Lloyd's. Chubb Limited received no dividends from CGM in 2019 and 2018.

The U.S. insurance subsidiaries of Chubb INA may pay dividends, without prior regulatory approval, subject to restrictions set out in state law of the subsidiary's domicile (or, if applicable, commercial domicile). Chubb INA's international subsidiaries are also subject to insurance laws and regulations particular to the countries in which the subsidiaries operate. These laws and regulations sometimes include restrictions that limit the amount of dividends payable without prior approval of regulatory insurance authorities. Chubb Limited received no dividends from Chubb INA in 2019 and 2018. Debt issued by Chubb INA is serviced by statutorily permissible distributions by Chubb INA's insurance subsidiaries to Chubb INA as well as other group resources. Chubb INA received dividends of $3.7 billion and $5.2 billion from its subsidiaries in 2019 and 2018, respectively. At December 31, 2019, the amount of dividends available to be paid to Chubb INA in 2019 from its subsidiaries without prior approval of insurance regulatory authorities totals $3.1 billion.

In January 2020, Chubb INA Holdings Inc. paid $1.5 billion towards the series of intercompany loans involving its parents, Chubb Group Holdings Inc. and Chubb Limited. Additionally, Chubb Limited contributed $1.2 billion to a Bermuda subsidiary.

Cash Flows

Our insurance and reinsurance operations provide liquidity in that premiums are received in advance, sometimes substantially in advance, of the time claims are paid. Generally, cash flows are affected by claim payments that, due to the nature of our operations, may comprise large loss payments on a limited number of claims and which can fluctuate significantly from period to period. The irregular timing of these loss payments can create significant variations in cash flows from operations between periods. Refer to “Contractual Obligations and Commitments” for our estimate of future claim payments by period. Sources of liquidity include cash from operations, routine sales of investments, and financing arrangements. The following is a discussion of our cash flows for 2019, 2018, and 2017.

Operating cash flows reflect Net income for each period, adjusted for non-cash items and changes in working capital.

Operating cash flows were $6.3 billion in 2019, compared to $5.5 billion and $4.5 billion in 2018 and 2017, respectively. Operating cash flow was higher in 2019 compared to 2018, primarily due to higher underwriting cash flow, partially offset by higher taxes paid compared to 2018 principally due to the timing of tax payments. The increase in operating cash flows of $977 million in 2018 compared to 2017 was primarily due to higher premiums collected, net of higher catastrophe loss payments related to the 2017 catastrophe events, and lower taxes paid principally due to the timing of tax payments.

Cash used for investing was $5.9 billion in 2019, compared to $2.9 billion and $2.4 billion in 2018 and 2017, respectively. The increase in cash used for investing of $3.0 billion in 2019 was primarily due to net purchases of short-term investments of $1.1 billion in 2019 compared to net proceeds of $516 million in 2018. Additionally, the increase in 2019 was due to the purchase of an additional 10.9 percent ownership interest in Huatai Group for $580 million. Cash used for investing in 2018 was higher compared to 2017, due to higher net private equity contributions, net of distributions received, of $793 million.

Cash used for financing was $151 million in 2019, compared to $2.0 billion and $2.3 billion in 2018 and 2017, respectively. Cash used for financing was lower by $1.8 billion in 2019 compared to 2018 primarily due to higher net proceeds from the issuance of long-term debt (net of repayments) of $2.1 billion offset by higher share repurchases of $486 million. Cash used for financing in 2018 was lower by $328 million, primarily due to higher net repayments of long-term debt in 2017.

Both internal and external forces influence our financial condition, results of operations, and cash flows. Claim settlements, premium levels, and investment returns may be impacted by changing rates of inflation and other economic conditions. In many cases, significant periods of time, ranging up to several years or more, may lapse between the occurrence of an insured loss, the reporting of the loss to us, and the settlement of the liability for that loss.

We use repurchase agreements as a low-cost funding alternative. At December 31, 2019, there were $1.4 billion in repurchase agreements outstanding with various maturities over the next five months.

In addition to cash from operations, routine sales of investments, and financing arrangements, we have agreements with a third-party bank provider which implemented two international multi-currency notional cash pooling programs to enhance cash management efficiency during periods of short-term timing mismatches between expected inflows and outflows of cash by currency. The programs allow us to optimize investment income by avoiding portfolio disruption. In each program, participating Chubb entities establish deposit accounts in different currencies with the bank provider. Each day the credit or debit balances in every account are notionally translated into a single currency (U.S. dollars) and then notionally pooled. The bank extends overdraft credit to all participating Chubb entities as needed, provided that the overall notionally pooled balance of all accounts in each pool at the end of each day is at least zero. Actual cash balances are not physically converted and are not commingled between legal entities. Chubb entities may incur overdraft balances as a means to address short-term liquidity needs. Any overdraft balances incurred under this program by a Chubb entity would be guaranteed by Chubb Limited (up to $300 million in the aggregate). Our syndicated letter of credit facility allows for same day drawings to fund a net pool overdraft should participating Chubb entities withdraw contributed funds from the pool.

Capital Resources

Capital resources consist of funds deployed or available to be deployed to support our business operations.

(in millions of U.S. dollars, except for percentages)	**December 31 2019**	December 31 2018
Short-term debt	**$ 1,299**	$ 509
Long-term debt	**13,559**	12,087
Total financial debt	**14,858**	12,596
Trust preferred securities	**308**	308
Total shareholders' equity	**55,331**	50,312
Total capitalization	**$ 70,497**	$ 63,216
Ratio of financial debt to total capitalization	**21.1%**	19.9%
Ratio of financial debt plus trust preferred securities to total capitalization	**21.5%**	20.4%

Repurchase agreements are excluded from the table above and are disclosed separately from short-term debt in the Consolidated balance sheets. The repurchase agreements are collateralized borrowings where we maintain the right and ability to redeem the collateral on short notice, unlike short-term debt which comprises the current maturities of our long-term debt instruments.

Refer to Note 9 to the Consolidated Financial Statements for details about the debt issued and debt redeemed.

We believe our financial strength provides us with the flexibility and capacity to obtain available funds externally through debt or equity financing on both a short-term and long-term basis. Our ability to access the capital markets is dependent on, among other things, market conditions and our perceived financial strength. We have accessed both the debt and equity markets from time to time. We generally maintain the ability to issue certain classes of debt and equity securities via an unlimited Securities and Exchange Commission (SEC) shelf registration which is renewed every three years. This allows us capital market access for refinancing as well as for unforeseen or opportunistic capital needs. In October 2018, we filed an unlimited shelf registration which allows us to issue certain classes of debt and equity. This shelf registration expires in October 2021.

Securities Repurchases
From time to time, we repurchase shares as part of our capital management program. The Board of Directors (Board) has authorized share repurchase programs as follows:

- $1.0 billion of Chubb Common Shares from November 17, 2016 through December 31, 2017
- $1.0 billion of Chubb Common Shares from January 1, 2018 through December 31, 2018
- $1.5 billion of Chubb Common Shares from December 1, 2018 through December 31, 2019
- $1.5 billion of Chubb Common Shares from November 21, 2019 through December 31, 2020

Share repurchases may be made in the open market, in privately negotiated transactions, block trades, accelerated repurchases and/or through option or other forward transactions. In 2017, 2018 and 2019, we repurchased $830 million, $1.02 billion and $1.53 billion, respectively, of Common Shares in a series of open market transactions under the Board share repurchase authorizations. The $1.5 billion December 2018 Board authorization remained effective through December 31, 2019, and was used in advance of the $1.5 billion share repurchase authorized in November 2019. For the period January 1 through February 26, 2020, we repurchased 947,400 Common Shares for a total of $151 million in a series of open market transactions. At February 26, 2020, $1.30 billion in share repurchase authorization remained through December 31, 2020.

Common Shares
Our Common Shares had a par value of CHF 24.15 each at December 31, 2019.

As of December 31, 2019, there were 27,812,297 Common Shares in treasury with a weighted average cost of $134.98 per share.

Under Swiss law, dividends must be stated in Swiss francs though dividend payments are made by Chubb in U.S. dollars.

At our May 2018 annual general meeting, our shareholders approved an annual dividend for the following year of up to $2.92 per share, which was paid in four quarterly installments of $0.73 per share at dates determined by the Board after the annual general meeting by way of a distribution from capital contribution reserves, transferred to free reserves for payment.

At our May 2019 annual general meeting, our shareholders approved an annual dividend for the following year of up to $3.00 per share, expected to be paid in four quarterly installments of $0.75 per share after the annual general meeting by way of distribution from capital contribution reserves, transferred to free reserves for payment. The Board will determine the record and payment dates at which the annual dividend may be paid until the date of the 2020 annual general meeting, and is authorized to abstain from distributing a dividend at its discretion. The first three quarterly installments each of $0.75 per share, have been distributed by the Board as expected.

Dividend distributions on Common Shares amounted to CHF 2.94 ($2.98) per share for the year ended December 31, 2019. Refer to Note 11 to the Consolidated Financial Statements for additional information on our dividends.

Contractual Obligations and Commitments

The following table presents our future payments due by period under contractual obligations at December 31, 2019:

	Payments Due By Period				
(in millions of U.S. dollars)	Total	2020	2021 and 2022	2023 and 2024	Thereafter
Payment amounts determinable from the respective contracts					
Deposit liabilities [1]	$ 2,092	$ 21	$ 51	$ 131	$ 1,889
Purchase obligations [2]	411	159	223	29	—
Investments, including Limited Partnerships [3]	3,994	1,328	1,721	895	50
Huatai share acquisition deposits [4]	1,550	1,550	—	—	—
Operating leases	660	158	243	154	105
Repurchase agreements	1,416	1,416	—	—	—
Short-term debt	1,301	1,301	—	—	—
Long-term debt [5]	13,292	—	1,000	1,954	10,338
Trust preferred securities	309	—	—	—	309
Interest on debt obligations [5]	6,199	479	898	810	4,012
Total obligations in which payment amounts are determinable from the respective contracts	31,224	6,412	4,136	3,973	16,703
Payment amounts not determinable from the respective contracts					
Estimated gross loss payments under insurance and reinsurance contracts	62,713	17,601	17,200	8,731	19,181
Estimated payments for future policy benefits	20,645	916	1,885	1,541	16,303
Total contractual obligations and commitments	$ 114,582	$ 24,929	$ 23,221	$ 14,245	$ 52,187

(1) Refer to Note 1 k) to the Consolidated Financial Statements.

(2) Primarily comprises audit fees and agreements with vendors to purchase system software administration and maintenance services.

(3) Funding commitment primarily related to limited partnerships. The timing of the payments of these commitments is uncertain and may differ from the estimated timing in the table.

(4) Chubb entered into agreements to purchase incremental ownership interests in Huatai Insurance Group Company Limited through two separate purchases, a 15.3 percent ownership interest for approximately $1.1 billion and a 7.1 percent ownership interest for approximately $493 million. The purchases are contingent upon obtaining regulatory approvals and other important conditions, which are expected to be obtained by the end of 2021. The 7.1 percent purchase is also contingent upon receipt of Chinese insurance regulatory approval of the 15.3 percent purchase. In connection with these purchase agreements, in January 2020, we paid collateralized deposits totaling $1.550 billion to the selling shareholders, which are accounted for as loans.

(5) Subject to foreign exchange fluctuations on interest expense and principal.

The above table excludes the following items:

- Pension obligations: Minimum funding requirements for our pension obligations are immaterial. Subsequent funding commitments are apt to vary due to many factors and are difficult to estimate at this time. Refer to Note 13 to the Consolidated Financial Statements for additional information.
- Liabilities for unrecognized tax benefits: The liability for unrecognized tax benefits, excluding interest and offsetting tax credits, was $47 million at December 31, 2019. At December 31, 2019, we had accrued $8 million in liabilities for income tax-related interest and penalties in our Consolidated balance sheet. We are unable to make a reasonably reliable estimate for the timing of cash settlement with respect to these liabilities. Refer to Note 8 to the Consolidated Financial Statements for additional information.

We have no other significant contractual obligations or commitments not reflected in the table above. We do not have any off-balance sheet arrangements that are reasonably likely to have a material effect on our financial condition, revenues or expenses, results of operations, liquidity, capital expenditures, or capital resources.

Estimated gross loss payments under insurance and reinsurance contracts
We are obligated to pay claims under insurance and reinsurance contracts for specified loss events covered under those contracts. Such loss payments represent our most significant future payment obligation as a P&C insurance and reinsurance company. In contrast to other contractual obligations, cash payments are not determinable from the terms specified within the contract. For example, we do not ultimately make a payment to our counterparty for many insurance and reinsurance contracts (i.e., when a loss event has not occurred) and if a payment is to be made, the amount and timing cannot be determined from the contract. In the table above, we estimate payments by period relating to our gross liability for unpaid losses and loss expenses included in the Consolidated balance sheet at December 31, 2019, and do not take into account reinsurance recoverable. These estimated loss payments are inherently uncertain and the amount and timing of actual loss payments are likely to differ from these estimates and the differences could be material. Given the numerous factors and assumptions involved in both estimates of loss and loss expense reserves and related estimates as to the timing of future loss and loss expense payments in the table above, differences between actual and estimated loss payments will not necessarily indicate a commensurate change in ultimate loss estimates. The liability for Unpaid losses and loss expenses presented in our balance sheet is discounted for certain structured settlements, for which the timing and amount of future claim payments are reliably determinable, and certain reserves for unsettled claims. Our loss reserves are not discounted for the time value of money. Accordingly, the estimated amounts in the table exceed the liability for Unpaid losses and loss expenses presented in our balance sheet. Refer to Note 1 h) to the Consolidated Financial Statements for additional information.

Estimated payments for future policy benefits
We establish reserves for future policy benefits for life, long-term health, and annuity contracts. The amounts in the table are gross of fees or premiums due from the underlying contracts. The liability for Future policy benefits for life, long-term health, and annuity contracts presented in our balance sheet is discounted and reflected net of fees or premiums due from the underlying contracts. Accordingly, the estimated amounts in the table exceed the liability for Future policy benefits presented in our balance sheet. Payment amounts related to these reserves must be estimated and are not determinable from the contract. Due to the uncertainty with respect to the timing and amount of these payments, actual results could materially differ from the estimates in the table.

Credit Facilities

As our Bermuda subsidiaries are non-admitted insurers and reinsurers in the U.S., the terms of certain U.S. insurance and reinsurance contracts require them to provide collateral, which can be in the form of letters of credit (LOCs). LOCs may also be used for general corporate purposes.

On October 25, 2017, we entered into a credit facility that provides for up to $1.0 billion of availability, all of which may be used for the issuance of LOC and for revolving loans. We have the ability to increase the capacity to $2.0 billion under certain conditions, but any such increase would not raise the sub-limit for revolving loans above $1.0 billion. Our existing credit facility has a remaining term expiring in October 2022. At December 31, 2019, our LOC usage was $567 million.

Our access to funds under an existing credit facility is dependent on the ability of the banks that are a party to the facility to meet their funding commitments. In the event that such credit support is insufficient, we could be required to provide alternative security to clients. This could take the form of additional insurance trusts supported by our investment portfolio or funds withheld using our cash resources. The value of LOCs required is driven by, among other things, statutory liabilities reported by variable annuity guarantee reinsurance clients, loss development of existing reserves, the payment pattern of such reserves, the expansion of business, and loss experience of such business.

The facility noted above requires that we maintain certain covenants, all of which have been met at December 31, 2019. These covenants include:

(i) a minimum consolidated net worth of not less than $34.985 billion; and
(ii) a ratio of consolidated debt to total capitalization of not greater than 0.35 to 1.

At December 31, 2019, (a) the minimum consolidated net worth requirement under the covenant described in (i) above was $34.985 billion and our actual consolidated net worth as calculated under that covenant was $54.7 billion and (b) our ratio of debt to total capitalization, as calculated under the covenant which excludes the fair value adjustment of debt acquired through the Chubb Corp acquisition, was 0.21 to 1, which is below the maximum debt to total capitalization ratio of 0.35 to 1 as described in (ii) above.

Our failure to comply with the covenants under any credit facility would, subject to grace periods in the case of certain covenants, result in an event of default. This could require us to repay any outstanding borrowings or to cash collateralize LOCs under such facility. Our failure to repay material financial obligations, as well as our failure with respect to certain other events expressly identified, would result in an event of default under the facility.

Should our existing credit provider experience financial difficulty, we may be required to replace credit sources, possibly in a difficult market. If we cannot obtain adequate capital or sources of credit on favorable terms, on a timely basis, or at all, our business, operating results, and financial condition could be adversely affected. To date, we have not experienced difficulty accessing our credit facility.

Ratings

Chubb Limited and its subsidiaries are assigned credit and financial strength (insurance) ratings from internationally recognized rating agencies, including S&P, A.M. Best, Moody's, and Fitch. The ratings issued on our companies by these agencies are announced publicly and are available directly from the agencies. Our Internet site (investors.chubb.com, under Shareholder Resources/Rating Agency Ratings) also contains some information about our ratings, but such information on our website is not incorporated by reference into this report.

Financial strength ratings reflect the rating agencies' opinions of a company's claims paying ability. Independent ratings are one of the important factors that establish our competitive position in the insurance markets. The rating agencies consider many factors in determining the financial strength rating of an insurance company, including the relative level of statutory surplus necessary to support the business operations of the company. These ratings are based upon factors relevant to policyholders, agents, and intermediaries and are not directed toward the protection of investors. Such ratings are not recommendations to buy, sell, or hold securities.

Credit ratings assess a company's ability to make timely payments of principal and interest on its debt. It is possible that, in the future, one or more of the rating agencies may reduce our existing ratings. If one or more of our ratings were downgraded, we could incur higher borrowing costs, and our ability to access the capital markets could be impacted. In addition, our insurance and reinsurance operations could be adversely impacted by a downgrade in our financial strength ratings, including a possible reduction in demand for our products in certain markets. Also, we have insurance and reinsurance contracts which contain rating triggers. In the event the S&P or A.M. Best financial strength ratings of Chubb fall, we may be faced with the cancellation of premium or be required to post collateral on our underlying obligation associated with this premium. We estimate that at December 31, 2019, a one-notch downgrade of our S&P or A.M. Best financial strength ratings would result in an immaterial loss of premium or requirement for collateral to be posted.

ITEM 7A. Quantitative and Qualitative Disclosures about Market Risk

Market Sensitive Instruments and Risk Management

Market risk represents the potential for loss due to adverse changes in the fair value of financial instruments. We are exposed to potential losses from various market risks including changes in interest rates, equity prices, and foreign currency exchange rates. Further, through writing the GLB and GMDB products, we are exposed to volatility in the equity and credit markets, as well as interest rates. Our investment portfolio consists primarily of fixed income securities, denominated in both U.S. dollars and foreign currencies, which are sensitive to changes in interest rates and foreign currency exchange rates. The majority of our fixed income portfolio is classified as available for sale. The effect of market movements on our available for sale investment portfolio impacts Net income (through Net realized gains (losses)) when securities are sold or when we record an OTTI charge in Net income. Changes in interest rates and foreign currency exchange rates will have an immediate effect on Shareholders' equity and Comprehensive income and in certain instances, Net income. From time to time, we also use derivative instruments such as futures, options, swaps, and foreign currency forward contracts to manage the duration of our investment portfolio and foreign currency exposures and also to obtain exposure to a particular financial market. At December 31, 2019 and 2018, our notional exposure to derivative instruments was $4.9 billion and $9.1 billion, respectively. These instruments are recognized as assets or liabilities in our consolidated financial statements and are sensitive to changes in interest rates, foreign currency exchange rates, and equity security prices. As part of our investing activities, we purchase to be announced mortgage backed securities (TBAs). Changes in the fair value of TBAs are included in Net realized gains (losses) and therefore, have an immediate effect on both our Net income and Shareholders' equity.

We seek to mitigate market risk using a number of techniques, including maintaining and managing the assets and liabilities of our international operations consistent with the foreign currencies of the underlying insurance and reinsurance businesses, thereby limiting exchange rate risk to net assets denominated in foreign currencies.

The following is a discussion of our primary market risk exposures at December 31, 2019. Our policies to address these risks in 2019 were not materially different from 2018. We do not currently anticipate significant changes in our primary market risk exposures or in how those exposures are managed in future reporting periods based upon what is known or expected to be in effect in future reporting periods.

Interest rate risk – fixed income portfolio and debt obligations

Our fixed income portfolio and debt obligations have exposure to interest rate risk. Changes in investment values attributable to interest rate changes are mitigated by corresponding and partially offsetting changes in the economic value of our insurance reserves and debt obligations. We monitor this exposure through periodic reviews of our asset and liability positions.

The following table presents the impact at December 31, 2019 and 2018, on the fair value of our fixed income portfolio of a hypothetical increase in interest rates of 100 bps applied instantly across the U.S. yield curve (an immediate time horizon was used as this presents the worst case scenario):

(in billions of U.S. dollars, except for percentages)	**2019**	2018
Fair value of fixed income portfolio	**$ 102.8**	$ 94.7
Pre-tax impact of 100 bps increase in interest rates:		
Decrease in dollars	**$ 3.9**	$ 3.5
As a percentage of total fixed income portfolio at fair value	**3.8%**	3.7%

Changes in interest rates will have an immediate effect on Comprehensive income and Shareholders' equity but will not ordinarily have an immediate effect on Net income. Variations in market interest rates could produce significant changes in the timing of prepayments due to available prepayment options. For these reasons, actual results could differ from those reflected in the tables.

Although our debt and trust preferred securities (collectively referred to as debt obligations) are reported at amortized cost and not adjusted for fair value changes, changes in interest rates could have a material impact on their fair value, albeit there would be no impact on our consolidated financial statements.

The following table presents the impact at December 31, 2019 and 2018, on the fair value of our debt obligations of a hypothetical decrease in interest rates of 100 bps applied instantly across the U.S. yield curve (an immediate time horizon was used as this presents the worst case scenario):

(in millions of U.S. dollars, except for percentages)	**2019**	2018
Fair value of debt obligations, including repurchase agreements	**$ 18,238**	$ 14,524
Pre-tax impact of 100 bps decrease in interest rates:		
Increase in dollars	**$ 1,570**	$ 1,201
As a percentage of total debt obligations at fair value	**8.6%**	8.3%

Foreign currency management

As a global company, Chubb entities transact business in multiple currencies. Our policy is to generally match assets, liabilities and required capital for each individual jurisdiction in local currency, which would include the use of derivatives. We do not hedge our net asset non-U.S. dollar capital positions; however, we do consider hedging for planned cross border transactions.

The following table summarizes the net assets in non-U.S. currencies at December 31, 2019 and 2018:

(in millions of U.S. dollars, except for percentages)	2019 Value of Net Assets	2019 Exchange rate per USD	2018 Value of Net Assets	2018 Exchange rate per USD	2019 vs. 2018 % change in exchange rate per USD
Canadian dollar (CAD)	$ 2,220	0.7698	$ 2,114	0.7333	5.0 %
British pound sterling (GBP)	2,024	1.3257	1,901	1.2754	3.9 %
Euro (EUR)	1,675	1.1213	1,896	1.1467	(2.2)%
Australian dollar (AUD)	1,100	0.7021	1,149	0.7049	(0.4)%
Brazilian real (BRL)	990	0.2485	938	0.2577	(3.6)%
Mexican peso (MXN)	942	0.0528	729	0.0509	3.7 %
Korean won (KRW) (x100)	788	0.0865	726	0.0900	(3.9)%
Hong Kong dollar (HKD)	653	0.1284	362	0.1277	0.5 %
Thai baht (THB)	606	0.0337	459	0.0309	9.1 %
Chilean peso (CLP) (x100)	489	0.1328	28	0.1441	(7.8)%
Euro denominated debt [(1)]	(4,804)	1.1213	(2,016)	1.1467	(2.2)%
Other foreign currencies	2,474	various	2,106	various	NM
Value of net assets denominated in foreign currencies [(2)]	$ 9,157		$ 10,392		
As a percentage of total net assets	16.6%		20.7%		
Pre-tax decrease to Shareholders' equity of a hypothetical 10 percent strengthening of the U.S. dollar	$ 832		$ 945		

NM – not meaningful

(1) Refer to Note 9 to the Consolidated Financial Statements for additional information.

(2) At December 31, 2019, net assets denominated in foreign currencies comprised approximately 6 percent tangible assets and 94 percent intangible assets, primarily goodwill.

Effective July 1, 2018, Argentina was designated as a highly inflationary economy and therefore we changed the functional currency for our Argentine operations from the Argentine Peso to the U.S. dollar. Our net assets denominated in the Argentine Peso represented less than 0.1 percent of consolidated shareholders' equity. Therefore, this change in the functional currency of our Argentine operations did not have a material impact on our financial condition or results of operations.

Reinsurance of GMDB and GLB guarantees

Chubb views its variable annuity reinsurance business as having a similar risk profile to that of catastrophe reinsurance with the probability of long-term economic loss relatively small, at the time of pricing. Adverse changes in market factors and policyholder behavior will have an impact on both Life Insurance underwriting income and net income. When evaluating these risks, we expect to be compensated for taking both the risk of a cumulative long-term economic net loss, as well as the short-term accounting variations caused by these market movements. Therefore, we evaluate this business in terms of its long-term economic risk and reward.

Net income is directly impacted by changes in benefit reserves calculated in connection with reinsurance of variable annuity guarantees. In addition, net income is directly impacted by changes in the fair value of the GLB liability (FVL), which is classified as a derivative for accounting purposes. The FVL established for a GLB reinsurance contract represents the difference between the fair value of the contract and the benefit reserves. Benefit reserves and FVL calculations are directly affected by market factors, including equity levels, interest rate levels, credit risk, and implied volatilities, as well as policyholder behaviors, such as annuitization and lapse rates, and policyholder mortality.

The tables below are estimates of the sensitivities to instantaneous changes in economic inputs (e.g., equity shock, interest rate shock, etc.) or actuarial assumptions at December 31, 2019 of the FVL and of the fair value of specific derivative instruments held (hedge value) to partially offset the risk in the variable annuity guarantee reinsurance portfolio. The following assumptions should be considered when using the below tables:

- No changes to the benefit ratio used to establish benefit reserves at December 31, 2019.
- Equity shocks impact all global equity markets equally
  - Our liabilities are sensitive to global equity markets in the following proportions: 75 percent—85 percent U.S. equity, and 15 percent—25 percent international equity.
  - Our current hedge portfolio is sensitive only to U.S. equity markets.
  - We would suggest using the S&P 500 index as a proxy for U.S. equity, and the MSCI EAFE index as a proxy for international equity.
- Interest rate shocks assume a parallel shift in the U.S. yield curve
  - Our liabilities are also sensitive to global interest rates at various points on the yield curve, mainly the U.S. Treasury curve in the following proportions: 5 percent—15 percent short-term rates (maturing in less than 5 years), 25 percent—35 percent medium-term rates (maturing between 5 years and 10 years, inclusive), and 55 percent—65 percent long-term rates (maturing beyond 10 years).
  - A change in AA-rated credit spreads impacts the rate used to discount cash flows in the fair value model. AA-rated credit spreads are a proxy for both our own credit spreads and the credit spreads of the ceding insurers.
- The hedge sensitivity is from December 31, 2019 market levels and only applicable to the equity and interest rate sensitivities table below.
- The sensitivities are not directly additive because changes in one factor will affect the sensitivity to changes in other factors. The sensitivities do not scale linearly and may be proportionally greater for larger movements in the market factors. The sensitivities may also vary due to foreign exchange rate fluctuations. The calculation of the FVL is based on internal models that include assumptions regarding future policyholder behavior, including lapse, annuitization, and asset allocation. These assumptions impact both the absolute level of the FVL as well as the sensitivities to changes in market factors shown below. Actual sensitivity of our net income may differ from those disclosed in the tables below due to differences between short-term market movements and management judgment regarding the long-term assumptions implicit in our benefit ratios.
- In addition, the tables below do not reflect the expected quarterly run rate of net income generated by the variable annuity guarantee reinsurance portfolio if markets remain unchanged during the period. All else equal, if markets remain unchanged during the period, the Gross FVL will increase, resulting in a realized loss. This realized loss occurs primarily because the guarantees provided in the underlying contracts continue to become more valuable even when markets remain unchanged. We refer to this increase in Gross FVL as “timing effect”. The unfavorable impact of timing effect on our Gross FVL in a quarter is not reflected in the sensitivity tables below. For this reason, when using the tables below to estimate the sensitivity of Gross FVL in the first quarter 2020 to various changes, it is necessary to assume an additional $5 million to $45 million increase in Gross FVL and realized losses. The impact to Net income is partially mitigated because this realized loss is partially offset by the positive quarterly run rate of Life Insurance underwriting income generated by the variable annuity guarantee reinsurance portfolio if markets remain unchanged during the period. Note that both the timing effect and the quarterly run rate of Life Insurance underwriting income change over time as the book ages.

Sensitivities to equity and interest rate movements

(in millions of U.S. dollars)		Worldwide Equity Shock					
Interest Rate Shock		+10%	Flat	-10%	-20%	-30%	-40%
+100 bps	(Increase)/decrease in Gross FVL	$ 343	$ 207	$ 49	$ (138)	$ (357)	$ (604)
	Increase/(decrease) in hedge value	(63)	—	63	125	188	250
	Increase/(decrease) in net income	$ 280	$ 207	$ 112	$ (13)	$ (169)	$ (354)
Flat	(Increase)/decrease in Gross FVL	$ 156	$ —	$ (182)	$ (394)	$ (636)	$ (904)
	Increase/(decrease) in hedge value	(63)	—	63	125	188	250
	Increase/(decrease) in net income	$ 93	$ —	$ (119)	$ (269)	$ (448)	$ (654)
-100 bps	(Increase)/decrease in Gross FVL	$ (74)	$ (249)	$ (451)	$ (681)	$ (936)	$ (1,215)
	Increase/(decrease) in hedge value	(63)	—	63	125	188	250
	Increase/(decrease) in net income	$ (137)	$ (249)	$ (388)	$ (556)	$ (748)	$ (965)

Sensitivities to Other Economic Variables	AA-rated Credit Spreads		Interest Rate Volatility		Equity Volatility	
(in millions of U.S. dollars)	+100 bps	-100 bps	+2%	-2%	+2%	-2%
(Increase)/decrease in Gross FVL	$ 73	$ (81)	$ —	$ 1	$ (9)	$ 9
Increase/(decrease) in net income	$ 73	$ (81)	$ —	$ 1	$ (9)	$ 9

Sensitivities to Actuarial Assumptions	Mortality			
(in millions of U.S. dollars)	+20%	+10%	-10%	-20%
(Increase)/decrease in Gross FVL	$ 18	$ 9	$ (9)	$ (19)
Increase/(decrease) in net income	$ 18	$ 9	$ (9)	$ (19)

	Lapses			
(in millions of U.S. dollars)	+50%	+25%	-25%	-50%
(Increase)/decrease in Gross FVL	$ 101	$ 52	$ (57)	$ (120)
Increase/(decrease) in net income	$ 101	$ 52	$ (57)	$ (120)

	Annuitization			
(in millions of U.S. dollars)	+50%	+25%	-25%	-50%
(Increase)/decrease in Gross FVL	$ (498)	$ (264)	$ 298	$ 585
Increase/(decrease) in net income	$ (498)	$ (264)	$ 298	$ 585

Variable Annuity Net Amount at Risk
All our VA reinsurance treaties include annual or aggregate claim limits and many include an aggregate deductible which limit the net amount at risk under these programs. The tables below present the net amount at risk at December 31, 2019 following an immediate change in equity market levels, assuming all global equity markets are impacted equally. For further information on the net amount at risk, refer to Note 5 c) to the Consolidated Financial Statements.

a) Reinsurance covering the GMDB risk only

	Equity Shock					
(in millions of U.S. dollars)	+20%	Flat	-20%	-40%	-60%	-80%
GMDB net amount at risk	$ 271	$ 256	$ 442	$ 797	$ 817	$ 696
Claims at 100% immediate mortality	160	167	166	156	138	122

The treaty claim limits function as a ceiling as equity markets fall. As the shocks in the table above become incrementally more negative, the impact on the NAR and claims at 100 percent mortality begin to drop due to the specific nature of these claim limits, many of which are annual claim limits calculated as a percentage of the reinsured account value. There is also some impact due to a small portion of the GMDB reinsurance under which claims are positively correlated to equity markets (claims decrease as equity markets fall).

b) Reinsurance covering the GLB risk only

	Equity Shock					
(in millions of U.S. dollars)	+20%	Flat	-20%	-40%	-60%	-80%
GLB net amount at risk	$ 724	$ 1,095	$ 1,738	$ 2,516	$ 3,021	$ 3,387

The treaty claim limits cause the net amount at risk to increase at a declining rate as equity markets fall.

c) Reinsurance covering both the GMDB and GLB risks on the same underlying policyholders

	Equity Shock					
(in millions of U.S. dollars)	+20%	Flat	-20%	-40%	-60%	-80%
GMDB net amount at risk	$ 76	$ 91	$ 105	$ 117	$ 123	$ 123
GLB net amount at risk	305	415	560	723	888	985
Claims at 100% immediate mortality	16	16	17	17	17	17

The treaty limits control the increase in the GMDB net amount at risk as equity markets fall. The GMDB net amount at risk continues to grow as equity markets fall because most of these reinsurance treaties do not have annual claim limits calculated as a percentage of the underlying account value. The treaty limits cause the GLB net amount at risk to increase at a declining rate as equity markets fall.

ITEM 8. Financial Statements and Supplementary Data

The financial statements and supplementary data are included in this Form 10-K commencing on page F-1.

ITEM 9. Changes in and Disagreements with Accountants on Accounting and Financial Disclosure

None.

ITEM 9A. Controls and Procedures

Chubb’s management, with the participation of Chubb’s Chief Executive Officer and Chief Financial Officer, evaluated the effectiveness of Chubb’s disclosure controls and procedures as defined in Rule 13a-15(e) and Rule 15d-15(e) under the Securities Exchange Act of 1934 as of December 31, 2019. Based upon that evaluation, Chubb’s Chief Executive Officer and Chief Financial Officer concluded that Chubb’s disclosure controls and procedures are effective in allowing information required to be disclosed in reports filed under the Securities Exchange Act of 1934 to be recorded, processed, summarized, and reported within time periods specified in the rules and forms of the SEC, and that such information is accumulated and communicated to Chubb’s management, including its Chief Executive Officer and Chief Financial Officer, as appropriate to allow timely decisions regarding required disclosure.

In 2016, Chubb completed the acquisition of The Chubb Corporation. For the year ended December 31, 2019, we continued to integrate the information technology environments of the two companies.

There were no other changes to Chubb's internal controls over financial reporting for the year ended December 31, 2019 that have materially affected, or are reasonably likely to materially affect, Chubb's internal controls over financial reporting. Chubb's management report on internal control over financial reporting is included on page F-3 and PricewaterhouseCoopers LLP's audit report is included on pages F-4, F-5, and F-6.

ITEM 9B. Other Information

Item not applicable.

ITEM 10. Directors, Executive Officers and Corporate Governance

Information pertaining to this item is incorporated by reference to the sections entitled “Agenda Item 5 - Election of the Board of Directors”, “Corporate Governance - The Board of Directors - Director Nomination Process”, and “Corporate Governance - The Committees of the Board - Audit Committee” of the definitive proxy statement for the 2020 Annual General Meeting of Shareholders which will be filed with the SEC not later than 120 days after the close of the fiscal year pursuant to Regulation 14A. Also incorporated herein by reference is the text under the caption “Information about our Executive Officers” appearing at the end of Part I Item 1 of the Annual Report on Form 10-K.

Code of Ethics

Chubb has adopted a Code of Conduct, which sets forth standards by which all Chubb employees, officers, and directors must abide as they work for Chubb. Chubb has posted this Code of Conduct on its Internet site (investors.chubb.com, under Corporate Governance/Highlights and Governance Documents/The Chubb Code of Conduct). Chubb intends to disclose on its Internet site any amendments to, or waivers from, its Code of Conduct that are required to be publicly disclosed pursuant to the rules of the SEC or the New York Stock Exchange.

ITEM 11. Executive Compensation

This item is incorporated by reference to the sections entitled “Executive Compensation”, “Compensation Committee Report” and “Director Compensation” of the definitive proxy statement for the 2020 Annual General Meeting of Shareholders which will be filed with the SEC not later than 120 days after the close of the fiscal year pursuant to Regulation 14A.

ITEM 12. Security Ownership of Certain Beneficial Owners and Management and Related Stockholder Matters

Plan category	Number of securities to be issued upon exercise of outstanding options, warrants, and rights	Weighted-average exercise price of outstanding options, warrants, and rights [3]	Number of securities remaining available for future issuance under equity compensation plans
Equity compensation plans approved by security holders [1]	11,801,420	$ 116.79	12,575,263
Equity compensation plans not approved by security holders [2]	27,914		

[1] These totals include securities available for future issuance under the following plans:

(i) Chubb Limited 2016 Long-Term Incentive Plan (LTIP). A total of 19,500,000 shares are authorized to be issued pursuant to awards made as options, stock appreciation rights, stock units, performance shares, performance units, restricted stock, and restricted stock units. The maximum number of shares that may be delivered to participants and their beneficiaries under the LTIP shall be equal to the sum of: (x) 19,500,000 shares of stock; and (y) any shares of stock that have not been delivered pursuant to the ACE LTIP (as defined in clause (ii) of this footnote (1) below) and remain available for grant pursuant to the ACE LTIP, including shares of stock represented by awards granted under the ACE LTIP that are forfeited, expire or are canceled after the effective date of the LTIP without delivery of shares of stock or which result in the forfeiture of the shares of stock back to the Company to the extent that such shares would have been added back to the reserve under the terms of the ACE LTIP. As of December 31, 2019, a total of 5,288,553 option awards and 706,535 restricted stock unit awards are outstanding, and 10,789,285 shares remain available for future issuance under this plan.

(ii) ACE Limited 2004 Long-Term Incentive Plan (ACE LTIP). As of December 31, 2019, a total of 5,496,523 option awards and 72,075 restricted stock unit awards are outstanding. No additional grants will be made pursuant to the ACE LTIP.

(iii) The Chubb Corporation Long-Term Incentive Plan (2014) (Chubb Corp. LTIP). As of December 31, 2019, a total of 99,759 option awards, 3,433 restricted stock unit awards, nil performance unit awards (representing 100% of the aggregate target in accordance with the Chubb Corp. merger agreement) and 83,173 deferred stock unit awards are outstanding. No additional grants will be made pursuant to the Chubb Corp. LTIP.

(iv) ESPP. A total of 6,500,000 shares have been authorized for purchase at a discount. As of December 31, 2019, 1,785,978 shares remain available for future issuance under this plan.

[2] These plans are the Chubb Corp. CCAP Excess Benefit Plan (CCAP Excess Benefit Plan) and the Chubb Corp. Deferred Compensation Plan for Directors, under which no Common Shares are available for future issuance other than with respect to outstanding rewards. The CCAP Excess Benefit Plan is a nonqualified, defined contribution plan and covers those participants in the Capital Accumulation Plan of The Chubb Corporation (CCAP) (Chubb Corp.'s legacy 401(k) plan) and Chubb Corp.'s legacy employee stock ownership plan (ESOP) whose total benefits under those plans are limited by certain provisions of the Internal Revenue Code. A participant in the CCAP Excess Benefit Plan is entitled to a benefit equaling the difference between the participant's benefits under the CCAP and the ESOP, without considering the applicable limitations of the Code, and the participant's actual benefits under such plans. A participant's excess ESOP benefit is expressed as Common Shares. Payments under the CCAP Excess Benefit Plan are generally made: (i) for excess benefits related to the CCAP, in cash annually as soon as practical after the amount of excess benefit can be determined; and (ii) for excess benefits related to the ESOP, in Common Shares as soon as practicable after the participant's termination of employment. Allocations under the ESOP ceased in 2004. Accordingly, other than dividends, no new contributions are made to the ESOP or the CCAP Excess Benefit Plan with respect to excess ESOP benefits.

[3] Weighted average exercise price excludes shares issuable under performance unit awards and restricted stock unit awards.

ITEM 13. Certain Relationships and Related Transactions and Director Independence

This item is incorporated by reference to the sections entitled "Corporate Governance - What Is Our Related Party Transactions Approval Policy And What Procedures Do We Use To Implement It?", "Corporate Governance - What Related Party Transactions Do We Have?", and "Corporate Governance - The Board of Directors - Director Independence" of the definitive proxy statement for the 2020 Annual General Meeting of Shareholders which will be filed with the SEC not later than 120 days after the close of the fiscal year pursuant to Regulation 14A.

ITEM 14. Principal Accounting Fees and Services

This item is incorporated by reference to the section entitled "Agenda Item 4 – Election of Auditors – 4.2 – Ratification of appointment of PricewaterhouseCoopers LLP (United States) as independent registered public accounting firm for purposes of U.S. securities law reporting" of the definitive proxy statement for the 2020 Annual General Meeting of Shareholders which will be filed with the SEC not later than 120 days after the close of the fiscal year pursuant to Regulation 14A.

ITEM 15. Exhibits, Financial Statement Schedules

(a) Financial Statements, Schedules, and Exhibits

Other schedules have been omitted as they are not applicable to Chubb, or the required information has been included in the Consolidated Financial Statements and related notes.

3. Exhibits

		Incorporated by Reference			
Exhibit Number	Exhibit Description	Form	Original Number	Date Filed	Filed Herewith
3.1	Articles of Association of the Company, as amended and restated	8-K	3.1	May 18, 2018	
3.2	Organizational Regulations of the Company as amended	8-K	3.1	November 21, 2016	
4.1	Articles of Association of the Company, as amended and restated	8-K	4.1	May 18, 2018	
4.2	Organizational Regulations of the Company as amended	8-K	3.1	November 21, 2016	
4.3	Specimen share certificate representing Common Shares	8-K	4.3	July 18, 2008	
4.4	Indenture, dated March 15, 2002, between ACE Limited and Bank One Trust Company, N.A.	8-K	4.1	March 22, 2002	
4.5	Senior Indenture, dated August 1, 1999, among ACE INA Holdings, Inc., ACE Limited and Bank of New York Mellon Trust Company, N.A. (as successor), as trustee	S-3 ASR	4.4	December 10, 2014	

Exhibit Number	Exhibit Description	Incorporated by Reference Form	Original Number	Date Filed	Filed Herewith
4.6	Indenture, dated November 30, 1999, among ACE INA Holdings, Inc. and Bank One Trust Company, N.A., as trustee	10-K	10.38	March 29, 2000	
4.7	Indenture, dated December 1, 1999, among ACE INA Holdings, Inc., ACE Limited and Bank One Trust Company, National Association, as trustee	10-K	10.41	March 29, 2000	
4.8	Amended and Restated Trust Agreement, dated March 31, 2000, among ACE INA Holdings, Inc., Bank One Trust Company, National Association, as property trustee, Bank One Delaware Inc., as Delaware trustee and the administrative trustees named therein	10-K	4.17	March 16, 2006	
4.9	Common Securities Guarantee Agreement, dated March 31, 2000	10-K	4.18	March 16, 2006	
4.10	Capital Securities Guarantee Agreement, dated March 31, 2000	10-K	4.19	March 16, 2006	
4.11	Form of 2.70 percent Senior Notes due 2023	8-K	4.1	March 13, 2013	
4.12	Form of 4.15 percent Senior Notes due 2043	8-K	4.2	March 13, 2013	
4.13	First Supplemental Indenture dated as of March 13, 2013 to the Indenture dated as of August 1, 1999 among ACE INA Holdings, Inc., as Issuer, ACE Limited, as Guarantor, and The Bank of New York Mellon Trust Company, N.A., as Successor Trustee	8-K	4.3	March 13, 2013	
4.14	Form of 3.35 percent Senior Notes due 2024	8-K	4.1	May 27, 2014	
4.15	Form of 3.150 percent Senior Notes due 2025	8-K	4.1	March 16, 2015	
4.16	Form of 2.30 percent Senior Notes due 2020	8-K	4.1	November 3, 2015	
4.17	Form of 2.875 percent Senior Notes due 2022	8-K	4.2	November 3, 2015	
4.18	Form of 3.35 percent Senior Notes due 2026	8-K	4.3	November 3, 2015	
4.19	Form of 4.35 percent Senior Notes due 2045	8-K	4.4	November 3, 2015	
4.20	First Supplemental Indenture to the Chubb Corp Senior Indenture dated as of January 15, 2016 to the Indenture dated as of October 25, 1989 among ACE INA Holdings, Inc., as Successor Issuer, ACE Limited, as Guarantor, and The Bank of New York Mellon Trust Company, N.A., as Trustee	8-K	4.1	January 15, 2016	
4.21	Second Supplemental Indenture to the Chubb Corp Junior Subordinated Indenture dated as of January 15, 2016 to the Indenture dated as of March 29, 2007 among ACE INA Holdings, Inc., as Successor Issuer, ACE Limited, as Guarantor, and The Bank of New York Mellon Trust Company, N.A., as Trustee	8-K	4.2	January 15, 2016	
4.22	Chubb Corp Senior Indenture (incorporated by reference to Exhibit 4(a) to Chubb Corp's Registration Statement on Form S-3 filed on October 27, 1989) (File No. 33-31796)	S-3	4(a)	October 27, 1989	
4.23	Chubb Corp Junior Subordinated Indenture (incorporated by reference to Exhibit 4.1 to Chubb Corp's Current Report on Form 8-K filed on March 30, 2007) (File No. 001-08661)	8-K	4.1	March 30, 2007	

Exhibit Number	Exhibit Description	Incorporated by Reference Form	Original Number	Date Filed	Filed Herewith
4.24	First Supplemental Indenture to the Chubb Corp Junior Subordinated Indenture dated as of March 29, 2007 between the Chubb Corporation and The Bank of New York Trust Company, N.A., as Trustee (incorporated by reference to Exhibit 4.2 to Chubb Corp's Current Report on Form 8-K filed on March 30, 2007) (File No. 001-08661)	8-K	4.2	March 30, 2007	
4.25	Form of 5.75 percent Chubb Corp Senior Notes due 2018 (incorporated by reference to Exhibit 4.1 to Chubb Corp's Current Report on Form 8-K filed on May 6, 2008) (File No. 001-08661)	8-K	4.1	May 6, 2008	
4.26	Form of 6.60 percent Chubb Corp Debentures due 2018 (incorporated by reference to Exhibit 4(a) to Chubb Corp's Registration Statement on Form S-3 filed on October 27, 1989) (File No. 33-31796)	S-3	4(a)	October 27, 1989	
4.27	Form of 6.80 percent Chubb Corp Debentures due 2031 (incorporated by reference to Exhibit 4(a) to Chubb Corp's Registration Statement on Form S-3 filed on October 27, 1989) (File No. 33-31796)	S-3	4(a)	October 27, 1989	
4.28	Form of 6.00 percent Chubb Corp Senior Notes due 2037 (incorporated by reference to Exhibit 4.1 to Chubb Corp's Current Report on Form 8-K filed on May 11, 2007) (File No. 001-08661)	8-K	4.1	May 11, 2007	
4.29	Form of 6.50 percent Chubb Corp Senior Notes due 2038 (incorporated by reference to Exhibit 4.2 to Chubb Corp's Current Report on Form 8-K filed on May 6, 2008) (File No. 001-08661)	8-K	4.2	May 6, 2008	
4.30	Form of debenture for the 6.375 percent Chubb Corp DISCs (incorporated by reference to Exhibit 4.3 to Chubb Corp's Current Report on Form 8-K filed on March 30, 2007) (File No. 001-08661)	8-K	4.3	March 30, 2007	
4.31	Procedures regarding the registration of shareholders in the share register of Chubb Limited	10-K	4.32	February 28, 2017	
4.32	Form of Officer's Certificate related to the 1.550% Senior Notes due 2028 and 2.500% Senior Notes due 2038	8-K	4.1	March 6, 2018	
4.33	Form of Global Note for the 1.550% Senior Notes due 2028	8-K	4.2	March 6, 2018	
4.34	Form of Global Note for the 2.500% Senior Notes due 2038	8-K	4.3	March 6, 2018	
4.35	Form of Officer's Certificate related to the 0.875% Senior Notes due 2027 and 1.400% Senior Notes due 2031	8-K	4.1	June 17, 2019	
4.36	Form of Global Note for the 0.875% Senior Notes due 2027	8-K	4.2	June 17, 2019	
4.37	Form of Global Note for the 1.400% Senior Notes due 2031	8-K	4.3	June 17, 2019	
4.38	Form of Officer’s Certificate related to the 0.300% Senior Notes due 2024 and 0.875% Senior Notes due 2029	8-K	4.1	December 5, 2019	
4.39	Form of Global Note for the 0.300% Senior Notes due 2024	8-K	4.2	December 5, 2019	
4.40	Form of Global Note for the 0.875% Senior Notes due 2029	8-K	4.3	December 5, 2019	

Exhibit Number	Exhibit Description	Incorporated by Reference Form	Original Number	Date Filed	Filed Herewith
4.41	Description of the Registrant's Securities				X
10.1*	Form of Indemnification Agreement between the Company and the directors of the Company, dated August 13, 2015	10-K	10.1	February 26, 2016	
10.2	Credit Agreement for $1,000,000,000 Senior Unsecured Letter of Credit Facility, dated as of November 6, 2012, among ACE Limited, and certain subsidiaries and Wells Fargo Bank, National Association as Administrative Agent, the Swingline Bank and an Issuing Bank	10-K	10.13	February 28, 2013	
10.3*	Employment Terms dated October 29, 2001, between ACE Limited and Evan Greenberg	10-K	10.64	March 27, 2003	
10.4*	Employment Terms dated November 2, 2001, between ACE Limited and Philip V. Bancroft	10-K	10.65	March 27, 2003	
10.5*	Executive Severance Agreement between ACE Limited and Philip Bancroft, effective January 2, 2002	10-Q	10.1	May 10, 2004	
10.6*	Letter Regarding Executive Severance between ACE Limited and Philip V. Bancroft	10-K	10.17	February 25, 2011	
10.7*	Employment Terms dated April 10, 2006, between ACE and John Keogh	10-K	10.29	February 29, 2008	
10.8*	Executive Severance Agreement between ACE and John Keogh	10-K	10.30	February 29, 2008	
10.9*	ACE Limited Executive Severance Plan as amended effective May 18, 2011	10-K	10.21	February 24, 2012	
10.10*	Form of employment agreement between the Company (or subsidiaries of the Company) and executive officers of the Company to allocate a percentage of aggregate salary to the Company (or subsidiaries of the Company)	8-K	10.1	July 16, 2008	
10.11*	Outside Directors Compensation Parameters				X
10.12*	ACE Limited Elective Deferred Compensation Plan (as amended and restated effective January 1, 2005)	10-K	10.24	March 16, 2006	
10.13*	ACE USA Officer Deferred Compensation Plan (as amended through January 1, 2001)	10-K	10.25	March 16, 2006	
10.14*	ACE USA Officer Deferred Compensation Plan (as amended and restated effective January 1, 2011)	10-Q	10.7	October 30, 2013	
10.15*	ACE USA Officer Deferred Compensation Plan (as amended and restated effective January 1, 2009)	10-K	10.36	February 27, 2009	
10.16*	First Amendment to the Amended and Restated ACE USA Officers Deferred Compensation Plan	10-K	10.28	February 25, 2010	
10.17*	Form of Swiss Mandatory Retirement Benefit Agreement (for Swiss-employed named executive officers)	10-Q	10.2	May 7, 2010	
10.18*	ACE Limited Supplemental Retirement Plan (as amended and restated effective July 1, 2001)	10-Q	10.1	November 14, 2001	
10.19*	ACE Limited Supplemental Retirement Plan (as amended and restated effective January 1, 2011)	10-Q	10.6	October 30, 2013	

Exhibit Number	Exhibit Description	Incorporated by Reference Form	Original Number	Date Filed	Filed Herewith
10.20*	Amendments to the ACE Limited Supplemental Retirement Plan and the ACE Limited Elective Deferred Compensation Plan	10-K	10.38	February 29, 2008	
10.21*	ACE Limited Elective Deferred Compensation Plan (as amended and restated effective January 1, 2009)	10-K	10.39	February 27, 2009	
10.22*	ACE Limited Elective Deferred Compensation Plan (as amended and restated effective January 1, 2011)	10-Q	10.5	October 30, 2013	
10.23*	Deferred Compensation Plan amendments, effective January 1, 2009	10-K	10.40	February 27, 2009	
10.24*	Amendment to the ACE Limited Supplemental Retirement Plan	10-K	10.39	February 29, 2008	
10.25*	Amendment and restated ACE Limited Supplemental Retirement Plan, effective January 1, 2009	10-K	10.42	February 27, 2009	
10.26*	ACE USA Supplemental Employee Retirement Savings Plan (see exhibit 10.6 to Form 10-Q filed with the SEC on May 15, 2000)	10-Q	10.6	May 15, 2000	
10.27*	ACE USA Supplemental Employee Retirement Savings Plan (as amended through the Second Amendment)	10-K	10.30	March 1, 2007	
10.28*	ACE USA Supplemental Employee Retirement Savings Plan (as amended through the Third Amendment)	10-K	10.31	March 1, 2007	
10.29*	ACE USA Supplemental Employee Retirement Savings Plan (as amended and restated)	10-K	10.46	February 27, 2009	
10.30*	First Amendment to the Amended and Restated ACE USA Supplemental Employee Retirement Savings Plan	10-K	10.39	February 25, 2010	
10.31*	The ACE Limited 1995 Outside Directors Plan (as amended through the Seventh Amendment)	10-Q	10.1	August 14, 2003	
10.32*	ACE Limited 1998 Long-Term Incentive Plan (as amended through the Fourth Amendment)	10-K	10.34	March 1, 2007	
10.33*	ACE Limited 2004 Long-Term Incentive Plan (as amended through the Fifth Amendment)	8-K	10	May 21, 2010	
10.34*	ACE Limited 2004 Long-Term Incentive Plan (as amended through the Sixth Amendment)	8-K	10.1	May 20, 2013	
10.35*	ACE Limited Rules of the Approved U.K. Stock Option Program (see exhibit 10.2 to Form 10-Q filed with the SEC on February 13, 1998)	10-Q	10.2	February 13, 1998	
10.36*	Form of Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-K	10.54	February 27, 2009	
10.37*	Form of Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-K	10.55	February 27, 2009	
10.38*	Director Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-Q	10.1	November 9, 2009	
10.39*	Form of Restricted Stock Unit Award Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-Q	10.1	May 8, 2008	

Exhibit Number	Exhibit Description	Incorporated by Reference Form	Original Number	Date Filed	Filed Herewith
10.40*	Form of Restricted Stock Unit Award Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-Q	10.2	May 8, 2008	
10.41*	Form of Restricted Stock Unit Award Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-K	10.60	February 27, 2009	
10.42*	Form of Restricted Stock Unit Award Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-Q	10.2	October 30, 2013	
10.43*	Form of Restricted Stock Unit Award Terms under the ACE Limited 2004 Long-Term Incentive Plan for Chief Executive Officer, Chief Financial Officer and the General Counsel	10-K	10.56	February 28, 2014	
10.44*	Form of Incentive Stock Option Terms under the ACE Limited 2004 Long-Term Incentive Plan	8-K	10.4	September 13, 2004	
10.45*	Form of Incentive Stock Option Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-Q	10.4	May 8, 2008	
10.46*	Form of Incentive Stock Option Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-K	10.63	February 27, 2009	
10.47*	Form of Incentive Stock Option Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-Q	10.3	October 30, 2013	
10.48*	Form of Non-Qualified Stock Option Terms under the ACE Limited 2004 Long-Term Incentive Plan	8-K	10.5	September 13, 2004	
10.49*	Form of Non-Qualified Stock Option Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-Q	10.3	May 8, 2008	
10.50*	Form of Non-Qualified Stock Option Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-Q	10.4	October 30, 2013	
10.51*	Form of Performance Based Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan, as updated through May 4, 2006	10-Q	10.3	May 5, 2006	
10.52*	Revised Form of Performance Based Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-Q	10.2	November 8, 2006	
10.53*	Revised Form of Performance Based Restricted Stock Award Terms under The ACE Limited 2004 Long-Term Incentive Plan	10-K	10.65	February 25, 2011	
10.54*	Form of Performance Based Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-K	10.67	February 28, 2014	
10.55*	Form of Performance Based Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan for Chief Executive Officer, Chief Financial Officer and the General Counsel	10-K	10.68	February 28, 2014	
10.56*	Form of Restricted Stock Unit Award Terms (for outside directors) under the ACE Limited 2004 Long-Term Incentive Plan	10-Q	10.2	November 7, 2007	
10.57*	Form of Restricted Stock Unit Award Terms (for outside directors) under the ACE Limited 2004 Long-Term Incentive Plan	10-Q	10.2	August 7, 2009	

Exhibit Number	Exhibit Description	Incorporated by Reference Form	Original Number	Date Filed	Filed Herewith
10.58*	Form of Incentive Stock Option Terms under the ACE Limited 2004 Long-Term Incentive Plan for Messrs. Greenberg and Cusumano	10-Q	10.1	August 4, 2011	
10.59*	Form of Non-Qualified Stock Option Terms under the ACE Limited 2004 Long-Term Incentive Plan for Messrs. Greenberg and Cusumano	10-Q	10.2	August 4, 2011	
10.60*	Form of Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan for Messrs. Greenberg and Cusumano	10-Q	10.3	August 4, 2011	
10.61*	ACE Limited Employee Stock Purchase Plan, as amended	8-K	10.1	May 22, 2012	
10.62*	Form of Performance Based Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan for Messrs. Greenberg and Cusumano	10-K	10.72	February 24, 2012	
10.63*	Form of Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan for Swiss Executive Management	10-K	10.68	February 27, 2015	
10.64*	Form of Performance Based Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan for Swiss Executive Management	10-K	10.69	February 27, 2015	
10.65*	Form of Restricted Stock Unit Award Terms under the ACE Limited 2004 Long-Term Incentive Plan for Swiss Executive Management	10-K	10.70	February 27, 2015	
10.66*	Form of Incentive Stock Option Terms under the ACE Limited 2004 Long-Term Incentive Plan for Swiss Executive Management	10-K	10.71	February 27, 2015	
10.67*	Form of Non-Qualified Stock Option Terms under the ACE Limited 2004 Long-Term Incentive Plan for Swiss Executive Management	10-K	10.72	February 27, 2015	
10.68*	Form of Executive Management Non-Competition Agreement	8-K	10.1	May 22, 2015	
10.69	Commitment Increase Agreement to increase the credit capacity under the Credit Agreement originally entered into on November 6, 2012 to $1,500,000,000 under the Senior Unsecured Letter of Credit Facility, dated as of December 11, 2015, among ACE Limited, and certain subsidiaries, and Wells Fargo Bank, National Association as Administrative Agent, the Swingline Bank and an Issuing Bank	10-K	10.72	February 26, 2016	
10.70*	Form of Performance Based Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan	10-K	10.73	February 26, 2016	
10.71*	Form of Performance Based Restricted Stock Award Terms under the ACE Limited 2004 Long-Term Incentive Plan for Special Award for Messrs. Greenberg and Keogh	10-K	10.74	February 26, 2016	
10.72*	Chubb Limited 2016 Long-Term Incentive Plan	S-8	4.4	May 26, 2016	
10.73*	Form of Incentive Stock Option Terms under the Chubb Limited 2016 Long-Term Incentive Plan	10-Q	10.2	August 5, 2016	
10.74*	Form of Restricted Stock Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan	10-Q	10.3	August 5, 2016	

Exhibit Number	Exhibit Description	Incorporated by Reference Form	Original Number	Date Filed	Filed Herewith
10.75*	Form of Restricted Stock Unit Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan	10-Q	10.4	August 5, 2016	
10.76*	Form of Non-Qualified Stock Option Terms under the Chubb Limited 2016 Long-Term Incentive Plan	10-Q	10.5	August 5, 2016	
10.77*	Form of Incentive Stock Option Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Swiss Executive Management	10-Q	10.6	August 5, 2016	
10.78*	Form of Restricted Stock Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Swiss Executive Management	10-Q	10.7	August 5, 2016	
10.79*	Form of Restricted Stock Unit Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Swiss Executive Management	10-Q	10.8	August 5, 2016	
10.80*	Form of Non-Qualified Stock Option Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Swiss Executive Management	10-Q	10.9	August 5, 2016	
10.81*	Form of Performance Based Restricted Stock Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Swiss Executive Management	10-K	10.84	February 28, 2017	
10.82*	Form of Performance Based Restricted Stock Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan	10-K	10.85	February 28, 2017	
10.83*	Chubb Limited Employee Stock Purchase Plan, as amended and restated	S-8	4.4	May 25, 2017	
10.84*	Director Restricted Stock Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan	10-Q	10.1	August 3, 2017	
10.85	Amended and Restated Credit Agreement for $1,000,000 Senior Unsecured Letter of Credit Facility, dated as of October 25, 2017, among Chubb Limited, and certain subsidiaries and Wells Fargo Bank, National Association as Administrative Agent, the Swingline Bank and an Issuing Bank	10-K	10.88	February 23, 2018	
10.86*	Form of Incentive Stock Option Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Executive Officers	10-K	10.89	February 23, 2018	
10.87*	Form of Restricted Stock Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Executive Officers	10-K	10.90	February 23, 2018	
10.88*	Form of Performance Based Restricted Stock Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Executive Officers	10-K	10.91	February 23, 2018	
10.89*	Form of Non-Qualified Stock Option Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Executive Officers	10-K	10.92	February 23, 2018	
10.90*	Form of Restricted Stock Unit Award Terms under the Chubb Limited 2016 Long-Term Plan for Executive Officers	10-K	10.93	February 23, 2018	
10.91*	Form of Incentive Stock Option Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Swiss Executive Management	10-K	10.94	February 23, 2018	
10.92*	Form of Non-Qualified Stock Option Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Swiss Executive Management	10-K	10.95	February 23, 2018	

Exhibit Number	Exhibit Description	Incorporated by Reference Form	Original Number	Date Filed	Filed Herewith
10.93*	Form of Restricted Stock Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Swiss Executive Management	10-K	10.96	February 23, 2018	
10.94*	Form of Restricted Stock Unit Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Swiss Executive Management	10-K	10.97	February 23, 2018	
10.95*	Form of Performance Based Restricted Stock Award Terms under the Chubb Limited 2016 Long-Term Incentive Plan for Swiss Executive Management	10-K	10.98	February 23, 2018	
10.96*	Chubb Limited Clawback Policy	10-K	10.99	February 23, 2018	
21.1	Subsidiaries of the Company				X
23.1	Consent of Independent Registered Public Accounting Firm				X
31.1	Certification Pursuant to Section 302 of The Sarbanes-Oxley Act of 2002				X
31.2	Certification Pursuant to Section 302 of The Sarbanes-Oxley Act of 2002				X
32.1	Certification Pursuant to 18 U.S.C. Section 1350, As Adopted Pursuant to Section 906 of The Sarbanes-Oxley Act of 2002				X
32.2	Certification Pursuant to 18 U.S.C. Section 1350, As Adopted Pursuant to Section 906 of The Sarbanes-Oxley Act of 2002				X
101	The following financial information from Chubb Limited's Annual Report on Form 10-K for the year ended December 31, 2019, formatted in Inline XBRL: (i) Consolidated Balance Sheets at December 31, 2019 and 2018; (ii) Consolidated Statements of Operations and Comprehensive Income for the years ended December 31, 2019, 2018, and 2017; (iii) Consolidated Statements of Shareholders' Equity for the years ended December 31, 2019, 2018, and 2017; (iv) Consolidated Statements of Cash Flows for the years ended December 31, 2019, 2018, and 2017; and (v) Notes to the Consolidated Financial Statements				X
104	The Cover Page Interactive Data File formatted in Inline XBRL (The cover page XBRL tags are embedded in the Inline XBRL document and included in Exhibit 101)				

* Management contract, compensatory plan or arrangement

ITEM 16. Form 10-K Summary

None.

SIGNATURES

Pursuant to the requirements of Section 13 or 15(d) of the Securities Exchange Act of 1934, the registrant has duly caused this report to be signed on its behalf by the undersigned, thereunto duly authorized.

CHUBB LIMITED

By: /s/ Philip V. Bancroft

Philip V. Bancroft
Executive Vice President and Chief Financial Officer

February 27, 2020

Pursuant to the requirements of the Securities Exchange Act of 1934, this report has been signed below by the following persons on behalf of the registrant and in the capacities and on the dates indicated.

Signature	Title	Date
/s/ Evan G. Greenberg **Evan G. Greenberg**	Chairman, President, Chief Executive Officer, and Director	February 27, 2020
/s/ Philip V. Bancroft **Philip V. Bancroft**	Executive Vice President and Chief Financial Officer (Principal Financial Officer)	February 27, 2020
/s/ Paul B. Medini **Paul B. Medini**	Chief Accounting Officer (Principal Accounting Officer)	February 27, 2020
/s/ Michael G. Atieh **Michael G. Atieh**	Director	February 27, 2020
/s/ Sheila P. Burke **Sheila P. Burke**	Director	February 27, 2020
/s/ James I. Cash **James I. Cash**	Director	February 27, 2020
/s/ Mary A. Cirillo **Mary A. Cirillo**	Director	February 27, 2020
/s/ Michael P. Connors **Michael P. Connors**	Director	February 27, 2020

Signature	Title	Date
/s/ John Edwardson **John Edwardson**	Director	February 27, 2020
/s/ Robert M. Hernandez **Robert M. Hernandez**	Director	February 27, 2020
/s/ Kimberly Ross **Kimberly Ross**	Director	February 27, 2020
/s/ Robert W. Scully **Robert W. Scully**	Director	February 27, 2020
/s/ Eugene B. Shanks, Jr. **Eugene B. Shanks, Jr.**	Director	February 27, 2020
/s/ Theodore E. Shasta **Theodore E. Shasta**	Director	February 27, 2020
/s/ David Sidwell **David Sidwell**	Director	February 27, 2020
/s/ Olivier Steimer **Olivier Steimer**	Director	February 27, 2020

Chubb Limited
Bärengasse 32
CH–8001 Zurich
Switzerland

chubb.com

Chubb. Insured.SM

O02CSNA958

EXHIBIT V

ISO Circular

FORMS - FILED JULY 6, 2006

FROM: LARRY PODOSHEN, SENIOR ANALYST

COMMERCIAL PROPERTY LI-CF-2006-175

NEW ENDORSEMENTS FILED TO ADDRESS EXCLUSION OF LOSS DUE TO VIRUS OR BACTERIA

This circular announces the submission of forms filings to address exclusion of loss due to disease-causing agents such as viruses and bacteria.

BACKGROUND

Commercial Property policies currently contain a pollution exclusion that encompasses contamination (in fact, uses the term *contaminant* in addition to other terminology). Although the pollution exclusion addresses contamination broadly, viral and bacterial contamination are specific types that appear to warrant particular attention at this point in time.

ISO ACTION

We have submitted forms filing CF-2006-OVBEF in all ISO jurisdictions and recommended the filing to the independent bureaus in other jurisdictions. This filing introduces new endorsement CP 01 40 07 06 - Exclusion Of Loss Due To Virus Or Bacteria, which states that there is **no coverage for loss or damage caused by or resulting from any virus, bacterium or other microorganism that induces or is capable of inducing physical distress, illness or disease**.

Note: In Alaska, District of Columbia, Louisiana*, New York and Puerto Rico, we have submitted a different version of this filing, containing new endorsement CP 01 75 07 06 in place of CP 01 40. The difference relates to lack of implementation of the mold exclusion that was implemented in other jurisdictions under a previous multistate filing.

Both versions of CF-2006-OVBEF are attached to this circular.

* In Louisiana, the filing was submitted as a recommendation to the Property Insurance Association of Louisiana (PIAL), the independent bureau with jurisdiction for submission of property filings.

PROPOSED EFFECTIVE DATE

Filing CF-2006-OVBEF was submitted with a proposed effective date of January 1, 2007, in accordance with the applicable effective date rule of application in each state, with the exception of various states for which the insurer establishes its own effective date.

Upon approval, we will announce the actual effective date and state-specific rule of effective date application for each state.

RATING SOFTWARE IMPACT

New attributes being introduced with this revision:

- A new form is being introduced.

CAUTION

This filing has not yet been approved. If you print your own forms, do not go beyond the proof stage until we announce approval in a subsequent circular.

RELATED RULES REVISION

We are announcing in a separate circular the filing of a corresponding rules revision. Please refer to the **Reference(s)** block for identification of that circular.

REFERENCE(S)

LI-CF-2006-176 (7/6/06) - New Additional Rule Filed To Address Exclusion Of Loss Due To Virus Or Bacteria

ATTACHMENT(S)

- Multistate Forms Filing CF-2006-OVBEF
- State-specific version of Forms Filing CF-2006-OVBEF (Alaska, District of Columbia, Louisiana, New York, Puerto Rico)

We are sending these attachments only to recipients who asked to be put on the mailing list for attachments. If you need the attachments for this circular, contact your company's circular coordinator.

PERSON(S) TO CONTACT

If you have any questions concerning:

- the content of this circular, please contact:

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Senior Analyst
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lnewman@iso.com

- the **mailing or distribution** of this circular, please contact our Customer Service Division:

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We provide participating insurers with information concerning the jurisdictions for which our products and services are distributed. Even in those jurisdictions, each insurer must determine what filing requirements, if any, apply and whether those requirements have been satisfied.

Now, as in the past, all of our products and services are advisory, and are made available for optional use by participating insurers as a matter of individual choice. Your company must decide for itself which, if any, ISO products or services are needed or useful to its operation and how those selected for use should be applied. We urge that you be guided by the advice of your attorneys on the legal requirements.

Amendatory Endorsement - Exclusion Of Loss Due To Virus Or Bacteria

About This Filing

This filing addresses exclusion of loss due to disease-causing agents such as viruses and bacteria.

New Form

We are introducing:

♦ Endorsement **CP 01 40 07 06 -** Exclusion Of Loss Due To Virus Or Bacteria

Related Filing(s)

Rules Filing CF-2006- OVBER

Introduction

The current pollution exclusion in property policies encompasses contamination (in fact, uses the term *contaminant* in addition to other terminology). Although the pollution exclusion addresses contamination broadly, viral and bacterial contamination are specific types that appear to warrant particular attention at this point in time.

An example of bacterial contamination of a product is the growth of listeria bacteria in milk. In this example, bacteria develop and multiply due in part to inherent qualities in the property itself. Some other examples of viral and bacterial contaminants are rotavirus, SARS, influenza (such as avian flu), legionella and anthrax. The universe of disease-causing organisms is always in evolution.

Disease-causing agents may render a product impure (change its quality or substance), or enable the spread of disease by their presence on interior building surfaces or the surfaces of personal property. When disease-causing viral or bacterial contamination occurs, potential claims involve the cost of replacement of property (for example, the milk), cost of decontamination (for example, interior building surfaces), and business interruption (time element) losses.

Current Concerns

Although building and personal property could arguably become contaminated (often temporarily) by such viruses and bacteria, the nature of the property itself would have a bearing on whether there is actual property damage. An allegation of property damage may be a point of disagreement in a particular case. In addition, pollution exclusions are at times narrowly applied by certain courts. In recent years, ISO has filed exclusions to address specific exposures relating to contaminating or harmful substances. Examples are the mold exclusion in property and liability policies and the liability exclusion addressing silica dust. Such exclusions enable elaboration of the specific exposure and thereby can reduce the likelihood of claim disputes and litigation.

While property policies have not been a source of recovery for losses involving contamination by disease-causing agents, the specter of pandemic or hitherto unorthodox transmission of infectious material raises the concern that insurers employing such policies may face claims in which there are efforts to expand coverage and to create sources of recovery for such losses, contrary to policy intent.

In light of these concerns, we are presenting an exclusion relating to contamination by disease-causing viruses or bacteria or other disease-causing microorganisms.

Features Of New Amendatory Endorsement

The amendatory endorsement presented in this filing states that there is **no coverage for loss or damage caused by or resulting from any virus, bacterium or other microorganism that induces or is capable of inducing physical distress, illness or disease**. The exclusion (which is set forth in Paragraph B of the endorsement) applies to property damage, time element and all other coverages; introductory Paragraph A prominently makes that point. Paragraphs C and D serve to avoid overlap with other exclusions, and Paragraph E emphasizes that other policy exclusions may still apply.

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THIS ENDORSEMENT CHANGES THE POLICY. PLEASE READ IT CAREFULLY.

EXCLUSION OF LOSS DUE TO VIRUS OR BACTERIA

This endorsement modifies insurance provided under the following:

COMMERCIAL PROPERTY COVERAGE PART
STANDARD PROPERTY POLICY

A. The exclusion set forth in Paragraph **B.** applies to all coverage under all forms and endorsements that comprise this Coverage Part or Policy, including but not limited to forms or endorsements that cover property damage to buildings or personal property and forms or endorsements that cover business income, extra expense or action of civil authority.

B. We will not pay for loss or damage caused by or resulting from any virus, bacterium or other microorganism that induces or is capable of inducing physical distress, illness or disease.

However, this exclusion does not apply to loss or damage caused by or resulting from "fungus", wet rot or dry rot. Such loss or damage is addressed in a separate exclusion in this Coverage Part or Policy.

C. With respect to any loss or damage subject to the exclusion in Paragraph **B.**, such exclusion supersedes any exclusion relating to "pollutants".

D. The following provisions in this Coverage Part or Policy are hereby amended to remove reference to bacteria:

1. Exclusion of "Fungus", Wet Rot, Dry Rot And Bacteria; and
2. Additional Coverage - Limited Coverage for "Fungus", Wet Rot, Dry Rot And Bacteria, including any endorsement increasing the scope or amount of coverage.

E. The terms of the exclusion in Paragraph **B.**, or the inapplicability of this exclusion to a particular loss, do not serve to create coverage for any loss that would otherwise be excluded under this Coverage Part or Policy.

N

E

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Amendatory Endorsement - Exclusion Of Loss Due To Virus Or Bacteria

About This Filing

This filing addresses exclusion of loss due to disease-causing agents such as viruses and bacteria.

New Form

We are introducing:

- Endorsement **CP 01 75 07 06 -** Exclusion Of Loss Due To Virus Or Bacteria

Related Filing(s)

Rules Filing CF-2006-OVBER

Introduction

The current pollution exclusion in property policies encompasses contamination (in fact, uses the term *contaminant* in addition to other terminology). Although the pollution exclusion addresses contamination broadly, viral and bacterial contamination are specific types that appear to warrant particular attention at this point in time.

An example of bacterial contamination of a product is the growth of listeria bacteria in milk. In this example, bacteria develop and multiply due in part to inherent qualities in the property itself. Some other examples of viral and bacterial contaminants are rotavirus, SARS, influenza (such as avian flu), legionella and anthrax. The universe of disease-causing organisms is always in evolution.

Disease-causing agents may render a product impure (change its quality or substance), or enable the spread of disease by their presence on interior building surfaces or the surfaces of personal property. When disease-causing viral or bacterial contamination occurs, potential claims involve the cost of replacement of property (for example, the milk), cost of decontamination (for example, interior building surfaces), and business interruption (time element) losses.

Current Concerns

Although building and personal property could arguably become contaminated (often temporarily) by such viruses and bacteria, the nature of the property itself would have a bearing on whether there is actual property damage. An allegation of property damage may be a point of disagreement in a particular case. In addition, pollution exclusions are at times narrowly applied by certain courts. In recent years, ISO has filed exclusions to address specific exposures relating to contaminating or harmful substances. Examples are the mold exclusion in property and liability policies and the liability exclusion addressing silica dust. Such exclusions enable elaboration of the specific exposure and thereby can reduce the likelihood of claim disputes and litigation.

While property policies have not been a source of recovery for losses involving contamination by disease-causing agents, the specter of pandemic or hitherto unorthodox transmission of infectious material raises the concern that insurers employing such policies may face claims in which there are efforts to expand coverage and to create sources of recovery for such losses, contrary to policy intent.

In light of these concerns, we are presenting an exclusion relating to contamination by disease-causing viruses or bacteria or other disease-causing microorganisms.

Features Of New Amendatory Endorsement

The amendatory endorsement presented in this filing states that there is **no coverage for loss or damage caused by or resulting from any virus, bacterium or other microorganism that induces or is capable of inducing physical distress, illness or disease**. The exclusion (which is set forth in Paragraph B of the endorsement) applies to property damage, time element and all other coverages; introductory Paragraph A prominently makes that point. Paragraph C serves to avoid overlap with another exclusion, and Paragraph D emphasizes that other policy exclusions may still apply.

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Important Note

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THIS ENDORSEMENT CHANGES THE POLICY. PLEASE READ IT CAREFULLY.

EXCLUSION OF LOSS DUE TO VIRUS OR BACTERIA

This endorsement modifies insurance provided under the following:

COMMERCIAL PROPERTY COVERAGE PART
STANDARD PROPERTY POLICY

A. The exclusion set forth in Paragraph **B.** applies to all coverage under all forms and endorsements that comprise this Coverage Part or Policy, including but not limited to forms or endorsements that cover property damage to buildings or personal property and forms or endorsements that cover business income, extra expense or action of civil authority.

B. We will not pay for loss or damage caused by or resulting from any virus, bacterium or other microorganism that induces or is capable of inducing physical distress, illness or disease.

However, this exclusion does not apply to loss or damage caused by or resulting from fungus. Such loss or damage is addressed in a separate exclusion in this Coverage Part or Policy.

C. With respect to any loss or damage subject to the exclusion in Paragraph **B.**, such exclusion supersedes any exclusion relating to "pollutants".

D. The terms of the exclusion in Paragraph **B.**, or the inapplicability of this exclusion to a particular loss, do not serve to create coverage for any loss that would otherwise be excluded under this Coverage Part or Policy.

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Supreme Court of California
Jorge E. Navarrete, Clerk and Executive Officer of the Court
Electronically FILED on 4/4/2023 by Karissa Castro, Deputy Clerk

STATE OF CALIFORNIA
Supreme Court of California

PROOF OF SERVICE

STATE OF CALIFORNIA
Supreme Court of California

Case Name: **ANOTHER PLANET ENTERTAINMENT v. VIGILANT INSURANCE COMPANY**
Case Number: **S277893**
Lower Court Case Number:

1. At the time of service I was at least 18 years of age and not a party to this legal action.

2. My email address used to e-serve: **krobinson@pasichllp.com**

3. I served by email a copy of the following document(s) indicated below:

Title(s) of papers e-served:

Filing Type	Document Title
REQUEST FOR JUDICIAL NOTICE	230404 AP - 1 Request for Judicial Notice
ADDITIONAL DOCUMENTS	230404 AP - 2 Compendium of Exhibits A-V

Service Recipients:

Person Served	Email Address	Type	Date / Time
Jonathan Hacker O'Melveny & Myers LLP 456553	jhacker@omm.com	e-Serve	4/4/2023 3:59:02 PM
Opinions Clerk United States Court of Appeals for the Ninth Circuit	Clerk_opinions@ca9.uscourts.gov	e-Serve	4/4/2023 3:59:02 PM
Nicolas Pappas Reed Smith, LLP 316665	NPappas@reedsmith.com	e-Serve	4/4/2023 3:59:02 PM
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This proof of service was automatically created, submitted and signed on my behalf through my agreements with TrueFiling and its contents are true to the best of my information, knowledge, and belief.

I declare under penalty of perjury under the laws of the State of California that the foregoing is true and correct.

4/4/2023

Date

/s/Kayla Robinson

Signature

Robinson, Kayla (322061)

Last Name, First Name (PNum)

Pasich LLP

Law Firm