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Health and Safety Impacts of Aircraft Cabin Temperatures

Autumn Downey and David H. Wegman, *Editors*

Committee on Health and Safety Impacts of Aircraft Cabin Temperatures

Biomedical and Health Sciences Program Area

Center for Health, People, and Places

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Consensus Study Report

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[1] NOTE: See Appendix D, Disclosure of Unavoidable Conflict of Interest.

Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **ERIC LARSON,** University of Washington, and **DEB NIEMEIER,** University of Maryland. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Preface

Well over a century ago, the Wright brothers proved that heavier than air, self-propelled machines could successfully fly. That event in 1903 was followed just over a decade later by the first commercial air flight. Granted, that flight was only 23 minutes long, but it occurred between St. Petersburg and Tampa, Florida, and greatly reduced the 2-hour time it took for an automobile to travel between the two cities. In the following years, commercial air travel developed rapidly, and by 1930 Boeing introduced the first female flight attendant. Ellen Church had convinced the airline of her added value as she was a nurse and could add comfort to the uncertain flying public. Today commercial air flights are so common it is hard to believe that little over a century ago this convenience was a novelty.

Along with the evolution of commercial airflight, there were important risks to consider for both crew and passengers. Among these were risks concerning the air cabin climate (cold temperatures were common and sometimes even heat proved problematic), excessive noise, turbulence, insufficient oxygen along with uncertain air pressure equalization, and, worst of all, fatal equipment failures that resulted in crashes and death. Toward the beginning of commercial flight in the late 1920s there was approximately 1 fatality per million miles flown.

Since those times, the growth of the air industry has been accompanied by a great reduction in these risks. Temperatures are generally comfortable, barometric pressure and oxygen supply are maintained at levels appropriate for human physiology, noise has been markedly reduced, and fatalities have been almost eliminated, being reduced by 99 percent by the late 1950s and by another 99 percent by the early 21st century.

Modern air travel by and large occurs in a well-controlled environment. That environment, however, has been under greater scrutiny as air quality and the overall environment have gained increasing public interest. Earlier this century the National Academies of Sciences, Engineering, and Medicine (the National Academies) was asked to examine air quality in the cockpit and in the cabin for commercial aviation. In the report, recommendations were made on a wide variety of environmental exposures that might present risks to crew or passengers. Interestingly, one environmental topic not addressed in that report was that of temperature extremes, a problem that has become of greater concern as both average temperatures and the frequency of extreme temperature events have been increasing across the United States.

In light of the fact that there has been little organized information about the frequency and degree of exposure to unsafe temperatures during air flight and the possible risks to the public and the cabin crew that might be associated with these exposures, Congress instructed the Federal Aviation Administration (FAA) to commission a National Academies study to address the issue. This report is the product of that effort.

The committee that undertook the FAA's charge included 13 members selected to represent a broad range of expertise, including mechanical and systems engineering, air cabin health and safety, human systems integration, human physiology, psychology, occupational and pediatric medicine, gerontology, and statistics. The committee had the added advantage that

several of its members had experience in the airline industry and were able to bring their practical experience and insights regularly into the discussions. Further, the National Academies provided its own expertise in several areas related to the charge, both through its staff and a National Academy of Medicine fellow, Roxana Chicas. Throughout the committee's deliberations, there was a willingness on the part of all members to learn from one another, which proved essential as the committee had to chart some new territory in addressing its charge. Ultimately, the committee operated with the wisdom so well-articulated by the eminent epidemiologist and statistician, Sir Austin Bradford Hill:

> All scientific work is incomplete—whether it be observational or experimental. All scientific work is liable to be upset or modified by advancing knowledge. That does not confer upon us a freedom to ignore the knowledge we already have, or to postpone the action that it appears to demand at a given time.

The committee meetings and deliberations were held entirely virtually, certainly a new experience for me. I had some concerns about chairing a committee entirely online; however, the task became quite a pleasure as a result of the friendly and supportive atmosphere of the meetings. Members volunteered readily for subgroup work, and the collaborative atmosphere greatly benefitted the final product. Chairing this committee has been both an education and a rewarding experience.

The committee benefitted greatly from the knowledge, administrative skills, and high-quality inputs from the National Academies staff. I know I speak for the committee that this work would not have been possible without the essential organizational inputs and gentle guidance of the study director, Autumn Downey. She was accompanied by a very able staff and their unfailingly efforts to assist at every turn.

I want to end this preface with great thanks to and acknowledgment of my fellow committee members, all of whom gave generously of their time in addressing a stimulating and challenging task. We all look forward to ongoing efforts to attend to the health and safety needs of air cabin passengers and cabin crew.

David Wegman, *Chair*
Committee on Health and Safety Impacts
of Aircraft Cabin Temperatures
June 2026

Acronyms and Abbreviations

AC	advisory circular
ACER	FAA Centers of Excellence for Aircraft Cabin Environment Research
ACGIH	American Conference of Governmental Industrial Hygienists
AFA	Association of Flight Attendants
AIDS	Accident and Incident Data System
AIR	Aerospace Information Report
AL	action limit
ANSI	American National Standards Institute
APU	auxiliary power unit
ARP	Aircraft Recommended Practice
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASIAS	Aviation Safety Information Analysis and Sharing
ASRS	Aviation Safety Reporting System
AVS	aviation safety
CBE	Center for the Built Environment
CEN	European Committee for Standardization
CFR	Code of Federal Regulations
DOT	U.S. Department of Transportation
ECS	environmental control system
EMS	emergency medical services
FAA	Federal Aviation Administration
GSE	ground support equipment
HEPA	high-efficiency particulate air
IFE	in-flight entertainment
ISO	International Organization for Standardization
MEL	minimum equipment list
MET	metabolic equivalent
NASA	National Aeronautics and Space Administration
NEMSIS	National Emergency Medical Services Information System
NRC	National Research Council
OACP	Office of Aviation Consumer Protection (at DOT)
OSHA	Occupational Safety and Health Administration

OSH Act	Occupational Safety and Health Act of 1970
PCA	preconditioned air
PMV	predicted mean vote
PPD	predicted percent dissatisfied
QAR	quick access recorder
SAFO	safety alert for operators
SDR	service difficulty report
SDRS	Service Difficulty Reporting System
SMS	safety management system
SOP	standard operating procedure
SRA	safety risk assessment
TLV	threshold limiting value
TSPP	Thermal Stress Prevention Program
WBGT	wet bulb globe temperature

Summary[1]

Commercial air travel is recognized as one of the safest modes of transportation per passenger-mile traveled. However, the enclosed environment of an airplane cabin can expose passengers and flight attendants to a range of environmental stressors. Among these, temperature—along with humidity—has received increasing attention due to reports of excessively hot or cold cabin conditions both during ground operations and in flight.

Extended exposure to high or low cabin temperatures may contribute to a range of physiological, cognitive, and behavioral effects. For flight attendants, such exposures may interfere with the performance of safety-critical duties. Because airline passengers and cabin crew have a limited ability to alter or escape the cabin environment, understanding and managing temperature-related risks is essential for maintaining safe air travel. Yet there are no regulations that define temperature requirements for passenger cabins during normal (non-emergency) operations.

In response to concerns about the safety of temperature conditions in passenger cabins, the Federal Aviation Administration (FAA), as directed by Congress, requested the National Academies of Sciences, Engineering, and Medicine to assess the health and safety impacts of temperatures in the passenger cabins of aircraft operating under Part 121 of the Federal Aviation Regulations.

CHARGE TO THE COMMITTEE AND STUDY APPROACH

The committee was charged with reviewing the available data on cabin temperatures, examining evidence on potential health and safety impacts on passengers and flight attendants, assessing the applicability and feasibility of existing temperature and humidity standards for indoor environments, and identifying strategies to monitor, assess, and manage cabin temperatures and associated risks. Importantly, the committee was not asked to recommend specific temperature or humidity limits that could be implemented as a standard.

In addressing its charge, the committee was asked to seek input from Part 121 operators (i.e., U.S. airlines operating under a Part 121 certificate of the FAA),[2] aviation labor organizations, aircraft manufacturers, and other interested parties. To inform its deliberations, the committee used several mechanisms to engage with stakeholders and gather information, including public meeting sessions, written information requests, and reviews of the published literature. The committee also examined and analyzed data from (1) research studies that

[1] This summary does not include references. Citations for the information presented herein are provided in the main text.

[2] Air carriers authorized to operate under a Part 121 certificate are generally large, U.S.-based airlines and regional air carriers but also include cargo operators, which are not within the scope of this study.

included measurements of cabin temperature and humidity and (2) aviation safety and complaint reporting systems.

A central component of the committee's approach was the application of established thermal comfort, heat stress, and cold stress standards and guidelines to define a set of "thermal response zones" ranging from cold stress to heat stress, with intermediate zones of discomfort and comfort (see Figure S-1). This approach served two purposes: first, to provide an objective framework for comparing the aircraft-specific thermal criteria in existing aviation industry standards with broader thermal comfort and heat and cold stress standards and guidelines; and, second, to assess whether measured cabin conditions from typical flights were likely to result in discomfort or thermal stress. To account for key modifying factors, the committee evaluated multiple case scenarios representing combinations of typical passenger and flight attendant clothing and activity levels during different phases of flight. This structured, scenario-based approach enabled the committee to compare measured cabin conditions to expected ranges of comfort, discomfort, and thermal stress and to identify circumstances under which thermal conditions may pose health or safety concerns.

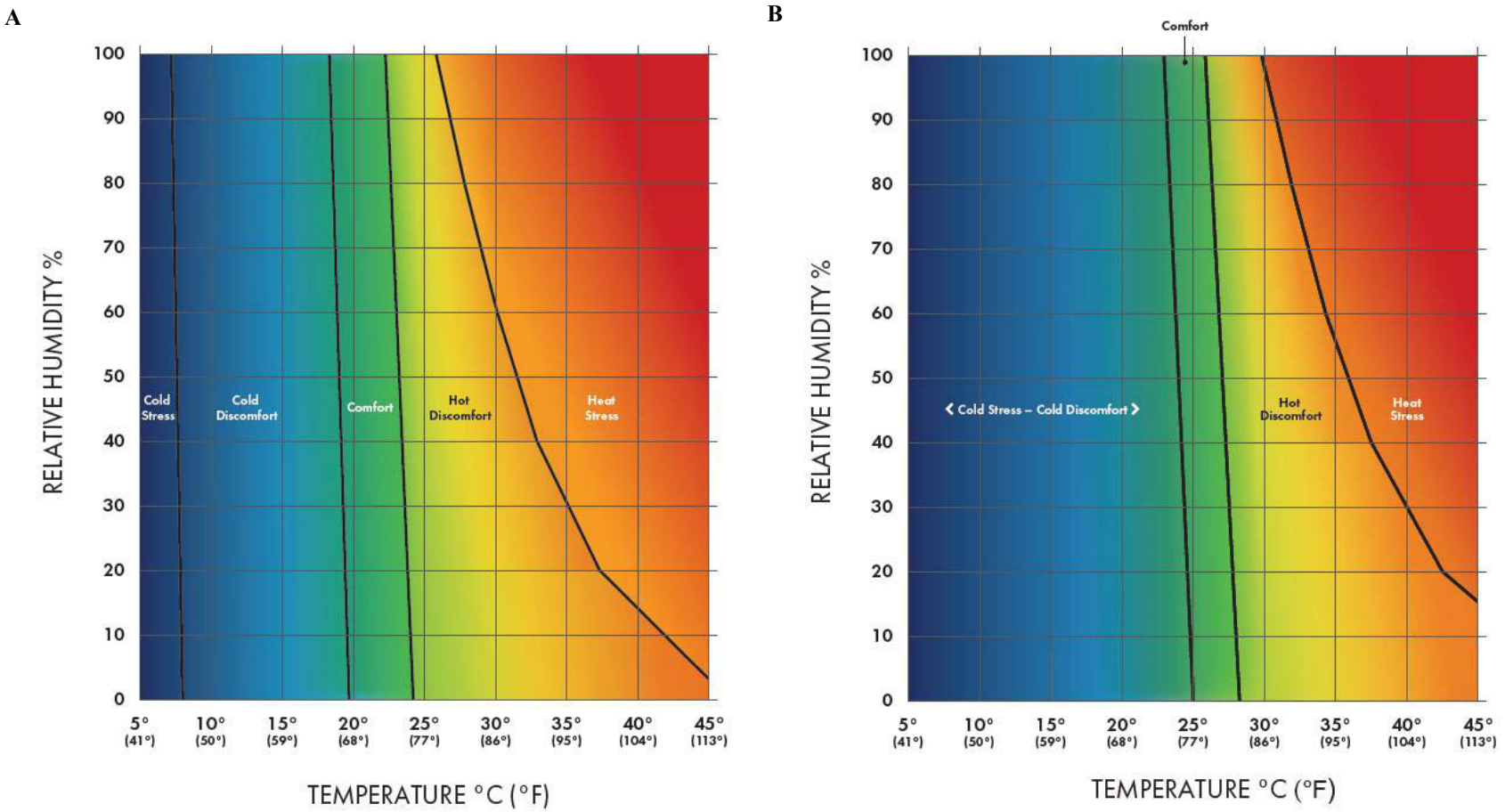

FIGURE S-1 Thermal response zones from the application of thermal comfort and heat and cold stress standards and guidelines.
NOTES: Shown are scenarios involving (A) an active flight attendant wearing typical clothing and (B) a seated passenger or flight attendant wearing typical clothing. See Chapter 4 for the methods used to generate boundaries between zones. Shading indicates that the transitions from comfort to discomfort and from discomfort to stress are gradual and continuous, rather than abrupt, and it reflects the variation in individual-level tolerances. Importantly, the methods used to generate the boundaries may underestimate exposure at high and low humidity, and the boundaries should not be applied outside the scope of this study. Exposure duration is not depicted, but the effects are not instantaneous; the potential for negative health effects and greater severity increases with longer durations of exposure.

THERMAL CONTROL ON AIRCRAFT

Thermal control in the aircraft cabin is achieved through a combination of onboard systems and ground-based equipment which must function across a wide range of operating environments. The primary onboard system for thermal control is the aircraft environmental control system (ECS), which regulates cabin temperature, ventilation, and humidity during flight[3] and, when engines or the auxiliary power unit (APU) are operating, during ground operations. The thermal environment in aircraft cabins is influenced by multiple interacting factors, including ambient conditions (temperature, humidity, and solar radiation), aircraft ECS design, air velocity, and the heat generated by cabin occupants and onboard equipment. During ground operations, thermal control may also rely on ground-based air conditioning systems supplied by gate-based or mobile equipment.

These systems for heating and cooling aircraft are generally effective when fully operational (i.e., working at expected efficiency) and utilized. In some circumstances, however, maintaining acceptable cabin temperatures can be challenging, particularly during ground operations in very hot or very cold ambient conditions when the engines are not running and there is no APU to power the ECS and no adequate ground-based conditioned-air supply. Such situations may arise because of malfunctions, improper use, or a lack of availability of the equipment; insufficient cooling capacity of ground-based air conditioning systems; and/or operational decisions that limit use of equipment and processes for thermal control (for example, decisions not to connect ground-based air conditioning systems in cases of short turnaround times or failure to close window shades). Challenges can also arise both on the ground and during flight when the components of the ECS are operating in a degraded state (e.g., an air conditioning pack is inoperable) and maintenance has been deferred in accordance with the minimum equipment list.[4]

Across both ground and in-flight phases, these challenges underscore the fact that excessively hot or cold cabin temperatures often reflect not a single failure, but a combination of environmental conditions, equipment limitations, and operational practices. Understanding these interacting factors is essential for identifying opportunities to prevent temperature-related health and safety impacts and for informing strategies to improve thermal management in aircraft.

UNDERSTANDING HEALTH AND SAFETY IMPACTS OF CABIN TEMPERATURES

Physiological, Cognitive, and Behavioral Effects of Thermal Exposures

Thermal exposures can have physiological, cognitive, and behavioral effects (see Figure S-2), all of which have the potential to impact the health and safety of aircraft cabin occupants. While there has been limited research in aircraft settings, the effects of thermal exposures in a cabin environment are likely similar to those in other environments but with added cognitive and behavioral effects that may be exacerbated in the enclosed space of the aircraft cabin.

[3] During flight, the ECS is also responsible for pressurizing the aircraft.

[4] A minimum equipment list is an FAA-approved document that specifies which aircraft equipment can be inoperative for a flight. It also specifies the maximum length of time that maintenance can be deferred.

The physiological effects of heat and cold exposure are well documented in occupational and environmental health literature and are most often associated with extreme or prolonged exposures. Heat exposure increases the body's thermal load and can lead to heat strain, characterized by hyperthermia, cardiovascular stress, dehydration, fatigue, dizziness, and, in more severe or prolonged cases, heat-related illnesses such as heat exhaustion or heat stroke. Elevated humidity can substantially increase heat strain at a given air temperature. Cold exposure, while less commonly reported by cabin occupants, can produce various physiological effects, including impaired manual dexterity and increased cardiovascular strain due to vasoconstriction; individuals with cardiovascular or respiratory conditions may be particularly susceptible.

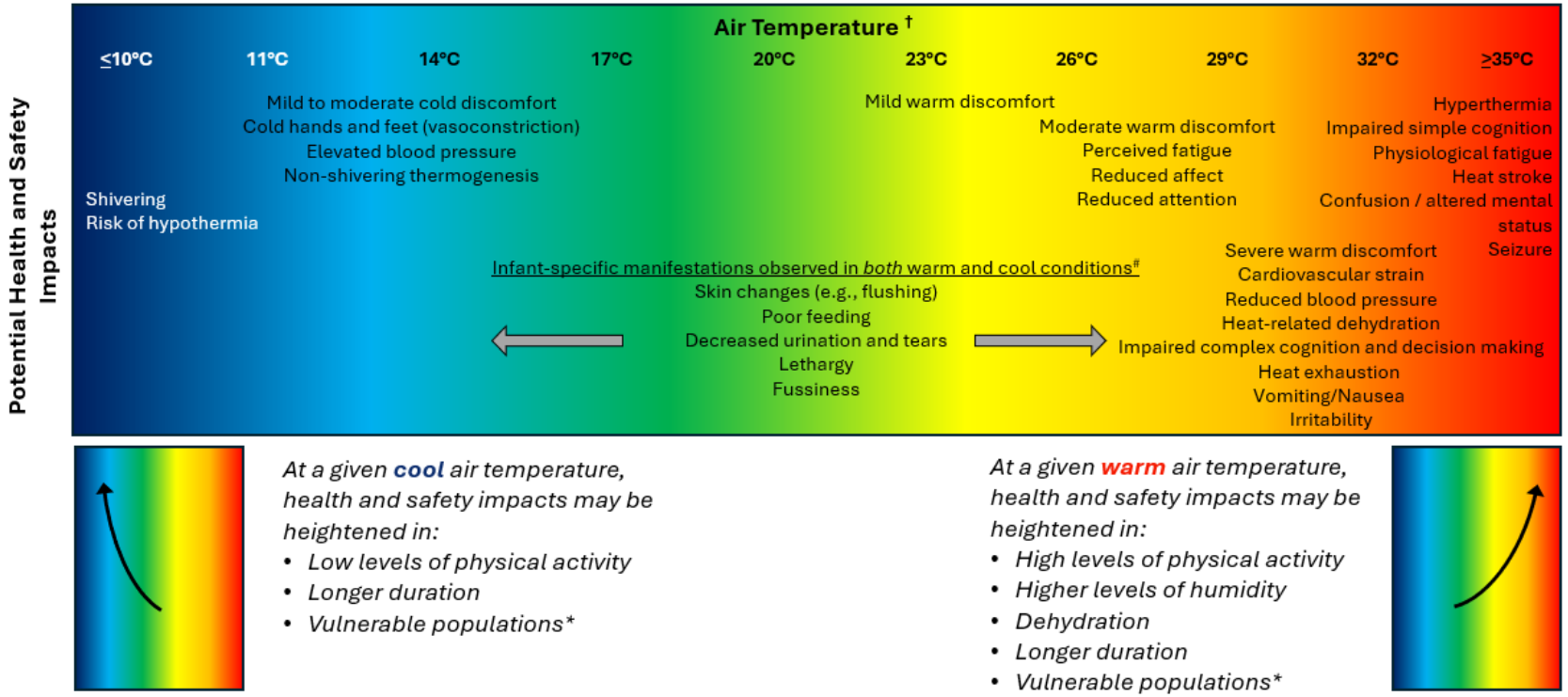

FIGURE S-2 Expected physiological, cognitive, and behavioral effects across the temperature spectrum.
†The stated air temperatures are general guidelines; the potential health and safety impacts exist on a continuum and are modified by multiple factors.
*Identified vulnerable populations include infants and young children, older adults, and people who are pregnant, taking certain medications, or with medical conditions that have primary or secondary effects on behavioral or autonomic thermoregulation.
#Infant-specific manifestations are highlighted separately but may occur across the full temperature spectrum. There is currently insufficient evidence to define temperature-specific thresholds for onset.

Although the evidence base for the cognitive and behavioral effects of thermal exposure is more limited than that for physiological outcomes, research suggests that perceptual and psychological responses, including reduced concentration, impaired decision making, irritability, and heightened emotional responses, may occur at more moderate deviations from thermal comfort, before clear physiological injury is evident. In the aircraft cabin environment, these proximal cognitive and behavioral effects are of particular concern because they may impair flight attendants' performance of safety-critical tasks and contribute to passenger distress or disruptive behavior. Accordingly, while discomfort alone is not typically a direct health concern, mitigating the cognitive and behavioral effects that arise from discomfort is important for protecting the health and safety of both passengers and flight attendants.

The effects of hot or cold air temperatures on health and safety do not occur upon reaching specific threshold temperatures. Rather, the risks exist on a continuum, with personal risk factors (e.g., age, personal health characteristics) and situational risk factors (e.g., duration of exposure, activity level, humidity, inability to leave the aircraft) worsening or alleviating the health and safety risks.

Flight Attendants and Passengers: Distinct Circumstances with Implications for Thermal Exposures and Risks

The study addressed two populations—flight attendants and passengers—who experience cabin temperature exposures under different circumstances. Although both groups share limited control over the cabin environment and, in many situations, limited ability to leave the aircraft, their needs, responsibilities, and susceptibility to temperature-related effects differ in ways that are important for assessing their health and safety risks. These differences can pose challenges to simultaneously maintaining thermal comfort for both flight attendants and passengers.

For flight attendants, the aircraft cabin is a workplace. Regulations require flight attendants to remain on board when one or more passengers is present.[5] For this reason, flight attendants are the first to board and the last to deplane an aircraft. Moreover, flight attendants may be assigned to multiple consecutive short-duration (e.g., regional) flights across their duty day, which can be scheduled to last up to 14 hours. Thus, flight attendants may have a longer exposure to inadequately controlled cabin temperatures than passengers. Flight attendants are also typically more physically active than passengers, particularly during boarding, resulting in higher metabolic heat production, and they have a limited ability to adjust clothing to mitigate effects of exposure to hot or cold cabin temperatures. Importantly, flight attendants are responsible for safety-critical duties—monitoring the cabin, assisting passengers, and responding to emergencies—that may be degraded by fatigue or impaired cognition secondary to thermal discomfort. Even conditions that do not rise to the level of heat or cold stress may therefore have safety implications for this workforce.

Passengers, by contrast, are generally sedentary during flights, which can contribute to thermal discomfort at cool temperatures. Warm conditions, on the other hand, may be exacerbated by being confined to seats and subjected to high seating-density configurations that contribute to a sense of crowding. Passengers have more autonomy over clothing choices as an adaptive opportunity but represent a far more heterogeneous population, including infants and young children, older adults, pregnant women, and people with chronic medical conditions or disabilities that can impair thermoregulation. For these vulnerable populations, temperatures that

[5] 14 CFR § 121.391.

might be tolerable for healthy adults may pose greater health risks or precipitate distress, particularly when the exposures are prolonged.

Evidence of Health and Safety Impacts of Aircraft Cabin Temperatures

The committee identified very limited direct evidence linking measured cabin temperatures to health and safety outcomes. Only one major study identified by the committee systematically examined in-flight temperature and humidity in relation to self-reported health symptoms among passengers and crewmembers. That study found associations between higher temperatures and symptoms such as musculoskeletal complaints and eye irritation and between cooler temperatures and upper respiratory symptoms. However, it did not capture boarding or ground delay conditions, did not include children, and relied on self-reported outcomes.

In the absence of robust direct evidence, the committee examined indirect evidence from multiple sources. Comparing data from research studies that included cabin temperature and humidity measurements against calculated thresholds for comfort, cold stress, and heat stress showed that many in-flight conditions fall outside comfort zones. The activity level of the cabin occupant influences whether cabin temperatures are likely to be experienced as hot or cold discomfort. Conditions during ground operations more frequently approach thresholds at which heat-related stress would be expected, in part due to higher humidity levels. While these conditions may not commonly result in acute medical events, they can produce substantial discomfort and are not consistent with what would be considered an appropriate workplace environment for flight attendants carrying out safety-critical work.

Aviation safety and complaint reporting systems present another perspective linking measured cabin temperatures to health and safety outcomes. Reports submitted through the National Aeronautics and Space Administration's Aviation Safety Reporting System included the most extreme conditions, often involving very high cabin temperatures (sometimes reaching 40°C [100°F] or more). Submissions to systems managed by flight attendant unions tended to report less extreme temperatures, reflecting complaint conditions—primarily hot cabin conditions, which are more common during ground operations. Reports of health and safety events from cold cabin conditions were comparatively rare, indicating that heat stress, rather than cold stress, is the primary concern. Cold conditions are likely more easily mitigated through adaptive strategies (e.g., clothing adjustment, redirecting air flow away from the body). Although these safety and complaint reports represent a small fraction of total flights, they document instances of physical symptoms (e.g., nausea, dizziness, loss of consciousness, fatigue), emotional distress, impaired cognitive performance, and passenger unruliness. These data suggest that severe events, while uncommon, do occur and that they represent more serious health and safety risks than have been described in research studies focused on more typical flight conditions.

> *Conclusion 5-2:*[6] *Conditions involving cabin temperatures that pose serious health and safety risks in the form of physiological effects are not routinely encountered in Part 121 operations. However, temperatures eliciting thermal discomfort are likely to occur more frequently and are capable of producing cognitive and behavioral effects. Although the frequency of health and safety incidents involving physiological, cognitive, or behavioral effects cannot be reliably estimated with currently available data, reports of cabin-*

[6] The conclusions and recommendations in this summary are numbered according to the chapter of the main text in which they appear. Not all chapter conclusions are included in this summary.

temperature-related health and safety incidents suggest a need for improved monitoring, reporting, and assessment of hazards and risk mitigation options.

Data Limitations and Future Data Needs

A key finding from the committee's assessment is the limited availability of reliable data from which to draw conclusions about the health and safety impacts of cabin temperatures. Currently, data on cabin temperatures and humidity are not routinely or systematically collected and analyzed by airlines for hazard identification or monitoring purposes. In many cases, aircraft in operation are not equipped with the necessary equipment to do so. Temperature, though monitored continuously on aircraft, may not be recorded (particularly during ground operations) and stored for future downloading of data, and passenger aircraft today are not equipped with integrated sensors for monitoring humidity. Health and safety outcome data are fragmented across multiple voluntary reporting systems, proprietary airline records, and databases maintained by medical consultation organizations. As a result, the frequency of serious health and safety events—and the prevalence of less severe but operationally significant cognitive and behavioral impacts—cannot be estimated with confidence. The absence of systematic data makes it difficult to characterize the magnitude of the problem, to identify exposure patterns and high-risk conditions, or to evaluate the effectiveness of mitigation strategies. Without such data, cabin temperature issues are unlikely to be prioritized within the aviation industry.

Addressing these data gaps will require investment in a research program to systematically collect cabin temperature and humidity data across a representative cross-section of aircraft types, routes, seasons, and flight phases. Sampling strategies need to account for the infrequent occurrence of serious events, which may be better captured by targeting suspected high-risk conditions—such as routes to locations with extreme ambient temperatures, airports where cabin temperature issues are more frequently reported, or aircraft with a deferred ECS component (e.g., air conditioning packs, bleed air system) and APU repairs. Analyses of newly captured data could help target risk mitigation approaches, although such actions need not wait on data collection efforts.

Recommendation 5-1: The Federal Aviation Administration, in collaboration with airlines and aircraft manufacturers, should establish a research program to systematically monitor, record, and assess temperature and humidity conditions in a representative sample of Part 121 passenger aircraft cabins.

STRATEGIES FOR MANAGING CABIN TEMPERATURES AND ASSOCIATED HEALTH AND SAFETY RISKS

Despite the limitations in the available data, the committee found sufficient evidence to support immediate proactive efforts to mitigate health and safety risks associated with cabin temperatures rather than to delay such efforts pending further data collection. These efforts should be implemented even while systems for improved data collection are being developed. Regulatory standards represent the most stringent mechanism for mitigating risks from thermal conditions. In general, publishing desirable norms and incentivizing voluntary compliance would be preferable, as it would allow flexibility while promoting best practices. However, in the absence of sufficient motivation or financial incentives, voluntary measures may fail to

adequately protect passenger and cabin crewmember health and safety. Under such circumstances, a regulatory standard could help address variability in airline policies, such as differences in boarding temperature limits, and define required actions when ECSs are not functioning as intended. While a standard cannot prevent all incidences of cabin-temperature-related health and safety events, enforcement of a standard that has been adopted into regulation would be expected to reduce the number of incidents that are predictable and preventable, particularly during ground operations when there is more opportunity to apply administrative and engineering practices to mitigate risks from exposure to hot or cold cabin temperatures.

Conclusion 6-1: Past recommendations from the National Academies of Sciences, Engineering, and Medicine and others prompted FAA-supported data collection efforts on aircraft cabin environmental conditions. These efforts focused primarily on air quality and have not led to meaningful improvements in temperature exposures for cabin occupants. Air carriers have been aware of these issues for many years but cabin-temperature-related health and safety incidents are still being reported. Without rulemaking, the committee is concerned about the adequacy of preventive actions to reduce or eliminate these incidents

In the absence of a regulatory standard, there are additional opportunities to better manage cabin temperatures and reduce the associated health and safety risks (e.g., through airline policies and the implementation of operational best practices). These measures, discussed below, will be most effective when implemented as part of a cohesive, system-wide approach that integrates temperature and humidity management into existing aviation safety frameworks.

Applicability and Feasibility of Existing Standards

Applicability to Protecting the Health and Safety of Cabin Occupants

The committee evaluated existing standards for indoor thermal environments—including the aircraft-specific Standard 161-2023 of the American National Standards Institute (ANSI) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as well as general thermal comfort standards (ANSI/ASHRAE Standard 55-2023 and Standard 7730:2025 of the International Organization for Standardization [ISO])—to assess their applicability for ensuring the health and safety of aircraft cabin occupants. A key finding is that fixed temperature limits (as in ANSI/ASHRAE Standard 161-2023) do not adequately protect health and safety because they fail to account for the interactions among temperature and humidity and duration of exposure. The upper temperature limits in ANSI/ASHRAE Standard 161-2023 may permit conditions associated with substantial discomfort or increased risk of heat stress, particularly when humidity is high, as can occur during ground operations. In contrast, thermal comfort standards that account for humidity may offer a more protective framework for health and safety than fixed temperature limits alone. However, these standards do not address the needs of vulnerable populations, including infants and young children, older adults, or individuals with chronic health conditions.

Conclusion 6-3: While ANSI/ASHRAE Standard 161-2023 establishes thermal requirements for aircraft cabins, its implementation may not fully protect occupant health and safety, particularly during ground operations when both cabin temperature and humidity can be elevated. The upper limits specified in ANSI/ASHRAE Standard 161-2023—up to 29.4°C (85°F) during ground operations with in-flight entertainment (IFE)

operating and 26.6°C (80°F) without IFE—may still permit conditions that pose health and safety risks to passengers and cabin crew, especially given that ANSI/ASHRAE Standard 161-2023 does not account for humidity or duration of exposure, both of which can alter the potential for heat stress under certain conditions.

Conclusion 6-4: Thermal comfort standards such as ANSI/ASHRAE Standard 55-2023 and ISO Standard 7730:2025 account for humidity and, therefore, offer a more comprehensive basis for protecting health and safety than fixed temperature limits alone. If applied to aircraft cabins, these standards could reduce the risks associated with thermal discomfort and heat stress, particularly during ground operations in humid environments. However, thermal comfort standards were developed based on healthy adult populations, which may or may not reflect the composition of aircraft occupants.

Feasibility of Implementation in the Aircraft Cabin Setting

Aircraft ECS design and operational guidance are shaped, in part, by voluntary standards with thermal criteria, such as ANSI/ASHRAE Standard 161, ANSI/ASHRAE Standard 55, and ISO Standard 7730. Maintaining aircraft within the recommended temperature ranges from these standards is in most cases achievable when onboard systems and APUs are fully functional.

However, the operational implications of applying thermal comfort standards or a defined temperature threshold in practice require careful consideration. While a regulatory cabin temperature standard could reduce variability in airline practices and define required mitigation actions when thermal control systems are degraded, such an approach would need to incorporate operational flexibility to avoid unintended consequences, such as excessive flight delays. Even under typical flight conditions (with no equipment malfunction), it is difficult to maintain cabin thermal conditions within the narrow range established by thermal comfort standards, thresholds for which will vary with the activity levels of passengers and cabin crew. Moreover, brief exceedances of a temperature threshold—such as during initial cooling after APU activation—may not present the same risk as prolonged exposure. Therefore, rigid enforcement without accounting for exposure duration could impose operational burdens without meaningful safety benefits.

Conclusion 6-5: It is technologically feasible for aircraft to maintain cabin temperatures within the thermal requirements outlined in ANSI/ASHRAE Standard 161-2023 in the vast majority of circumstances, provided that the ECS and APU are fully operational during both flight and ground operations. However, challenges arise when these systems are inoperative, under deferred maintenance, during periods of extreme ambient temperatures during ground operations, or when ground-sourced conditioned air is unavailable or inadequate. Such scenarios increase the likelihood of cabin temperatures exceeding recommended limits, particularly during boarding and extended ground delays.

Conclusion 6-6: Basing cabin temperature limits on thermal comfort thresholds from applying ANSI/ASHRAE Standard 55-2023 or ISO Standard 7730:2025 may be difficult due to the variable activity levels of flight attendants and passengers throughout a flight, especially given the lack of current monitoring of cabin humidity levels to inform temperature limits. Additionally, these standards have narrow acceptable temperature ranges, which would need to be examined for operational practicability.

A Systems Approach to Risk Mitigation

Regardless of whether formal standards are adopted into regulation, there are effective strategies to mitigate risks from thermal exposures by integrating cabin temperature and humidity management into existing aviation safety frameworks. A systems approach will ensure that these efforts are coordinated, comprehensive, and sustainable. Key elements of this approach include

- identifying hazards and managing risks;
- establishing and implementing operational best practices; and
- training and education.

Whenever possible, the committee encourages leveraging existing systems to lower the burden for implementing the strategies discussed below and integrating them into broader efforts to ensure a safe and healthy cabin environment.

Approaches to Identifying Hazards and Managing Risks

Leveraging safety management systems (SMSs)

The aviation industry has established processes for identifying and managing hazards through FAA-approved SMSs. By incorporating cabin temperature and humidity as recognized hazards within these systems, operators can embed thermal risk management into a broader, established safety framework. The FAA can support airlines in these efforts by issuing guidance, such as advisory circulars and safety alerts for operators, which provide important safety information and may recommend actions for managing specific hazards. Airlines would also benefit from FAA guidance on acceptable limits for duration of exposure when cabin temperatures and humidity levels approach health and safety limits. This approach will ensure that temperature and humidity risks are addressed systematically and consistently across the industry while allowing airlines to determine the best way to manage them while maintaining operational flexibility.

Recommendation 6-1: Airlines should integrate the management of cabin temperature and humidity hazards associated with health and safety risks into their safety management systems, as approved by the Federal Aviation Administration. This integration would ensure that temperature-related risks are addressed within an established, organization-wide safety framework, using formal processes for hazard identification, risk assessment, and mitigation.

Recommendation 6-2: To inform airline efforts to integrate the management of cabin temperature and humidity hazards into their Federal Aviation Administration (FAA)–approved safety management systems (SMSs), FAA should

- **issue a safety alert for operators (SAFO) advising air carriers of the hazards and risks associated with cabin temperatures and humidity of varying durations as well as their potential impacts on crewmembers and passengers, including higher-risk subpopulations. The SAFO should emphasize that successful management of these risks should be evaluated through each carrier's FAA-approved SMS;**

- **update Advisory Circular 121-35, *Management of Passengers during Ground Operations without Cabin Ventilation,* to reflect technological advances, industry feedback, and recommended best practices; and**

- **establish guidance on the acceptable duration of thermal exposure where cabin temperatures and humidity levels may approach health and safety limits.**

Improving utilization of health and safety event data and identifying sentinel events

Voluntary reports of health and safety incidents among passengers, flight attendants, and pilots provide potentially valuable but currently underutilized information about the effects of cabin temperature exposures. To make better use of these reports, there should be a single common system designed to aggregate and organize them into a pre-determined set of categories of type and severity of outcome and, where possible, link outcomes to aircraft thermal conditions. Developing a structured, common format for organizing health, safety, and complaint data would facilitate the linkage of outcomes to environmental data, supporting more effective monitoring, analysis, and risk mitigation as well as benchmarking for airlines. Information derived from this improved management of reports could also be used as an important input to an airline's SMS.

Recommendation 6-3: To link environmental factors to possible health and safety outcomes, the Federal Aviation Administration, in collaboration with airlines, should develop a standardized approach to systematically collect, report, and periodically analyze health and safety outcome data (including cognitive and behavioral effects) from complaint and health and safety reports.

By leveraging the standardized system to collect and organize health, safety, and complaint reports called for in Recommendation 6-3, a sentinel event program could be introduced with little additional effort to make better use of the organized data to help prevent future occurrences. Sentinel events are adverse outcomes that serve as warning signals of potential failures in prevention and prompt timely investigation and corrective action when the events are deemed preventable. Applying this concept to the aircraft cabin environment would involve identifying a limited set of temperature-related health and safety outcomes, coupled with specific exposure circumstances, that are indicative of preventable heat or cold illness. The ongoing analysis of structured complaint and health and safety incident data could include alerts when a sentinel event occurs, which would elevate the importance of timely action to address a health or safety risk in accordance with an airline's SMS. Establishing an approach for identifying sentinel events would enable airlines and regulators to address events requiring specific immediate attention, facilitate the detection of trends over time, and guide targeted operational or system-level improvements to reduce future temperature-related health and safety risks.

Recommendation 6-4: The Federal Aviation Administration should work with airlines to define sentinel events that would enhance the value of reported cabin-temperature-related health and safety events for identifying a hazard. This should include developing a preliminary list of conditions and symptoms reasonably predicted to be associated with adverse thermal exposures in aircraft cabins. The

sentinel events would supplement analyses of health and safety reports for use in airline safety management systems.

Establishing and Implementing Operational Best Practices

Information from aviation safety and complaint reporting systems indicates that temperature-related health and safety events often arise not from a single technical failure, but from a combination of equipment limitations and operational or logistical decisions. Examples include allowing the boarding of an aircraft with compromised cooling capability, dispatching aircraft with inoperative APUs to airports lacking adequate ground-based air conditioning, and delays in connecting ground-sourced conditioned air in hot environments. These cases suggest that preventable factors—such as inconsistent policies and inadequate implementation of existing operating procedures—can exacerbate thermal conditions and prolong exposure for passengers and flight attendants.

Engineering and administrative operational practices and policies capable of reducing cabin-temperature-related risks are already in use across the industry, but implementation is uneven across airlines and airports. The committee identified two areas where focused action could yield meaningful benefit:

1. **Leveraging existing mechanisms for routinely collecting, sharing, and evaluating operational best practices and establishing new ones where needed** would support continuous improvement and integration of effective strategies for mitigating cabin-temperature-related health and safety risks into existing SMSs. Industry-led efforts—including consensus guidelines such as the operational best practices guide currently being developed by the ASHRAE Standard 161 committee, professional fora, and safety information-sharing mechanisms (e.g., the semi-annual InfoShare industry event)—offer opportunities to improve consistency and accelerate the dissemination of effective practices.
2. **Empowering flight attendants to better protect their own safety and that of passengers when cabin-temperature-related issues arise.** This should include ensuring that flight attendants have the necessary authority to address unsafe thermal conditions on aircraft without risk of disciplinary action and providing greater flexibility in uniform options to improve individual thermal comfort across varying activity levels and environmental conditions.

Recommendation 6-5: The Federal Aviation Administration and airlines should leverage existing mechanisms and establish new ones where needed for collecting and sharing operational best practices—as well as barriers to the successful implementation of those best practices—to mitigate cabin-temperature-related health and safety impacts. This mechanism should support the continuous improvement and integration of best practices into existing safety management systems and operational procedures as applicable. The following operational practices that address issues commonly raised in complaint and safety reports should be prioritized by air carriers:

- **Working with airports to ensure that the ground-based air conditioning systems used to manage cabin thermal environments are reliable and**

adequate, taking into consideration capacity needs related to different aircraft types and historical data on ambient temperatures and humidity.

- **Ensuring that ground personnel are trained on the proper connection and operation of ground-based air conditioning sources as well as visual checks of hoses.**

- **Prohibiting the dispatch of aircraft operating with an inoperative auxiliary power unit or air conditioning pack to locations experiencing extreme ambient temperatures when functional ground-based air conditioning sources are not available.**

Recommendation 6-6: The Federal Aviation Administration and airlines should periodically review master minimum equipment lists and minimum equipment lists to consider whether current allowances regarding deferred maintenance of environmental control system components, as well as auxiliary power units, allow adequate thermal control.

Recommendation 6-7: Airlines should ensure that input from flight attendants is included in real-time operational decisions related to cabin thermal conditions that may affect the health and safety of cabin occupants.

Recommendation 6-8: Airlines should provide flight attendants maximum feasible flexibility in uniform options and outfit selection to allow adjustments for varying thermal conditions and individual preferences.

Training and Education

Preventing adverse health and safety outcomes related to cabin temperature exposures depends in part on the ability of both crewmembers and passengers to recognize conditions that contribute to excessively hot or cold cabin environments and to take timely actions to reduce risks. This requires an understanding that susceptibility to thermal stress varies across the population and that certain groups—including infants and young children, older adults, and individuals with medical conditions or disabilities that impair thermoregulation—are at increased risk from both heat and cold exposures.

Flight attendants and pilots have distinct but complementary responsibilities for managing cabin conditions and responding to temperature-related health concerns that should be reflected in training content for each of these groups. While airlines provide some training on cabin temperature issues, there are opportunities to strengthen both the content and delivery of this training by addressing the variability in vulnerability across passenger groups, reinforcing practical mitigation actions, emphasizing communication between crewmember roles, and incorporating recurrent, scenario-based training approaches that support skill retention and coordinated response.

Recommendation 6-9: Airlines should require initial and recurrent training for flight attendants and pilots on the contributors to cabin temperature issues, signs and symptoms of temperature-related illness (including variability across age and health groups), and preventive and responsive mitigation measures. This training should

meet established effectiveness guidelines and be continuously evaluated and updated as needed.

Public education represents a complementary strategy for reducing temperature-related risks in the aircraft cabin. Providing accessible information on the potential health effects of hot and cold cabin conditions, identifying higher-risk groups, and describing practical steps—such as appropriate clothing choices, hydration, and early communication with crewmembers—can empower passengers to manage their own comfort and safety. Making use of existing airline communication channels to share such information can enhance awareness without imposing significant additional burden.

Recommendation 6-10: Airlines should provide passengers with access to information about the hazards of varying cabin temperatures and actions they can take to prepare for and respond to hot and cold conditions. These efforts should include

- **identifying higher-risk groups;**
- **describing mitigation measures, such as adjustable clothing, hydration strategies, and the use of personal air outlets, to improve comfort and ensure safety while aboard the aircraft; and**
- **urging passengers to alert flight attendants if an issue related to thermal stress arises.**

CONCLUDING REMARKS

Managing cabin temperatures and associated health and safety risks is not simply a technical or regulatory issue, but also a systems challenge that spans aircraft design, airline operations, airport infrastructure, and oversight frameworks. Addressing these challenges will require coordinated action that recognizes the dynamic nature of the aircraft cabin environment and the shared responsibilities among stakeholders.

The committee's recommendations, summarized and categorized according to stakeholder in Box S-1, are intended to provide a practical path forward toward reducing the likelihood and severity of adverse thermal exposures while accommodating the operational realities of Part 121 operations. Implementing these recommendations would also establish a stronger empirical foundation for future decision making, enabling regulators and operators to better assess risks, evaluate mitigation strategies, and adapt to evolving conditions in air travel.

BOX S-1
Recommendations Aligned with Stakeholders[a]

FAA

• Establish a program to systematically monitor, record, and assess temperature and humidity conditions in passenger aircraft cabins. (Recommendation 5-1)
• Update Advisory Circular 121-35, issue a SAFO advising air carriers of the hazards and risks associated with cabin temperatures and humidity, and establish guidance on the acceptable duration of thermal exposure where cabin temperatures and humidity levels may approach health and safety limits. (Recommendation 6-2)

• Collaborate with airlines to develop a standardized approach to systematically collect, report, and periodically analyze health and safety outcome data. (Recommendation 6-3)
• Define sentinel events to enhance the value of temperature-related health and safety reports for hazard identification. (Recommendation 6-4)
• Leverage existing mechanisms and establish new ones where needed for collecting and sharing operational best practices as well as information on barriers to successful implementation. (Recommendation 6-5)
• Periodically review master MELs and MELs to consider whether current allowances for deferred maintenance of ECS components and APUs allow adequate thermal control (Recommendation 6-6)

Airlines
• Integrate the management of cabin temperature and humidity hazards associated with health and safety risks into FAA-approved SMSs. (Recommendation 6-1)
• Leverage existing mechanisms and establish new ones where needed for collecting and sharing operational best practices as well as information on barriers to successful implementation. (Recommendation 6-5)
• Periodically review master MELs and MELs to consider whether current allowances for deferred maintenance of ECS components and APUs allow adequate thermal control. (Recommendation 6-6)
• Ensure that input from flight attendants is included in real-time operational decisions related to cabin thermal conditions. (Recommendation 6-7)
• Provide flight attendants maximum feasible flexibility in uniform options and outfit selection. (Recommendation 6-8)
• Require initial and recurrent training for flight attendants and pilots on contributors to cabin temperature issues, signs and symptoms of temperature-related illness, and preventive and responsive mitigation measures. (Recommendation 6-9)
• Provide passengers with access to information about the hazards of varying cabin temperatures and actions they can take to prepare for and respond to hot and cold conditions. (Recommendation 6-10)

Airports
• Work with airlines to ensure that the ground-based air conditioning systems used to manage cabin thermal environments are reliable and adequate. (Recommendation 6-5)

[a] *Recommendations in this box have been abbreviated. See main Summary text for complete recommendation language.*

1
Introduction

Airline travel is recognized as one of the safest modes of transportation per passenger-mile traveled (NSC, 2026). Nevertheless, the enclosed environment of an airplane cabin can expose passengers and flight attendants to a range of environmental stressors. Among them, temperature extremes—whether excessive heat during boarding and ground delays or uncomfortably cold conditions during flight—have the potential to pose health and safety risks for cabin occupants. Extended exposure to high or low cabin temperatures may contribute to a range of physiological, cognitive, and behavioral effects and, for flight attendants, may interfere with the performance of safety-critical duties. Because airline passengers and cabin crew have a limited ability to alter or escape the cabin environment, understanding and managing temperature-related risks is an essential aspect of maintaining safe air travel. Yet there are no regulations that define temperature requirements for passenger cabins during normal (non-emergency) operations. In response to concerns about the safety of temperature conditions in passenger cabins, the Federal Aviation Administration (FAA), as directed by Congress, requested the National Academies of Sciences, Engineering, and Medicine (the National Academies) to evaluate the potential health and safety impacts of cabin temperatures. This report presents the findings, conclusions, and recommendations of the National Academies committee convened to conduct the requested study.

This introductory chapter begins with background on trends in U.S. air travel and the evolving profiles of airline passengers and cabin crew—factors that may help explain whether cabin temperature extremes are becoming more common and problematic for cabin occupants. The discussion then turns to factors that influence thermal comfort in the airplane cabin. Next, the regulatory context for the management of thermal exposure in aircraft is discussed, including the implications of shared authorities and responsibilities for protecting passengers and crewmembers.[1] The chapter concludes by outlining the study's origin, scope, and approach as well as the organization of the report.

[1] The term "crewmembers" includes cabin crewmembers (flight attendants) and flight crewmembers (pilots, flight engineers, and flight navigators). Throughout this report, "crewmembers," is used without a descriptor when intended to be inclusive of both cabin and flight crewmembers.

STUDY CONTEXT

Trends in Airline Travel and Implications for Cabin Temperature Exposures

Airline travel in the United States has become increasingly accessible, affordable, and efficiency-driven over time (A4A, 2025). These changes have led to notable increases in passenger volumes, flight load factors (percentage of seats occupied), and cabin seating densities. Such developments may have contributed to incidents of illness, anxiety, and discomfort among airline passengers and cabin crew, particularly related to cabin air temperature conditions.

Annual U.S. domestic and international airline passenger enplanements (i.e., boardings) increased from approximately 705 million in 2004 to 983 million in 2024 (see Table 1-1).[2] Notably, the growth in enplanements outpaced the growth in available seats, as airlines have become more adept at filling seats through yield management and dynamic pricing strategies. While industry average load factor[3] has remained relatively stable at just over 80 percent since 2010 notwithstanding a decline during the COVID-19 pandemic[4] (see Figure 1-1), to accommodate more passengers, airlines are increasingly adding seats to economy cabins by reducing the spacing between seat rows (i.e., pitch) (NASEM, 2025). For passengers, the reduced seat spacing and increased numbers of passengers can make airplane cabins feel more crowded. The greater number of occupants also results in higher metabolic heat generation, which can significantly impact cabin temperatures (see Chapter 2). Another consequence is that cooling equipment failures, especially during delays, can have a more pronounced effect on cabin temperature, leading to heat-related incidents in the confined space of an aircraft cabin. Media reports have described incidents where passengers and flight attendants experienced heat-related illness, anxiety, and discomfort when required to remain in overheated cabins during ground delays (Cook, 2017; Fingert, 2025; Grant and Sweeney, 2023). Data from the U.S. Department of Transportation (DOT) indicate that on-time departures and arrivals have remained near 80 percent, with a brief increase during the COVID-19 pandemic and then a return to pre-pandemic levels (DOT, 2024a). However, in the 12 months ending in July 2025, delays of more than 1 hour affected 717 flights (DOT, 2025b). DOT reports that the common causes of departure delays in that 1-year period included aircraft arriving late (33 percent), air carrier delays (issues within the air carriers' area of responsibility, such as maintenance or crew problems) (29 percent), and national aviation system delays (26 percent). Extreme weather was identified as the cause of less than 5 percent of delays (DOT, 2025b).

[2] Passenger enplanement data are available from the FAA at https://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger (accessed March 10, 2026).

[3] Load factor is a measure of the percentage of available seats filled with paying passengers (IATA, 2024).

[4] Load factor data are available from the DOT Bureau of Transportation Statistics at https://www.transtats.bts.gov/Data_Elements.aspx?Data=4 (accessed March 5, 2026).

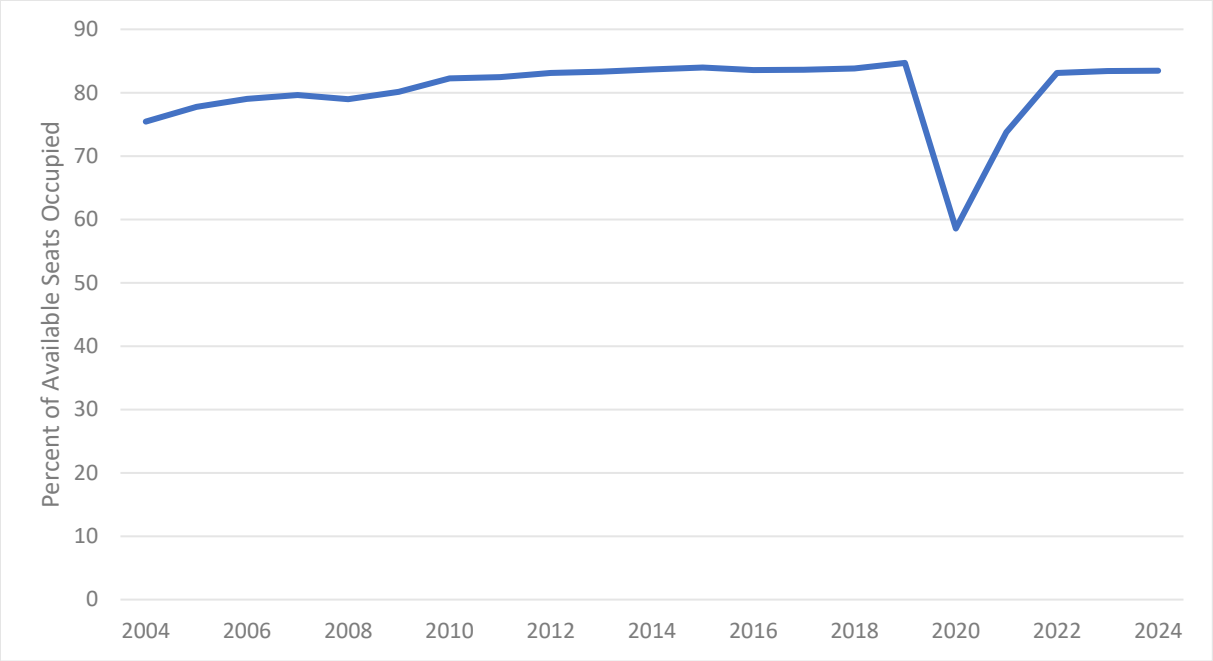

FIGURE 1-1 Load factor for U.S. air carrier domestic and international scheduled passenger flights, 2004–2024.
NOTE: The significant dip in 2020–2022 is attributed to the COVID-19 pandemic.
SOURCE: Data from BTS (2026).

As seat spacing has been reduced and numbers of passengers on flights have been increasing, the geographic distribution of the nation's air traffic activity has also shifted in response to regional population changes and to airlines' adjustments to the locations of hub airports for their hub-and-spoke operations. As shown in Table 1-1, from 2004 to 2024, all FAA regions of the United States (see Figure 1-2) experienced increases in passenger enplanements. However, some of the highest percentage growth occurred in the western and southern regions. Over this 20-year period, the absolute number of annual enplanements in the Southeast, Southwest, and Pacific West regions increased by more than 175 million. Some of the largest and fastest-growing hub airports are located in southern and western cities with long, hot (and, in some cases, humid) summers, including Las Vegas, Phoenix, Miami, Orlando, and Houston. The increase in flights and passengers traveling through these and other airports in the country's southern latitudes may contribute to a higher incidence of elevated cabin temperatures during ground operations, given the correlation between ambient temperatures and cabin temperatures during this phase (Nicholls and Vink, 2025). Additionally, changing U.S. temperature norms and increasing frequency of extreme temperature events—both nationally and regionally (CDC, 2024; Shenoy et al., 2022)—may further heighten concerns about high cabin temperatures. Given these changes, combined with the shifting air travel trends discussed above, a fresh look at the adequacy of systems and procedures for thermal control in aircraft cabins seems timely.

TABLE 1-1 Changes in Passenger Enplanements by FAA Region, 2004 to 2024

FAA region	Enplanements 2004	Percent of total	Enplanements 2024	Percent of total	Percent change 2004–2024
Northwest Mountains	58,189,121	8.25%	103,531,520	10.5%	77.9%
Southwest	77,953,635	11.1%	121,193,463	12.3%	55.5%
Southern	161,265,445	22.9%	247,150,819	25.2%	53.3%
Eastern	111,087,711	15.8%	149,664,716	15.2%	34.7%
New England	23,088,148	3.3%	30,426,788	3.1%	31.8%
Western Pacific	146,170,006	20.7%	192,142,900	19.6%	31.5%
Central	16,349,068	2.3%	20,845,461	2.1%	27.5%
Alaskan	4,513,933	0.6%	5,107,406	0.5%	13.1%
Great Lakes	106,689,596	15.1%	112,541,917	11.5%	5.5%
Total	705,306,663	100.0%	982,604,990	100.0%	39.3%

SOURCE: FAA (2025a, 2026).

FIGURE 1-2 Map of FAA regions.
SOURCE: FAA (2022a).

Passenger and Flight Attendant Profiles and Implications for Temperature Vulnerability

Another factor influencing sensitivity to cabin temperatures is the demographic (particularly age) and health characteristics of air travelers and cabin crew. While there are no comprehensive data on the demographic, health, and anthropometric profiles of U.S. air travelers specifically, trends in the general population would suggest a heterogeneous passenger population. According to U.S. Census Bureau data, the U.S. population is aging, with the share of individuals age 65 and older increasing from 12.4 percent in 2004 to 18.0 percent in 2024 (U.S. Census Bureau, 2025). As discussed further in Chapter 3, older adults have a reduced

ability to regulate temperature (Van Someren, 2007) and are more likely to have underlying health conditions (e.g., diabetes, cardiovascular disease) or disabilities or to be prescribed medications that interfere with temperature regulation. Thus, if the age distribution of air travelers is skewing older, increasing numbers of cabin occupants may experience discomfort or more serious health effects from exposure to fluctuating and extreme cabin temperatures.

On the opposite end of the age spectrum, the FAA estimates that approximately 1 percent of all passengers are children younger than age 2, although exact numbers are not available (NTSB, 2010). Extreme cabin temperatures can create unsafe conditions for infants and young children (Cook, 2017). As discussed further in Chapter 3, infants are more susceptible to extremes of temperature than adults, and for those children under 2 years old who are held on an adult's lap, body contact with the caregiver can cause the child to overheat more quickly, as both are producing metabolic heat.

Unlike the case with the flying public, some demographic data are available for flight attendants. Occupational data from 2023 show that the U.S. flight attendant workforce totaled 111,801 individuals, with an average age of 45.8 years (Data USA, 2023). The largest portions of the workforce were concentrated in the 55–59 age group (16,759 individuals, or 15 percent), followed by ages 50–54 (14,332, or 13 percent). Together, these two age groups accounted for about 28 percent of flight attendants. This demographic profile reflects an aging workforce (Figure 1-3).

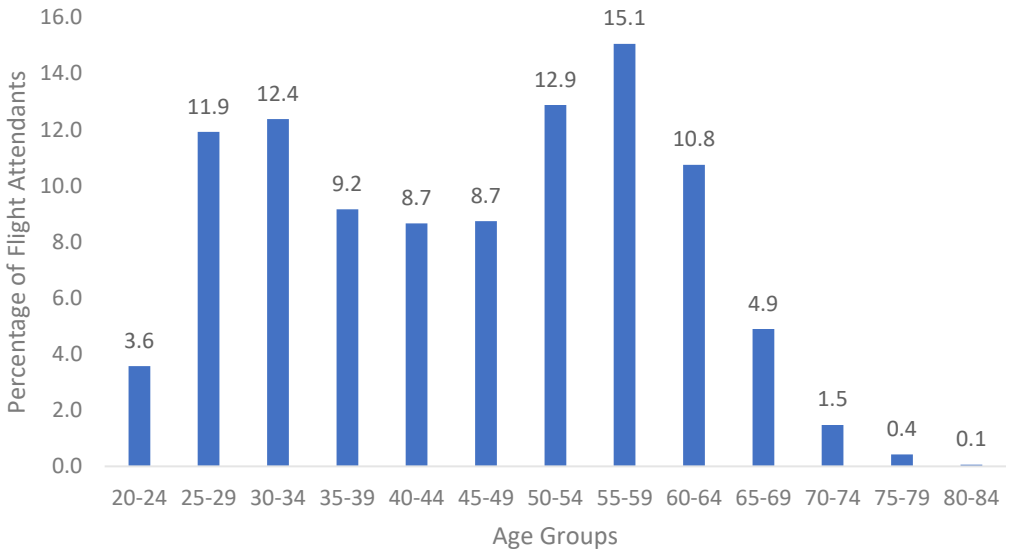

FIGURE 1-3 Age profile of flight attendants, 2023.
SOURCE: Data from Data USA (2023). GNU Affero General Public License, Version 3, 19 November 2007.

Factors Affecting Thermal Comfort in the Cabin Environment

The thermal environment—one of several elements that affect the health, safety, and comfort of the aircraft cabin environment (see Figure 1-4)—is influenced by temperature, humidity, and air velocity (Bezold, 2021). The aircraft's environmental control system (ECS) is the primary system for controlling cabin temperature and cooling technical equipment, although external preconditioned air (PCA) units may be used for thermal control during ground operations (NASEM, 2019). PCA units are ground-based sources of conditioned air that, for the

purposes of this report, include both fixed (e.g., jet bridge–attached units) and mobile units (e.g., ground carts). These systems are described in greater detail in Chapter 2.

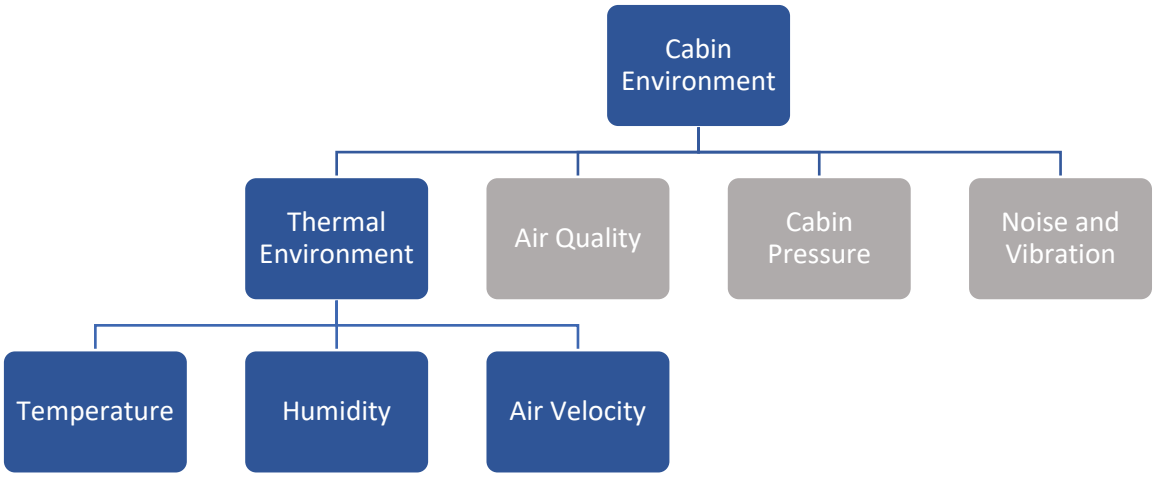

FIGURE 1-4 Physical environmental factors influencing the health, safety, and comfort of the cabin environment.
NOTE: Cabin occupant load/density, not represented on this figure, will affect cabin thermal environment, among other cabin conditions.
SOURCE: Adapted from Bezold (2021). © Airbus SAS 2021. All rights reserved.

The increasing average age of the U.S. commercial aircraft fleet reflects a global trend that has continued since 2019 and is expected to persist (IATA, 2025), and it presents additional challenges for managing cabin temperatures. Newer aircraft are equipped with smart ECS that can adjust airflow to match occupant density. These advanced ECS are specifically designed to handle hot-day ground operations and high seating-density configurations. In contrast, older aircraft—often with fixed-capacity, non-adaptable ECS—may be more susceptible to overheating, especially at high passenger loads.

As depicted in Figure 1-5, multiple stakeholders play a role in creating the conditions necessary for optimal thermal comfort and in preventing unsafe cabin temperatures. Manufacturers are responsible for ensuring that aircraft design and system performance adhere to regulations and for providing instructions to airlines in the form of maintenance and pilot manuals to assist operators with ensuring that aircraft continue to meet airworthiness requirements. Airlines are responsible for the operation and maintenance of the aircraft systems involved in thermal control. However, responsibility for ground-based air conditioning systems varies across airports and is often shared among airlines, airport authorities, and their contractors. This complexity adds to the challenges of addressing risks from thermal exposures in aircraft settings.

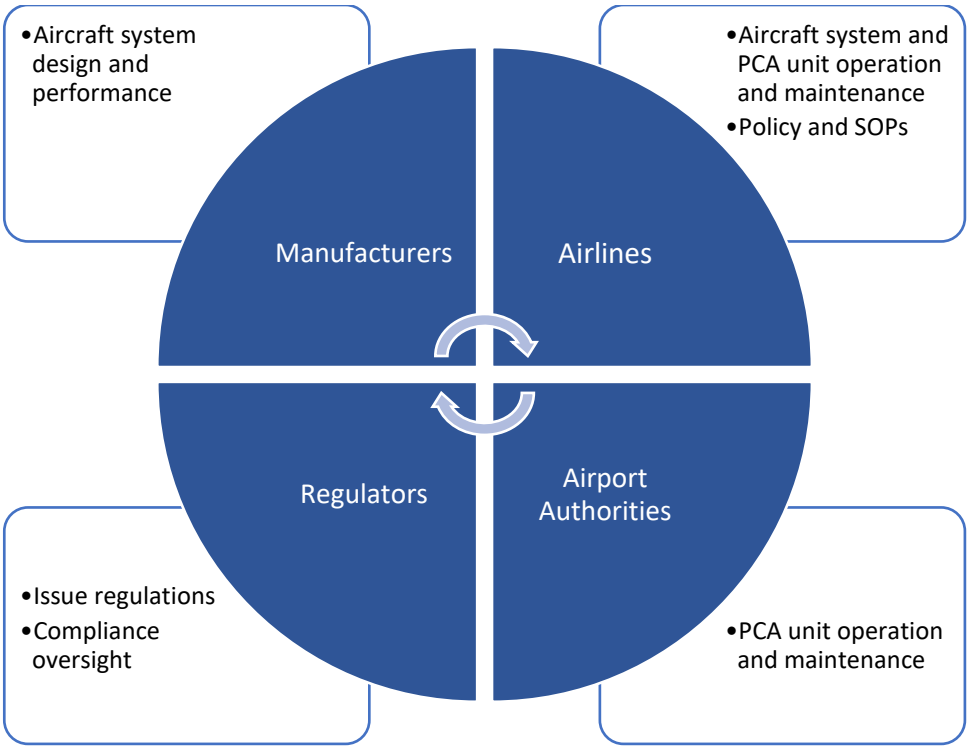

FIGURE 1-5 Multiple stakeholders share responsibility for ensuring a safe thermal cabin environment.
NOTE: PCA = preconditioned air; SOPs = standard operating procedures.

Regulatory Context for Managing Thermal Exposures in Aircraft Settings

An assessment of the health and safety impacts of aircraft cabin must be placed within the context of the regulatory authorities responsible for the oversight of cabin occupant health and safety. The Federal Aviation Act of 1958 grants the FAA regulatory authority over the operation of civil aircraft in the United States.[5] As a result, aviation safety falls primarily under the oversight of the FAA (NRC, 2002). While the FAA maintains primary regulatory authority over aviation safety, other federal entities oversee discrete aspects of the aircraft cabin environment. Specifically, the DOT's Office of Aviation Consumer Protection (OACP) ensures that carriers meet their statutory obligation to provide a comfortable cabin temperature under 49 U.S.C. § 42301[6], and the Occupational Safety and Health Administration (OSHA) exercises limited jurisdiction over cabin crew workplace safety. This results in a complex regulatory oversight structure. The following overview summarizes current regulatory protections related to the safety and health of airplane cabin occupants.

FAA and DOT Regulatory Roles and Actions Related to Ensuring a Safe and Healthy Cabin Environment

Table 1-2 describes how the statutory and regulatory authorities for the protection of air travelers are divided between the FAA and the DOT's OACP. The FAA is authorized by 49

[5] P.L. 85-726. *Federal Aviation Act of 1958* (85th Cong.), August 23, 1958.
[6] See FAA Extension, Safety and Security Act of 2016, PL 114-190, § 2308, July 15, 2016, 130 Stat 615.

U.S.C. § 40101(d) (safety considerations of public interest) and 49 U.S.C. § 44701(a) (promoting safety of civil aircraft) to protect the safety of air travel, which includes the health and safety of crewmembers and passengers. In exercising these authorities, the FAA may issue regulations and guidance. Examples of FAA regulations related to the health and safety of cabin conditions include those addressing carbon monoxide, carbon dioxide, ozone levels, cabin pressure, and—most relevant to the thermal environment—ventilation requirements (NRC, 2002). The standards for the design of aircraft ventilation systems are described in 14 CFR § 25.831 and are detailed further in Chapter 2. Notably, temperature requirements are specified only in the context of improbable failure conditions.[7] While voluntary industry standards for cabin thermal conditions exist, such as those from the American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers [ANSI/ASHRAE] (see Chapter 2), FAA regulations do not specify cabin temperature limits for normal operating conditions. Note that the regulations that address aircraft ventilation systems are design limits, and compliance is determined by analysis at the time of aircraft certification. Although there is currently not a requirement for onboard monitoring, robust air carrier maintenance programs help to ensure that the cabin requirements continue to be met during operation.

In 2003 the FAA published Advisory Circular (AC) 121-35, which provides guidance to air carriers regarding procedures during ground operations for providing ventilation and the use of ground-based air conditioning as well as the management of passengers in the event of cabin ventilation failure or shutdown. The AC recommends, but does not require, the removal of passengers from an aircraft no later than 30 minutes following a ventilation failure or shutdown on the ground (FAA, 2003).[8] When making the decision to deplane, the FAA advises air carriers to consider both the adverse health effects of time spent in the cabin on the ground without ventilation and the operational and safety considerations regarding deplaning passengers.

In addition to regulations and guidance focused on specific safety hazards, the FAA also addresses aviation safety by requiring aircraft operators to have an FAA-approved safety management system (SMS), which allows operators to implement tailored systems for identifying hazards and mitigating risks (FAA, 2024). SMSs are discussed further in Chapter 6.

[7] The probability of failure conditions is defined in Title 14 CFR, part 25, § 25.4(b) in terms of the likelihood of occurrence in the operational life of an individual airplane and the likelihood of occurrence in the total operational life of all airplanes of a given type. For example, a probable failure condition would be "anticipated to occur one or more times during the entire operational life of each airplane of a given type," whereas a remote failure condition is one "that is not anticipated to occur to each airplane of a given type during its operational life but which may occur several times during the total operational life of a number of airplanes of a given type."

[8] An AC is not mandatory or regulatory in nature. It does not constitute a regulation. Rather an AC describes acceptable means, but not the only ones, for demonstrating compliance with a regulation. The contents of an AC do not have the force and effect of law and are not meant to be binding. An AC is intended only to provide clarity regarding requirements under the law or an agency's policies.

TABLE 1-2 OACP and FAA Authorities Related to Safety and Health of Cabin Occupants

Domain	OACP authority	FAA authority
Regulatory Authority	Economic and consumer protection regulations and policy	Safety and operational regulations
Health and Safety Standards	No authority to mandate or enforce health or safety rules or standards	Prescribes minimum safety standards for air carriers and enforces safety rules
Passenger Protections	Enforces consumer protections (e.g., failure to adhere to tarmac delay plans)	Limited to safety-related concerns
Enforcement Power	Enforces consumer protection statutes and regulations	Enforces violations of safety statutes and regulations

SOURCE: Adapted from presentation by Tvaryanas, July 10, 2025.

DOT's OACP has broad authority related to aviation consumer protection, including the prevention of unfair and deceptive practices and enforcement of civil rights under 49 U.S.C. § 41712 and § 41705. OACP receives and investigates passenger complaints related to air travel and uses these complaints to identify trends or areas of concern. When warranted by the results of an investigation, OACP may bring enforcement action against airlines and ticket agents for violations of aviation consumer protection regulations (DOT, 2022). The committee acknowledges, however, that the health and safety of passengers is not a primary focus of OACP and it has no authority to mandate or enforce health or safety rules or standards.

With respect to cabin-temperature-related health and safety concerns, OACP enforces adherence to tarmac delay[9] contingency plans, which air carriers are required to adopt under federal law.[10] A tarmac delay, as defined in 14 CFR § 259.3, is the period of time when an aircraft is on the ground with passengers and the passengers have no opportunity to deplane.[11] Under 49 U.S.C. § 42301, as amended by Section 415 of the FAA Modernization and Reform Act of 2012 (P.L. 112-95),[12] air carriers are required to submit to DOT an emergency contingency plan for tarmac delays. These plans must describe how the carrier will provide a comfortable cabin temperature, adequate food, and potable water when a flight's departure or passenger disembarkation is delayed.[13] Plans must also address passenger deplaning rights (within 3 hours for domestic flights and 4 hours for international flights), timely updates about the delay, and access to medical treatment for passengers.[14] OACP further regulates and enforces these requirements through the Tarmac Delay Rule, 14 CFR § 259.4.

In its response to a committee request for information, OACP indicated that it reviews and investigates all written descriptions of tarmac delay incidents submitted by covered

[9] When discussing DOT regulations, the committee refers to "tarmac delays" for consistency with the regulatory language but otherwise uses the term "ground delay" throughout this report.

[10] 49 U.S.C. § 42301.

[11] 49 U.S.C. § 42301(i)(3) defines a tarmac delay as the period during which passengers are on board an aircraft on the tarmac (A) awaiting takeoff after the aircraft doors have been closed or after passengers have been boarded if the passengers have not been advised they are free to deplane; or (B) awaiting deplaning after the aircraft has landed.

[12] Available at https://www.congress.gov/bill/112th-congress/house-bill/658/text.

[13] DOT did not include the comfortable cabin requirement in its final regulation but enforces it pursuant to 49 USC § 42301.

[14] See U.S.C. § 42301; see also 14 CFR § 259.4.

operating carriers pursuant to 49 U.S.C. § 42301(h) and 14 CFR 259.4(g) and that these investigations include assessing whether the carrier maintained a comfortable cabin temperature during the incident through a totality of the circumstances evidentiary standard (DOT, 2025a). However, a 2014 DOT Inspector General report found that DOT had not defined "comfortable cabin temperature," making the requirement difficult to enforce; the report recommended that DOT "define comfortable cabin temperature and include the requirement in DOT regulations" (DOT, 2014, p. 12). Without such requirements, the report stated, "DOT cannot be sure that passengers are being afforded the relief intended during lengthy flight delays" (p. 3), and, as of this writing, this recommendation has not been implemented.

In a 2018 consent order from DOT concerning violations by Allegiant Air, OACP explained that it "considered written passenger complaints, crewmember statements, temperature readings, reported medical incidents, operational considerations such as the use of external cooling units or air carts during the delays, and decisions to deplane passengers" to determine whether a comfortable cabin temperature violation occurred (DOT, 2018). This order was referenced by OACP for industry to consider in determining the meaning of "comfortable cabin temperature" (DOT, 2025a).

FAA and OSHA Regulatory Roles Related to Occupational Safety and Health Protections for Flight Attendants

Flight attendants play a critical role in ensuring the safety and health of air travelers. The aircraft cabin is a unique work environment where flight attendants encounter a range of environmental exposures, work irregular hours, and face significant physical demands (e.g., standing and walking for long periods in confined spaces, moving and securing heavy beverage carts, maintaining balance during turbulence). Before becoming certificated,[15] flight attendants must complete intensive initial training on a wide range of subjects, including emergency procedures (such as evacuations and firefighting), passenger safety, first aid, and cabin decompression scenarios. After completing an FAA-approved initial training course, flight attendants are required to complete regular recurrent training to maintain proficiency and update their knowledge and skills. While passenger safety and security are flight attendants' highest priority, their own health and safety must also be safeguarded to ensure they can fulfill safety-critical duties during all phases of flight.

The Occupational Safety and Health Act of 1970 ("OSH Act")[16] established OSHA as the primary U.S. federal agency responsible for occupational safety and health for U.S. workers. However, the OSH Act preempts OSHA from regulating the working conditions for workers over whom another federal agency exercises statutory authority to regulate occupational safety and health. In the case of cockpit and cabin crews operating in civil aircraft, the FAA asserted its jurisdiction in 1975 (40 FR 29114), stating that its authority to promote the safety of civil aircraft operations "completely encompass[ed] the safety and health aspects of the work environments of aircraft crewmembers." As a result, "OSHA was preempted from regulating the working conditions of aircraft cabin crew members onboard aircraft in operation."[17]

[15] In response to the 2003 Vision 100-Century of Aviation Reauthorization Act, FAA implemented a certification process to ensure no person serves as a flight attendant aboard an aircraft of an air carrier unless that individual holds a Certificate Of Demonstrated Proficiency issued by the FAA (FAA, 2008).

[16] P.L. 91-596. Occupational Safety and Health Act (91st Cong.), April 28, 1971. 84 Stat. 1590.

[17] 84 FR 68947.

Consequently, most OSHA standards do not apply to flight attendants while they are working in an aircraft in operation (defined as the period of arrival of the first cabin crew member on the aircraft to the departure of the last cabin crew member after completion of the flight) (FAA, 2013). However, in 2013 the then FAA Administrator published a policy statement clarifying that the FAA had not exercised statutory authority to cover all working conditions affecting cabin crew members and that OSHA could apply some of its occupational safety and health standards (FAA, 2013). In 2014, OSHA and the FAA entered into a memorandum of understanding that allows a limited number of OSHA standards to be enforced for cabin crew members, including standards on hazard communication, bloodborne pathogen exposure, and occupational noise exposure (FAA and OSHA, 2014). OSHA does not have a standard for either heat or cold in the work environment, however. Finally, while OSHA's authority is preempted from regulating occupational safety and health, the agency retains the authority to enforce its regulations on recordkeeping and access to employee exposure and medical records.[18] The applicability of this recordkeeping requirement, though limited, is relevant as OSHA records of occupational injuries and illnesses may serve as a potential source of data on the health and safety impacts of cabin temperatures.

The OSH Act also grants OSHA-approved state plans the authority to regulate working conditions of employees in the private sector.[19] The FAA has expressed concern that with state plans, airlines could be subject to different sets of rules when flying in and out of different states.[20] In 2019, OSHA required the state plans to elect whether to amend their plans to include coverage of aircraft cabin crew or to decline such authority; all 22 OSHA-approved state plans declined to cover the working conditions of aircraft cabin crew members aboard aircraft.[21]

Of note, in 2022 the FAA established a Thermal Stress Prevention Program (TSPP) to protect its aviation safety (AVS) employees (e.g., aviation safety inspectors, accident investigators) from exposure to heat and cold stress (FAA, 2022b). The FAA's TSPP establishes requirements for the protection of AVS employees working under a variety of thermal conditions, both indoors and outdoors, that can impair physical health and ensures that covered FAA employees understand how to protect themselves against thermal stress and exposure. The TSPP does not apply to airline employees, including flight attendants.

Previous National Academies Studies on the Aircraft Cabin Environment

Two previous National Academies reports addressed health and safety issues related to exposures in the aircraft cabin (NRC, 1986, 2002). Of particular relevance to the current study, the 2002 report *Airliner Cabin Environment and the Health of Passengers and Crew* made recommendations to the FAA regarding research on and surveillance of environmental factors in the aircraft cabin that may impact occupant health (NRC, 2002). Following these recommendations, a congressional mandate[22] required the FAA to initiate a research program in response to input from the National Academies and other stakeholders, such as ASHRAE's Technical Committee 9.3 Aviation Research Subcommittee, which included representatives from

[18] 29 CFR § 1904 and 29 CFR § 1910.1020.

[19] 84 FR 68947.

[20] 78 FR 52848.

[21] 84 FR 68947.

[22] P.L. 108–176. Vision 100—Century of Aviation Reauthorization Act (108th Cong.), December 12, 2003.

regulators, unions, industry, academics, and independent researchers (Space et al., 2000). This congressional mandate led to the establishment of the FAA Centers of Excellence for Aircraft Cabin Environmental Research (ACER) (Chen et al., 2010). Although the research recommendations were largely focused on air contaminants (e.g., ozone, pesticides), air pressure, and altitude, the FAA-supported research program also considered multiple other interacting environmental and operational factors in its flight research, including temperature and humidity. Many of the resulting aircraft cabin environment data were captured in an ASHRAE Research Project (RP-1262), which sought to relate air quality and other factors to comfort and health-related symptoms reported by airplane passengers and crewmembers (Battelle, 2018). Additional details on cabin temperature and other relevant data from ACER and ASHRAE RP-1262 can be found in Chapter 5.

STUDY ORIGIN AND SCOPE

In the FAA Reauthorization Act of 2024,[23] Congress directed the FAA to commission an independent National Academies study to assess the health and safety impacts of unsafe temperatures in the passenger cabins of commercial aircraft.[24] The committee's full statement of task is presented in Box 1-1.

BOX 1-1
Statement of Task

An ad hoc committee of the National Academies of Sciences, Engineering, and Medicine will assess the health and safety impacts of temperatures in the passenger cabins of airlines operating under a Part 121 certificate of the Federal Aviation Administration. Specifically, the committee will:

- Identify and review available data from Part 121 operators on cabin air temperatures and available evidence on potential health and safety impacts on passengers and cabin crewmembers.
- Review existing standards on safe air temperatures and humidity levels in enclosed environments intended for public occupancy and consider their applicability to ensuring the health and safety of occupants of aircraft operated by Part 121 airlines.
- Examine the feasibility of applying identified temperature and humidity standards to aircraft cabin environments, considering input gathered from aircraft manufacturers.
- Seek input from Part 121 operators, aviation labor organizations, and other interested parties on health and safety impact of cabin temperatures.

Based on this review, the committee will develop a short consensus report with its findings and conclusions and, as appropriate, recommendations to inform strategies for monitoring,

[23] The congressional language requesting this consensus study can be found in Section 323 of the FAA Reauthorization Act of 2024, (P. L. 118-63) here: https://www.govinfo.gov/content/pkg/BILLS-118hr3935enr/pdf/BILLS-118hr3935enr.pdf (accessed September 5, 2025).

[24] The FAA Reauthorization Act of 2024 also included requests that FAA commission National Academies studies on radiation exposures to crewmembers aboard aircraft operated by airlines under a Part 121 certificate of the FAA (Section 322) and risks to passengers and crewmembers from fume or smoke events that impact air quality onboard passenger-carrying aircraft (Section 362).

assessing, and managing passenger cabin air temperature levels and any associated health and safety impacts.

In accordance with the statement of task, this report examines the health and safety impacts of temperatures (both hot and cold) on cabin occupants, defined as passengers and cabin crewmembers (i.e., flight attendants), in airlines operating under a Part 121 certificate of the FAA. Non-human occupants (e.g., pets or service animals) were excluded from the study. The committee recognizes that other workers, including pilots, cleaning staff, and maintenance workers, may also be exposed to very hot or cold temperatures while working on aircraft.[25] While these other workers are not within the formal study scope, the committee's findings, conclusions, and recommendations may also be relevant to this broader set of workers.

As directed by Congress in Section 323 of the 2024 FAA Reauthorization Act, [26] the term ''covered aircraft'' refers to an aircraft operated under Part 121 of title 14, Code of Federal Regulations. Air carriers authorized to operate under a Part 121 certificate are generally large, U.S.-based airlines and regional air carriers[27] as well as all-cargo operators. Part 121 operations do not include private, not-for-hire flights (Part 91) or commercial on-demand air charter services for passengers and cargo (Part 135). Although large cargo operators are certificated under Part 121, certificated flight attendants are not assigned to cargo operations, and passengers do not purchase seats on cargo flights. Therefore, the committee's assessment did not include data from or consideration of Part 121 cargo operators.

The primary focus of the study was health and safety. However, the impact on thermal comfort was also considered, given the potential for discomfort to contribute to cognitive or behavioral issues that affect health and safety (see Chapter 3). Health impacts are understood broadly, encompassing physical discomfort, illness, or medical symptoms as well as mental health effects. These may not immediately affect flight safety but can pose cumulative risk and degrade passenger or crewmember well-being. While health effects for most passengers would be expected to be acute, cabin temperature exposures for flight attendants may be recurring. Consequently, the committee considered both acute and long-term health effects. Safety impacts were defined as conditions that could lead to injury or hazards affecting the safe completion of a flight, including impacts on aircraft performance, cabin crew functioning, and passenger behavior.

The aircraft cabin is a unique environment, with myriad other environmental factors besides temperature (Figure 1-4) that can have physiologic and psychologic effects and that may interact with temperature. Humidity is a relevant example. While health effects of very low humidity have been identified (Morse, 2013; Nagda and Hodgson, 2001; Nagda and Koontz, 2003), the committee addressed humidity only in the context of its impact on the physiological effects of temperature. Interactions between temperature and other cabin environmental factors

[25] In 2026, the Transportation Research Board of the National Academies initiated an effort to develop guidance for airports to mitigate outdoor worker exposure to extreme temperature conditions (TRB, 2026).

[26] P.L. No. 118-63. FAA Reauthorization Act of 2024 (118th Cong.), May 16, 2024.

[27] Major Part 121 air carriers, defined for this purpose as those with at least 0.5 percent of total domestic scheduled-service passenger revenue, include Alaska Airlines, Allegiant Air, American Airlines, Delta Air Lines, Envoy Air, Frontier Airlines, Hawaiian Airlines, JetBlue Airways, PSA Airways, Republic Airways, SkyWest Airlines, Southwest Airlines, Spirit Airlines, and United Airlines (DOT, 2024b). DOT publishes a complete list of certificated U.S. air carriers (DOT, 2025c).

(e.g., carbon dioxide levels) were similarly considered only in terms of how they modify the impacts of temperature. Issues of cabin temperature and humidity overlap to some degree with broader issues of cabin air quality. Cabin air quality events have been the focus of ongoing concern and evaluation within the aviation industry and several previous National Academies studies (NRC, 1986, 2002), but they are not a focus of this report.[28]

As discussed later in this report, several scenarios can contribute to abnormally high or low cabin temperatures. During the first committee meeting, the FAA representative clarified that the committee is not being asked to address extreme cabin conditions resulting from catastrophic equipment malfunctions.

In aviation, an emergency is any situation that significantly threatens the safety of the aircraft or its occupants. Emergencies can include mechanical failures, severe weather, medical emergencies, or security threats. When such a situation arises, the highest priority for the crewmembers is to ensure the safety of everyone on board.

The FAA classifies emergencies into two main categories: distress and urgency (FAA, 2025b). A distress situation is the most serious type of emergency, indicating that the aircraft is in immediate and grave danger and requires urgent assistance. Examples include engine failure, an onboard fire, or loss of control of the aircraft. Distress situations also include critical medical emergencies, such as a passenger or crewmember experiencing a life-threatening condition (e.g., heart attack or stroke). In such cases, immediate medical attention is required, and the pilot may declare an emergency to expedite landing at the nearest suitable airport.

Urgency situations, while serious, do not pose an immediate threat to the aircraft's safety but still require prompt attention to prevent escalation. Examples include partial engine failure, fuel shortage, bird strike, or landing gear malfunction. An urgency situation could also involve a non-critical medical issue, such as a passenger or crewmember falling ill without an immediate life-threatening condition. In these cases, the pilot may decide to continue to the intended destination and request that first responders meet the flight upon landing.

In this report, the term "emergency" may refer to both distress and urgency situations, as both can potentially impact the safety of the aircraft and its occupants. This includes scenarios caused by mechanical or system failures that could result in an untenable cabin condition.

The committee was asked to review existing standards and guidelines on safe air temperatures and humidity levels in enclosed environments intended for public occupancy and to consider their feasibility of implementation and their applicability to protecting the health and safety of occupants on aircraft operated by Part 121 air carriers. Importantly, the committee was not asked to recommend a specific standard. As a result, this report does not provide specific temperature and humidity ranges that the committee believes the FAA should adopt into regulation. Instead, it outlines the risks associated with cabin temperatures and provides the FAA with information that can guide its efforts in managing these risks.

[28] While issues related to airborne contaminants (e.g., fumes, tobacco smoke, carbon dioxide, ozone) are not addressed in this report, cabin air quality remains a topic of concern. At the direction of Congress, the FAA commissioned a National Academies study in 2025 that is being conducted in parallel with the study described in this report and investigates the risk of persistent and accidental fume or smoke events in the aircraft cabin. More information can be found at https://www.nationalacademies.org/projects/DELS-BEST-25-01 (accessed January 31, 2026).

STUDY APPROACH

Committee Formation

To address the Statement of Task, the National Academies convened a 13-member committee of individuals with expertise in cabin and aviation safety, aircraft environmental control systems, measurement and monitoring of thermal environments in aircraft cabins, airline operations (from both cabin crew and airline executive perspectives), human factors, occupational safety and health and occupational medicine, human physiology and psychology in response to the thermal environment and thermoregulation in extreme environments, geriatric and pediatric populations, environmental health, standards development, and data analytics for human health and performance. Biographies of the committee members can be found in Appendix C.

Information Gathering

The Statement of Task explicitly charged the committee with seeking input from a range of stakeholders, including Part 121 operators, aircraft manufacturers, and aviation labor organizations, among others. To fulfill this charge, the committee employed a multi-pronged approach to stakeholder engagement, which included direct engagement during public meetings and solicitation of information through targeted data requests. In addition, the committee conducted targeted reviews of both peer-reviewed and gray literature and gathered and analyzed additional data from public databases (e.g., aviation safety reporting databases). More detailed information on the committee's information gathering approach—including descriptions of public meetings, information requests, and methods for collection and analysis—can be found in Appendix A.

REPORT ORGANIZATION

This report is organized into six chapters and several appendixes. Following this introductory chapter, Chapter 2 describes systems and processes for thermal control in the aircraft cabin environment. Chapter 3 provides an overview of the physiological, cognitive, and behavioral impacts of thermal exposure. Chapter 4 describes the application of standards and guidelines for thermal comfort and for heat and cold stress as they pertain to aircraft cabin occupants. Chapter 5 examines the evidence on health and safety impacts of cabin temperatures. Chapter 6 presents strategies for managing cabin temperatures and mitigating associated health and safety risks. As noted previously, Appendix A details the methods used by the committee for data collection and analysis. Appendix B provides additional supporting data for the assessment of temperature-related health and safety impacts presented in Chapter 5. Biographical sketches of the committee members and disclosures regarding the members' conflicts of interest can be found in Appendix C and Appendix D, respectively.

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2
Thermal Control in the Aircraft Cabin Environment

This chapter addresses thermal control in the aircraft cabin environment both during ground operations and in flight. It begins with an overview of aircraft operating environments and the primary factors that contribute to cabin thermal conditions. The chapter then describes the design requirements for the environmental control system (ECS), relevant regulations and industry standards, and the configuration and operation of the ECS as it relates to thermal management. The discussion then turns to ground-based air conditioning systems used for thermal control while the aircraft is parked at the gate. Finally, the chapter examines the challenges associated with maintaining cabin temperature in both ground and in-flight conditions and discusses operational practices that can be implemented to ensure effective thermal control.

AIRCRAFT OPERATING ENVIRONMENTS

Commercial aircraft operate in a wide range of environments, from virtually any location on earth to altitudes up to 45,000 feet. On the ground, aircraft may be exposed to extreme ambient temperatures, sometimes exceeding 50°C (122°F). Shortly after takeoff—typically within 30 minutes—the aircraft transitions to an external environment that is extremely dry, with water vapor pressure less than 2.4 Pascal (0.00035 pounds per square inch absolute), corresponding to less than 1 percent relative humidity at room temperature. At cruising altitude, outside air temperatures can drop below -55°C [-65°F]) (NRC, 2002), and atmospheric pressure is significantly lower than at sea level—lower than on the summit of Mount Everest (NRC, 2002). To maintain a safe and comfortable cabin environment under these demanding conditions, the aircraft's ECS is engineered to manage multiple functions: thermal comfort, air quality, pressurization, and ventilation. The ECS also supports other critical operations such as engine and wing anti-icing and cargo compartment conditioning. These diverse and extreme operating environments place substantial demands on the ECS and related systems responsible for controlling the aircraft cabin's thermal environment.

CONTRIBUTORS TO THE AIRCRAFT INTERNAL THERMAL ENVIRONMENT

The internal thermal environment of an aircraft is influenced by a combination of both external and internal factors. External factors include:

- **Ambient temperature:** Aircraft may be exposed to extreme temperatures on the ground, requiring significant heating or cooling to maintain comfort. When aircraft doors are open for catering or boarding, ambient air can enter, causing rapid changes in cabin temperature gradients within the cabin.

- **Ambient humidity:** High ambient humidity during ground operations can increase the cooling load, while very low ambient humidity at altitude can contribute to drying of the eyes, nose, and skin.
- **Solar load:** Solar load is the cumulative thermal energy transferred into the aircraft cabin through the aircraft skin and interior windows from the sun's solar radiation. The higher the solar radiation, the more cooling is required to maintain a comfortable cabin temperature (Giuffrè and De Servi, 2024).

Maintaining comfortable thermal conditions in the aircraft cabin is more challenging during ground operations on hot humid days, when ambient temperatures, humidity, and solar loads can be high, as well as on very cold days.

Additional internal factors influencing the aircraft thermal environment include:

- **Occupancy and metabolic heat:** Each sedentary passenger generates about 80–100 watts of heat, with higher outputs for more active individuals (Cramer et al., 2022). Flight attendants, due to their activity level, can produce more than double the heat output of a seated passenger. However, because passengers outnumber cabin crew, their collective heat load is significant.
- **Heat-generating equipment:** Internal equipment, including the in-flight entertainment (IFE) systems, galley equipment for food and beverage preparation, and cabin lighting, all contribute additional heat loads (ASHRAE, 2023). Passenger electronic devices such as laptops and tablets brought into the aircraft as carry-on items and used in-flight may also contribute to the heat load. At times, the heat generated by equipment and lighting can be comparable to that produced by passengers and crewmembers.

The aircraft ECS is designed to account for these varying heat loads and, consequently, is often in cooling mode while the aircraft is on the ground and during flight.

AIRCRAFT ENVIRONMENTAL CONTROL SYSTEM AND ITS ROLE IN THERMAL CONTROL

Thermal control systems for the aircraft cabin include both internal and external components. The primary internal system is the aircraft ECS, which operates during both ground and in-flight phases to regulate cabin temperature, ventilation, and air quality. In flight, the ECS is also responsible for pressurizing the aircraft (ASHRAE, 2023; Bezold, 2021). The following subsections describe the design, configuration, and operation of the ECS.

In addition to ECS, external preconditioned air (PCA) units—ground-based air conditioning systems that may be fixed (e.g., jet bridge–attached units) or mobile (e.g., ground carts)—may be used during ground operations as alternatives to the aircraft ECS. These external systems are particularly important when aircraft are parked at the gate; ground-based air conditioning systems are discussed in detail later in this chapter.

Design and Operating Specifications for Thermal Control on Aircraft

An aircraft ECS is designed to provide a safe, healthy, and comfortable cabin environment (ASHRAE, 2023, NRC, 2002). In particular, the systems are designed to rapidly adjust cabin temperatures under extreme conditions. For example, the ECS can heat a "cold

soaked" airplane—one that has been exposed to very low ambient temperatures—to approximately 21–23.8°C (70–75°F) in less than 30 minutes, assuming that there are no passengers or other internal heat loads and that all exterior doors and window shades are closed. Conversely, the ECS can cool a "heat soaked" cabin—one exposed to high ambient temperatures and solar load—to about 23–26.7°C (75–80°F) in less than 30 minutes with no passengers, minimum electrical heat loads, and all exterior doors and window shades closed (ASHRAE, 2023).

A critical factor influencing the cabin thermal environment and the comfort of its occupants is relative humidity. During ground operations, especially boarding, open cabin doors can allow hot and humid outside air to enter the cabin. The ECS is responsible for controlling humidity, which is important not only for occupant comfort and health but also for aircraft safety. High humidity, particularly when combined with elevated temperatures, can cause discomfort. Following a flight when the airplane structure has been cold soaked, high ambient humidity entering the cabin can cause condensation and dripping on the airplane structures. The moisture on the aircraft structures can freeze during the next flight, potentially leading to corrosion. Condensation can also support pathogen growth, which can impact air quality. To mitigate these risks, the ECS removes moisture from the outside air before it enters the cabin, especially while the aircraft is parked on the ground and during low altitude flight (NRC, 2002). Water separators built into the air conditioning packs are specifically designed for this purpose. However, when ground-based systems (e.g., ground carts or airport jet bridge–attached systems) supplying preconditioned (low-pressure) air are used during ground operations (discussed in more detail later in this chapter), the air is supplied downstream of the aircraft's air conditioning packs. In these cases, cabin humidity is largely determined by ambient conditions, though some condensation and humidity removal may still occur as the PCA cools the incoming air.

During flight, the outside air used for cabin ventilation is very dry, and the humidity within the cabin is primarily a function of the number of occupants and the rate of outside airflow per person. This low humidity (10–20 percent) can cause temporary effects such as dryness of the nose, eyes, and skin for passengers and crewmembers (Nagda and Hodgson 2001; Wyon et al., 2006). The main source of humidity in flight is the cabin occupants, with a smaller contribution from meal and beverage services (ASTM, 2000). At lower altitudes, ambient conditions can influence cabin humidity, and air conditioning packs can remove humidity as needed from the ambient air.

The design of temperature and humidity control systems is informed by a combination of regulatory requirements, industry standards and guidelines, and manufacturers' operational experiences. Other resources referenced by manufacturers to help establish the design envelope include ambient temperature data in the Integrated Surface Database (NCEI, n.d.) and MIL-HDBK-310, *Global Climatic Data for Developing Military Products* (DOD, 1997), which provides information on extreme temperatures worldwide that can be used during the design and sizing of ECS (OEM, 2025). The relevant regulations and standards are discussed in the following sections.

Regulations Relevant to the Aircraft Thermal Environment

Current Federal Aviation Administration (FAA) regulations do not specify explicit limits for cabin temperature or other thermal parameters, such as humidity and air speed, under normal operating conditions. Explicit temperature limits are only addressed under improbable failure

conditions,[1] as discussed below. Instead, thermal design requirements and operational guidance are primarily provided by aircraft manufacturers (discussed in the section that follows), which are influenced by existing standards and regulatory requirements (OEM, 2025).

The design, construction, and operation of commercial aircraft in the United States are regulated under Title 14 of the Code of Federal Regulations (14 CFR). Within 14 CFR, Federal Aviation Regulation § 25.831 addresses ventilation requirements and includes several provisions relevant to the cabin thermal environment (FAA, 1996). Subsection (a) of § 25.831 states:

> Under normal operating conditions and in the event of any probable failure conditions of any system that would adversely affect the ventilating air, the ventilation system must be designed to provide a sufficient amount of uncontaminated air to enable the crewmembers to perform their duties without undue discomfort or fatigue and to provide reasonable passenger comfort. For normal operating conditions, the ventilation system must be designed to provide each occupant with an airflow containing at least 0.55 pounds of fresh air per minute.

While not explicitly mentioned, the requirements for crewmembers to perform their duties without undue discomfort or fatigue and the requirements for reasonable passenger comfort would reasonably be interpreted to include thermal conditions.

Subsection (e) of § 25.831 requires that means be provided to enable control of both the temperature and quantity of ventilating air supplied to the flight crew and crewmember compartments.[2] Subsection (g) specifies upper temperature limits as a function of flight duration for an improbable failure condition (e.g., loss of all air conditioning packs).[3] These upper temperature limits do not apply during normal operation or probable failure conditions.

Additional guidance on complying with FAA regulations in § 25.831 (among others) is provided by Advisory Circular (AC) 25-20. For example, the AC notes that the requirement to provide 0.55 pounds of fresh air per minute per person translates to 10 cubic feet per minute of air at 8,000 feet pressure altitude and at a cabin temperature of 23.9°C (75°F) and that under probable failure conditions, airflow should not fall below 0.4 pounds of fresh air per minute per occupant for periods exceeding 5 minutes (FAA, 1996). Also of relevance, the AC indicates that aircraft "environmental systems should be investigated for the extremes of the airplane operating envelope. Tests (component, sub-system, airplane) and/or analysis should be used to establish the capabilities of the environmental systems at temperatures anticipated to be encountered in service" (FAA, 1996, p. 2).

It is important to note that these requirements in Part 25 are design requirements rather than operational requirements[4]—they define capabilities that the aircraft must possess, not how

[1] FAA defines improbable failure conditions as "those failure conditions unlikely to occur in each airplane during its total life, but that may occur several times when considering the total operational life of a number of airplanes of this type. Also, those failure conditions not anticipated to occur to each airplane during its total life but that may occur a few times when considering the total operational life of all airplanes of this type" (FAA, 2011).

[2] 14 CFR § 25.831.

[3] 14 CFR § 25.831(g).

[4] 14 CFR Part 25.

those aircraft are to be operated in practice. Nevertheless, design requirements are expected to reflect the intended operational conditions of the aircraft.

Another relevant FAA regulation, § 25.771, states: "Each pilot compartment and its equipment must allow the minimum flight crew (established under § 25.1523) to perform their duties without unreasonable concentration or fatigue."[5] Although this requirement applies specifically to the flight crew and does not explicitly address thermal conditions, thermal environments that result in unreasonable concentration or fatigue would appear to fall within the intent of this requirement. Acknowledging the difference in pilot and flight attendant roles, ensuring that conditions in the cabin do not interfere with flight attendants' safety-critical duties without unreasonable concentration or fatigue would be similarly important.

Taken together, the implications of § 25.831 and § 25.771 are that the ECS must be designed to provide reasonable passenger thermal comfort during normal and probable failure conditions and to ensure thermal conditions that do not result in unreasonable concentration or fatigue for all crewmembers, including flight attendants.

Industry Standards and Guidelines for Aircraft

The committee identified five aviation industry standards and guidelines relevant to the aircraft cabin environment. While three of these documents primarily address chemical contamination and its role in aircraft air quality, each also includes provisions related to thermal conditions in the cabin or flight deck or both.

The ANSI/ASHRAE Standard 161-2023, *Air Quality within Commercial Aircraft*,[6] along with its companion document, ASHRAE Guideline 28-2021, sets forth specific requirements and recommendations for the aircraft's thermal environment (see Table 2-1) (ANSI/ASHRAE, 2021, 2023a). For example, ANSI/ASHRAE Standard 161-2023 requires minimizing both vertical and horizontal temperature gradients within each temperature control zone.[7] These gradients can be influenced by such factors as cabin airflow, seating configuration, IFE, solar load, cooled sidewalls, and air leakage from door seals during flight. In addition to the requirements in Table 2-1, ANSI/ASHRAE Standard 161-2023 also requires the provision of personal air outlets[8] (discussed later in this chapter) at each crewmember workstation, jump seat, and crew bunk (ANSI/ASHRAE, 2023a) to allow for localized thermal comfort adjustments. While ANSI/ASHRAE Standard 161-2023 does not detail the derivation of its thermal requirements, it notes that they are based in part on ANSI/ASHRAE Standard 55 and on manufacturer experience (ANSI/ASHRAE, 2023a,b). The relationship between ANSI/ASHRAE Standard 161-2023 and broader thermal comfort standards is discussed further in Chapter 4.

[5] 14 CFR § 25.771(a).

[6] As for all American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards, ANSI/ASHRAE Standard 161-2023 is a consensus document developed by a balanced committee of stakeholders. The designated stakeholder groups for ANSI/ASHRAE Standard 161-2023 include manufacturers (aircraft manufacturers, aircraft subsystem manufacturers, and component manufacturers); owners and operators, including airlines; crew members and their unions; and passenger representatives; among others.

[7] A temperature control zone is defined as an identified section of the aircraft designed with the capability for independent supply air for temperature control (such as between business and economy classes.

[8] Small outlets above the seat that can be controlled by the passenger and supply high-velocity air directly to the seat. Also called gasper vents.

ANSI/ASHRAE Standard 161-2023 also acknowledges the practical challenges of maintaining required thermal conditions on the ground, especially during extreme ambient conditions. Although it does not explicitly exclude such exceedances, it requires airlines to take reporting action in cases of repeated thermal complaints (ANSI/ASHRAE, 2023a).

TABLE 2-1 Aircraft Cabin Temperature Design and Operating Requirements

Parameter	Acceptable Condition [a]
Cabin temperature [b]	• Target operative temperature range, in-flight and ground operations: 65°F to 75°F (18.3°C to 23.9°C) • Operative temperature in flight shall not exceed 80°F (26.7°C), regardless of whether in-flight entertainment systems (IFE) are operating. • Operative temperature during ground operations shall not exceed 80°F (26.7°C) if IFE are not present or not operating, and 85°F (29.4°C) if all IFE are operating. • Design control tolerance to set point: ±2°F (±1.1°C) • Design overshoot to set point: <3°F (<1.7°C)
Local air speed [c]	• Seated passengers and crew: <70 ft/min (<0.36 m/s) • Draft-sensitive bare body areas: <60 ft/min (<0.30 m/s) (<40 ft/min [<0.20 m/s] recommended) • Head level with PAO turned on: >200 ft/min (>1.0 m/s) • Head level with PAO not installed: >20 ft/min (>0.1 m/s)
Temperature spatial variations [d]	• Horizontal operative temperature variation across each temperature control zone: <8°F (4.4°C) • Vertical operative temperature variation within a seat (seat centerline): <5°F (2.8°C) variation in temperatures measured at 4, 24, and 43 in. (100, 610, and 1090 mm)
Maximum surface temperature differential for seated occupants	Average temperature of sidewall surface [e] shall be within 10°F (5.6°C) of the average operative seating area temperature (the average for 4, 24, and 43 in. [100, 610, and 1090 mm] from the floor). Temperature of the floor surface measured at the occupant's feet shall be within 10°F (5.6°C) of the average operative seating area temperature (the average for 4, 24, and 43 in. [100, 610, and 1090 mm] from the floor).
Maximum surface temperature differential in galleys, adjacent to doors	Average temperature of galley sidewall surface [f] should be within 10°F (5.6°C) and shall be within 15°F (8.4°C) of the average operative galley temperature measured at 43 in. (1090 mm) from the floor. Average temperature of galley floor surface measured at crew work stations or jumpseats should be within 10°F (5.6°C) and shall be within 15°F (8.4°C) of the average operative galley temperature measured at 43 in. (1090 mm) from the floor.

a. See ANSI/ASHRAE Standard 55 [5] for measurement and calculation of operative temperatures in this table.
b. Applies to all occupied locations.
c. Maximum value averaged over two-minute period. Occupant acceptability of a given air velocity will vary with supply air temperature. Draft-sensitive body areas are the ankles and the neck.
d. Includes the region 2 in. (50 mm) or more from the sidewalls, between 4 in. (100 mm) and 43 in. (1.1 m) above the floor in seating areas, and between 4 in. (100 mm) and 67 in. (1.7 m) in aisles and galleys. These requirements shall apply when the personal air outlet nozzles are closed.
e. Sidewall temperature measured at ankle, waist, and head levels: 4 in. (100 mm) (or at the lowest practical location on the sidewall), 24 in. (0.6 m), and 43 in. (1.1 m) from the floor.
f. Sidewall temperature measured at ankle, waist, and head levels: 4 in. (100 mm), 43 in. (1.1 m), and 67 in. (1.7 m) from the floor.

SOURCE: ©ASHRAE, www.ashrae.org. (2023) ASHRAE Standard-161-2023.

ASHRAE Guideline 28-2021 is intended as a companion to ANSI/ASHRAE Standard 161. While it does not provide any additional quantitative thermal requirements, it offers qualitative guidance. For example, it notes that cooling and heating loads on the ground are more variable and less predictable than in flight and that additional cooling and heating capacity may be required during ground operations (ANSI/ASHRAE, 2021, 2023a).

The SAE International Aerospace Recommended Practice Report ARP85G, *Air Conditioning Systems for Subsonic Airplanes* (SAE, 2024a), provides guidelines and recommendations for subsonic airplane air conditioning systems and components, including requirements, design philosophy, testing, and ambient conditions. This guideline was referenced by manufacturers of narrow- and wide-body aircraft, in addition to regional aircraft (OEM, 2025).

The SAE International Aerospace Information Report 4766, *Air Quality for Commercial Aircraft Cabins*, provides information on the engineering aspects of ECS design needed to achieve acceptable air quality in commercial aircraft cabins (SAE, 2024b). However, the

temperature section of this document primarily references and summarizes the relevant federal regulations discussed earlier in this chapter, rather than establishing independent quantitative requirements.

It is important to note that industry standards such as those developed by ANSI/ASHRAE and SAE are voluntary. They become mandatory only if a relevant regulatory authority, such as the FAA, formally adopts them, incorporates their provisions into regulatory requirements, or includes them as part of the aircraft certification process. As of this writing, the FAA has not formally adopted the standards discussed in this section, but it acknowledges that manufacturers may use these standards and handbooks to support the design and certification of ECS.

Configuration and Operation of the ECS[9]

The aircraft ECS is responsible for conditioning and distributing pressurized air to meet requirements for ventilation, thermal comfort, and cabin pressurization. In conventional transport aircraft, supply air is extracted from the propulsion system and undergoes staged cooling and pressure regulation before being delivered to the flight deck and passenger cabin. The following section describes the principal ECS components and operation for maintaining thermal comfort.

During flight, the engine compressors pressurize outside air to a high temperature—typically between 170°C and 350°C (340–660°F)—with pressures ranging from 2 to 10 atmospheres (ANSI/ASHRAE, 2021) (step 1 in Figure 2-1 below). The high-pressure air, known as "bleed air," is drawn from the engines upstream of the combustor (see Figure 2-2 for a typical bleed air system). The bleed air is cooled with ambient air through the airplane's precooler heat exchangers to about 175°C (350°F) (NRC, 2002). The cooled bleed air is then supplied to the air conditioning packs (step 2 in Figure 2-1), where it is further cooled to a temperature typically between 10°C and 18°C (50–65°F). The temperature is set to meet the needs of the temperature control zone requiring the most cooling—usually the flight deck or a densely occupied economy cabin. Air conditioning packs consist of valves, turbines, heat exchangers, and compressors which work together to cool the air to the required temperature for provision to the aircraft (see Figure 2-3 for a schematic of a typical air conditioning pack). An exception to the traditional engine bleed system is the Boeing 787, which uses electrically driven compressors to provide and condition outside air, without use of the engine compressors (Subramanya et al., 2024).

[9] Descriptions in this section of ECS components and operation are for typical commercial aircraft, applying to those that fall in narrow-body and wide-body classes as well as regional jets. It should be understood, however, that aircraft models differ in their thermal control systems and some details may not apply to every specific aircraft model. ECS configurations and operation for turboprop aircraft were not specifically considered as no (or almost no) such aircraft continue to be used in Part 121 operations (see Appendix A), although the committee acknowledges that air carriers outside the United States continue to operate these aircraft models.

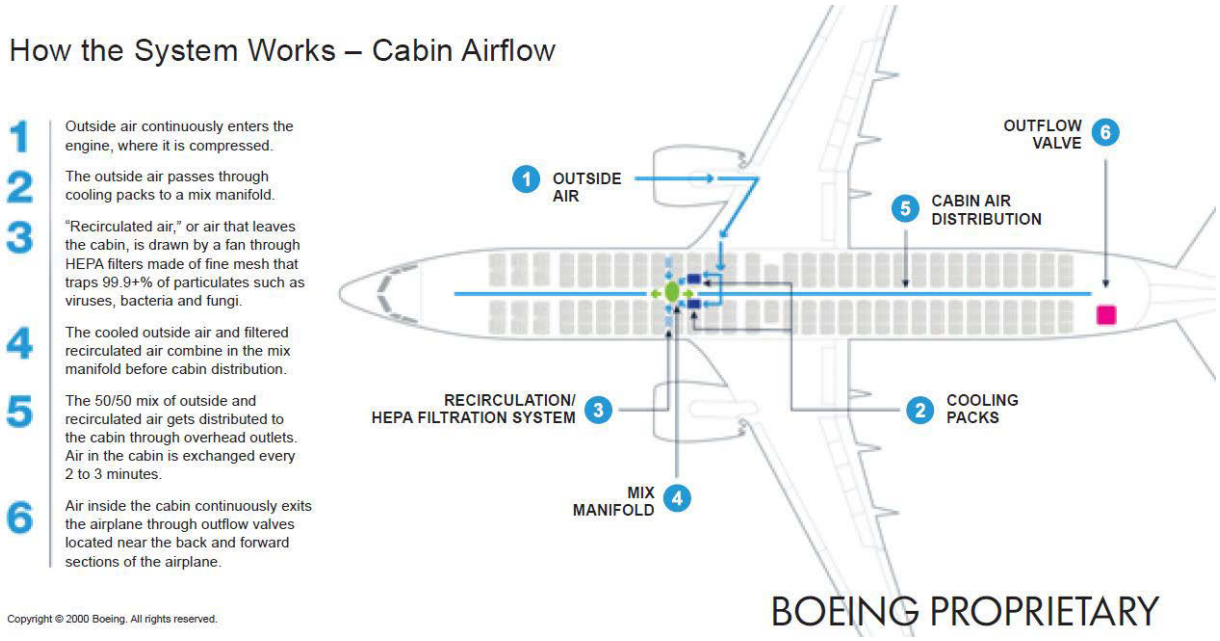

FIGURE 2-1 Simplified environmental control system schematic.
SOURCE: The Boeing Company, 2020. Copyright © 2020 Boeing. All rights reserved.

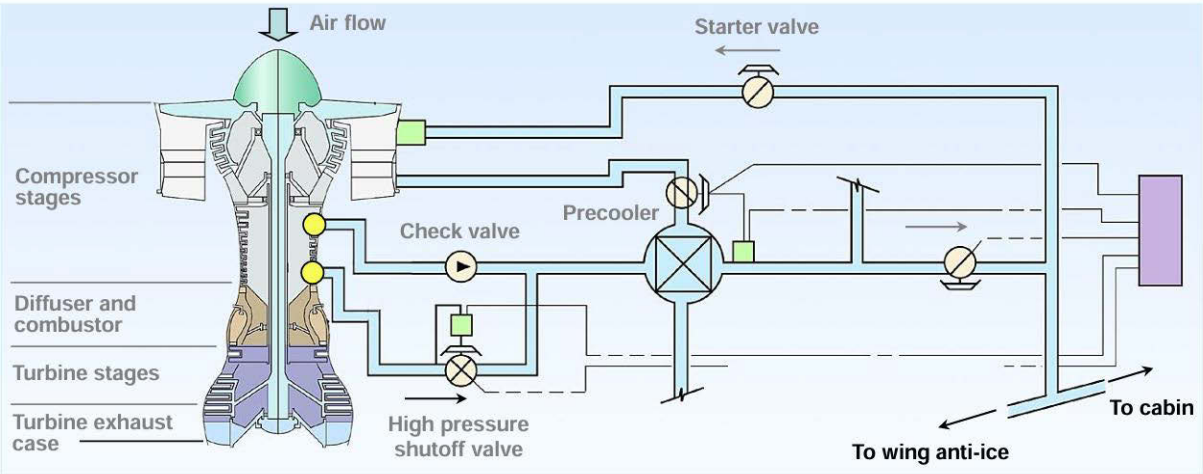

FIGURE 2-2 Schematic representation of a typical aircraft engine bleed-air system.
NOTES: Figure shows compressor extraction points, pressure regulation and shutoff, temperature control via a precooler, and distribution to pneumatic users. Arrows depict the flow of air through the bleed-air system, leading to the air conditioning packs (see Figure 2-3).
SOURCE: The Boeing Company (2001). Copyright © 2026 Boeing. All rights reserved.

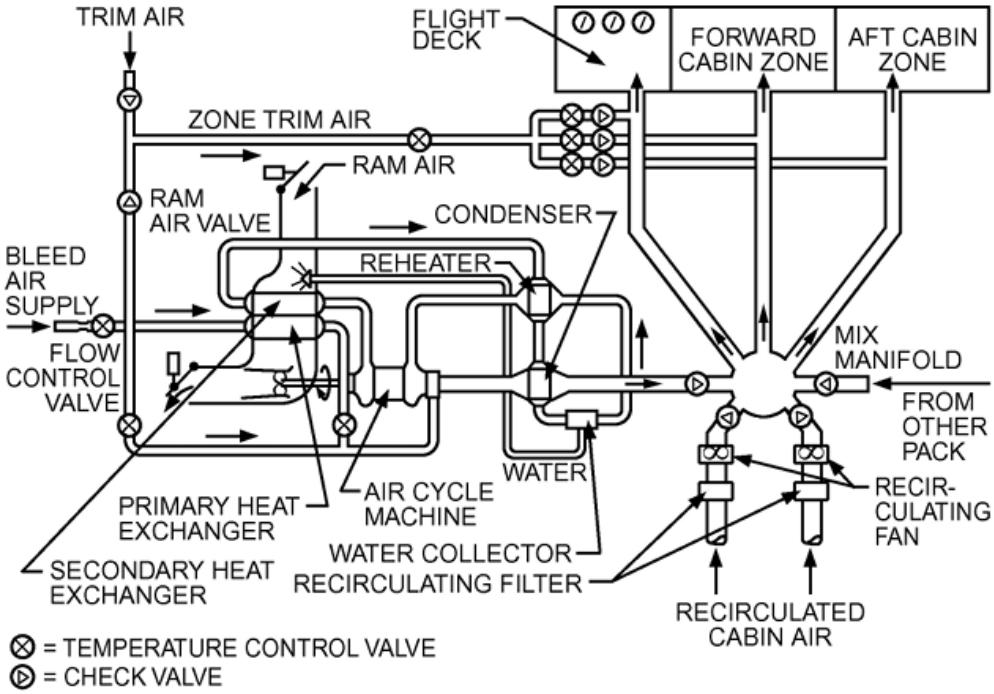

FIGURE 2-3 Schematic of a representative aircraft air-conditioning pack and cabin air-distribution system.
NOTE: Figure illustrates air-cycle cooling, moisture removal, recirculation, mixing, and zonal temperature control.
SOURCE: ©ASHRAE www.ashrae.org (2019).

After conditioning, the air from the air conditioning packs is combined with recirculated cabin air that has been drawn through high-efficiency particulate air (HEPA) filters in the mix manifold (steps 3 and 4 in Figure 2-1). HEPA filters can also include carbon-based adsorption layers, which are standard on some aircraft models (e.g., Boeing 787) and available as options on others (Zhang et al., 2022). The mixed air is then supplied to the cabin through overhead nozzles that run the length of the cabin, typically on both sides. Larger aircraft may have two air distribution nozzles per side to ensure even airflow (step 5 in Figure 2-1).

Before entering the cabin, the supply air can be heated further with trim air—additional bleed air added downstream of the air conditioning packs. This allows for independent, fine temperature control in each cabin zone, providing for lower-density seating zones that require warmer supply air for passenger comfort.

Newer aircraft are equipped with smart ECS that dynamically adjust airflow to match occupant density, meeting regulatory requirements (14 CFR § 25.831(a)) and improving airplane performance during flight and hot ground operations and in high-density seating configurations.

A visualization of the aircraft air distribution system is provided in Figure 2-4. Clean supply air flows continuously into the cabin and is exhausted via return air grilles that run along both sides of the cabin, typically where the sidewalls meet the floor. Approximately half of the exhaust air is recirculated through the HEPA filters (and, if equipped, carbon filters), while the other half is expelled from the aircraft through an outflow valve located near the tail, which also helps maintain cabin pressure (step 6 in Figure 2-1).

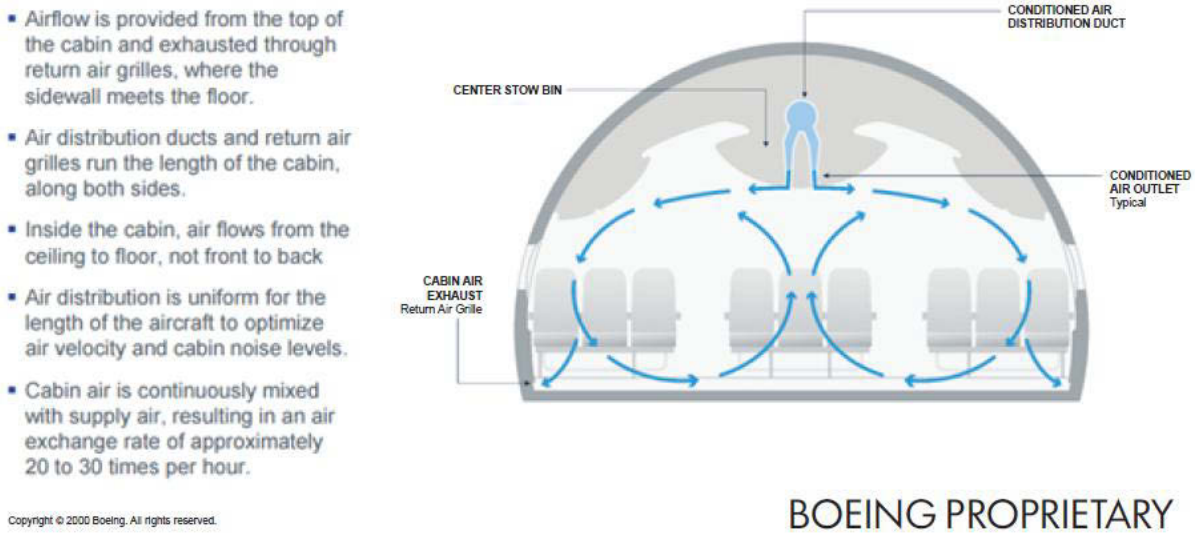

FIGURE 2-4 Schematic representation of typical cabin airflow.
NOTE: Figure shows the overhead air supply, lateral circulation within seating rows, floor-level air return for heat, and contaminant removal in the occupied zone.
SOURCE: The Boeing Company, 2020. Copyright © 2020 Boeing. All rights reserved.

Auxiliary Power Unit as an Air Supply Source for the ECS

During ground operations, aircraft require energy to power onboard systems. While the aircraft ECS can use the engine compressors for this purpose, it is more common—especially when engines are not running—for the onboard auxiliary power unit (APU) to be used. The APU is a small gas turbine engine, typically located in the tail cone of the aircraft. Its primary function is to provide the power necessary to start the main aircraft engines, but it can also be used to continuously supply electrical power for onboard systems (such as avionics) and deliver high-pressure, high-temperature air to the air conditioning packs to meet heating and cooling needs while the aircraft is on the ground (NRC, 2002). An aircraft's pilot or qualified maintenance personnel can activate the APU.

Cabin Temperature Control Zones

Cabin temperature is managed through multiple temperature control zones, which can be adjusted by the pilot using an overhead panel dial in the flight deck (see Figure 2-5 for an example). These controls typically provide qualitative guidance—such as a dial ranging from "cold" (or "C") to warm (or "W")—rather than specifying exact temperatures. The typical selectable range for cabin temperature is approximately 18.3°C to 29.4°C (65–85°F) (ASHRAE, 2023). Importantly, it is not possible to similarly manage humidity levels independently in an aircraft.

FIGURE 2-5 Representative flight-deck interfaces from Boeing 737 aircraft showing flight crew controls for cabin and flight-deck temperature setpoints used to manage thermal comfort.
NOTE: C = cold; W = warm.
SOURCE: Copyright © 2026 Boeing. All rights reserved.

Commercial aircraft are divided into multiple temperature control zones. There is a separate zone for the flight deck and typically two to eight temperature zones in the passenger cabin, depending on the aircraft model. Cargo bays and crew rest areas may also be configured as a separate temperature control zone (ASHRAE, 2023). Larger aircraft generally have more zones; for example, the Airbus A380 and Boeing 777X can each have up to 16 temperature control zones (OAT, 2023). During flight, the pilot typically sets the cabin temperature dial to Auto for cabin comfort, but further adjustments can be made as needed. Some aircraft are equipped with additional temperature controls at the flight attendant station, allowing flight attendants to adjust settings for specific zones as needed (A4A, 2026). On some aircraft, personal airflow outlets, commonly known as air gaspers, allow passengers additional thermal control. These small air outlet nozzles, located above each seat, supply high-velocity air which passengers can direct and adjust in quantity, though not in temperature. Depending on the aircraft model, the air supply for these personal airflow outlets may come directly from the air conditioning system, from recirculated air, or from the general air distribution system (NRC, 2002). Personal airflow outlets are optional features and therefore may not be available on every aircraft.

The response time for temperature changes in the cabin is relatively quick, due to the high air exchange rate and cooling capacity of modern aircraft. Typically, an aircraft achieves an outside air exchange rate of 10 to 20 air exchanges per hour, and a total air exchange rate (including HEPA-filtered recirculated air) of 20 to 30 per hour. This enables rapid cooling or heating of the cabin. As part of certification, commercial aircraft are subjected to “cold soaked” and “heat soaked” tests, in which the aircraft is placed in extremely cold (-32°C, or -25°F) or extremely hot (above 46°C, or 115°F) environments and must demonstrate the ability to reach comfortable temperatures within 30 minutes (ASHRAE, 2023).

Systems for Monitoring Cabin Temperatures

Aircraft typically have one to two temperature sensors in each temperature control zone, located in the overhead ceiling panel or upper sidewall panels. These sensors provide feedback to the air conditioning packs, which in turn adjust the supply air temperature to maintain the selected cabin zone temperature based on control panel settings in the flight deck or, if installed, at the flight attendant control panel.

Some aircraft are equipped to continuously record cabin temperature data both in flight and on the ground, allowing for later download and analysis. For example, Boeing 777 and Airbus A350 aircraft feature quick access recorder (QAR) capabilities. However, not all commercial aircraft have this functionality (A4A, 2026), and a QAR does not capture humidity data, which, as discussed in later chapters, are critical for assessing the potential health and safety impacts of cabin temperatures. Monitoring humidity levels with current aircraft equipment requires the installation of dedicated humidity sensors and the use of portable data loggers (OAT, 2023).

Battery-operated data loggers may be temporarily installed in various cabin locations to gather temperature and humidity data for purposes other than routine monitoring (e.g., research, troubleshooting). These devices allow for rapid characterization of cabin thermal conditions over multiple flights, with data available for later review and assessment (NRC, 2002). However, such installations are typically temporary and require the airline to verify that the installation meets the requirements of all applicable regulations. Prior to installation, airlines may seek to obtain a No Technical Objection letter from the aircraft manufacturer on technology for which they lack detailed data before obtaining approval from the regulator. Additionally, the data logger may need to undergo electromagnetic interference testing to ensure that it does not interfere with airplane electrical systems (such testing determines if the device emits signals that could disrupt other equipment) (FAA, 2017).

GROUND-BASED AIR CONDITIONING SYSTEMS FOR THERMAL CONTROL OF AIRCRAFT

During ground operations, thermal control of cabin temperature is essential for efficient aircraft turnaround, as it serves to support the safety and comfort of crewmembers and service personnel as well as of passengers. According to a 2010 FAA report, active heating is needed when ambient temperatures fall below 7.2°C (45°F), and active cooling is needed when ambient temperatures rise above 10°C (50°F) (FAA, 2010), reflecting the narrow range of ambient temperatures in which cabin thermal comfort can be maintained without conditioning of the air supply.

In designing an aircraft ECS, manufacturers seek to optimize fuel efficiency, weight, payload, range, and environmental performance. As a result, the ECS reflects a series of trade-offs among environmental performance, system weight, power consumption, and aircraft range and is designed to accommodate the vast majority of expected ambient operating conditions. Designing the system to meet the most extreme possible conditions would require additional capacity, which would increase weight and reduce aircraft range and overall performance. Under

normal inflight operating conditions and throughout the certified flight envelope[10] (including the vast majority of expected ambient operating conditions based upon statistical environmental conditions), the ECS meets safety requirements and typically maintains thermal comfort. However, during extreme hot-weather ground conditions, when ECS performance is inherently less effective, the availability of ground-based sources of conditioned air is important for supplementing the onboard ECS.

A variety of ground-based air conditioning systems are available to provide supplemental heating, cooling, and ventilation of aircraft when an onboard ECS cannot operate or is not in use. These include:

- **Airport centralized PCA system:** These systems supply conditioned air from a central plant to the aircraft at the gate.
- **Low-pressure ground carts and jet bridge PCA systems:** Jet bridge PCA units are located beneath the jet bridge and can be ground- or bridge-mounted (see Figure 2-6) (NASEM, 2019). Along with low-pressure portable PCA units, they provide conditioned air directly to the aircraft's air distribution system downstream of the air conditioning packs (NASEM, 2012; NRC, 2002). PCA units reduce the need for aircraft to operate their APUs (or engines) during ground operations—a preferred outcome, as APU operation consumes fuel, generates emissions, increases noise, and adds to maintenance costs while the aircraft is parked.
- **High pressure ground carts:** These units connect to the aircraft via high-pressure ground connections and deliver high-pressure, high-temperature air upstream of the aircraft's air conditioning packs (Bezold, 2021, NRC, 2002).

[10] The flight envelope is defined as the bounds within which a certain aircraft can operate, commonly depicted with a graphic representation of these bounds that shows the interrelationships of the different operational parameters (NRC, 1997).

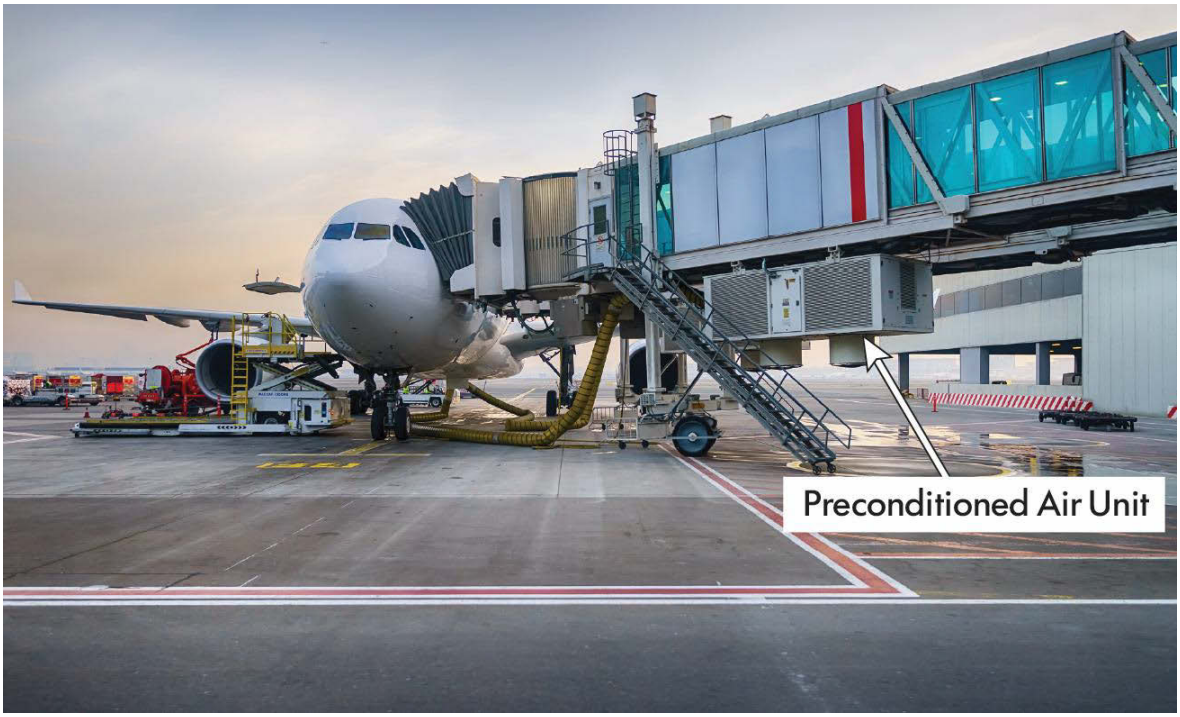

FIGURE 2-6 Preconditioned air unit attached to a jet bridge.
SOURCE: Hearshe/stock.adobe.com

Responsibility for supplying, operating, and maintaining PCA units varies depending on such factors as equipment type (e.g., mobile versus fixed) and gate ownership model (airline-owned or -leased versus shared or common gates). PCA units may be owned, operated, and maintained by airports, airlines, or their contractors (NASEM, 2012, 2019). In some cases, equipment owned by the airport might be maintained by airlines. These differing arrangements can complicate efforts to ensure consistent equipment availability, reliability and performance, particularly when PCA units are relied upon for thermal control (NASEM, 2019), as discussed later in this chapter.

CHALLENGES WITH THERMAL CONTROL ON AIRCRAFT

The following sections outline the challenges associated with maintaining optimal thermal control in aircraft, both during ground operations and in flight. This discussion begins with a high-level review of available data on thermal complaints, with a more detailed analysis provided in Chapter 5.

Frequency of Equipment Issues that Contribute to Thermal Complaints

Table 2-2 presents system failure data related to the aircraft thermal environment, extracted from reports collected by the National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS) over 35 years (1990 to February 2025) and from reports submitted to the Association of Flight Attendant's (AFA's) 2Hot2Cold app over 7 years (2018–2025). Details on the committee's data collection methods can be found in Appendix A.

The NASA ASRS data reviewed by the committee include 154 reports submitted between 1990 and 2025 of issues with the aircraft thermal environment that could impact occupant health and safety; all but eight were heat related. Of the 132 reports mentioning one or more equipment contributors to cabin temperature issues, approximately 29 percent noted issues with ground-based air conditioning systems (alone or in combination with other equipment issues), while more than half involved the ECS. Among ECS system failures, about 87 percent were related to air conditioning packs, 11 percent to the bleed system, and 2 percent to other components. Analysis by flight phase shows that cabin temperature events were most common during ground operations (mentioned in 65 percent of reports). Regardless of the type of equipment issue, prevalence was highest during the summer, with fewer incidents reported in spring and fall (see Figure 2-7). Data on ECS mechanical malfunctions obtained from an analysis of reports describing cabin temperature issues from FAA's Service Difficulty Reporting System (SDRS) show a similar seasonal pattern, with malfunctions in the cabin temperature control system (trim system, cabin temperature sensors) and the cabin cooling system (air conditioning packs) reported most frequently (FAA, 2026).

In contrast, ECS issues were less commonly reported in the 2Hot2Cold dataset among those reports that mentioned a contributing equipment issue. The most frequently reported problems were with the APU—inoperable or not activated—followed by reports of multiple simultaneous equipment issues, most of which involved both the APU and PCA units. These findings underscore the importance of having an operable APU and/or PCA unit with sufficient capacity to manage cabin temperatures during ground operations, particularly on days with elevated ambient temperatures.

The difference in emphasis on pack malfunctions among the three datasets may reflect the distinct purposes of these three reporting systems. NASA ASRS is intended for reporting serious safety issues and may be more likely to capture urgent in-flight ECS malfunctions; FAA SDRS is intended to capture mechanical malfunctions, defects, and failures on aircraft and focuses on hazards rather than specific incidents; and the 2Hot2Cold app is designed to collect reports of cabin temperatures that become uncomfortably too warm or too cold. Notably, the majority of 2Hot2Cold reports—89 percent of the nearly 5,000 reports—were submitted by cabin crew (AFA, 2026). Both the ASRS and 2Hot2Cold datasets are discussed in greater detail in Chapter 5.

TABLE 2-2 Contributions of Different Equipment Issues to Thermal Complaint Data from NASA ASRS Reports (1990–2025) and 2Hot2Cold Reports (2018–2025)

Equipment System	Frequency (ASRS) N=132 [a]	Percentage of Reports Specifying One or More Equipment Issues (ASRS)	Frequency (2Hot2Cold) N=1,217 [a]	Percentage of Reports Specifying One or More Equipment Issues (2Hot2Cold)
ECS/Pack	75	56.8%	118	9.7%
APU	18	13.6	759	62.3%
PCA unit	5	3.8%	131	10.8%
Multiple [b]	34	25.8%	209	17.2%

NOTES: FAA SDRS data not presented because analysis of those data was limited to ECS mechanical issues. APU = auxiliary power unit; ECS = environmental control system; PCA = preconditioned air.

[a] N represents the number of reports for which one or more equipment issues was indicated. For NASA ASRS reports, 22 of 154 committee-identified reports did not specify a contributing equipment issue, and 3,462 of the 4,679 2Hot2Cold reports did not specify a contributing equipment issue.
[b] The majority of ASRS and 2Hot2Cold reports noting multiple equipment contributors to cabin temperature issues involved a combination of APU and PCA equipment problems.

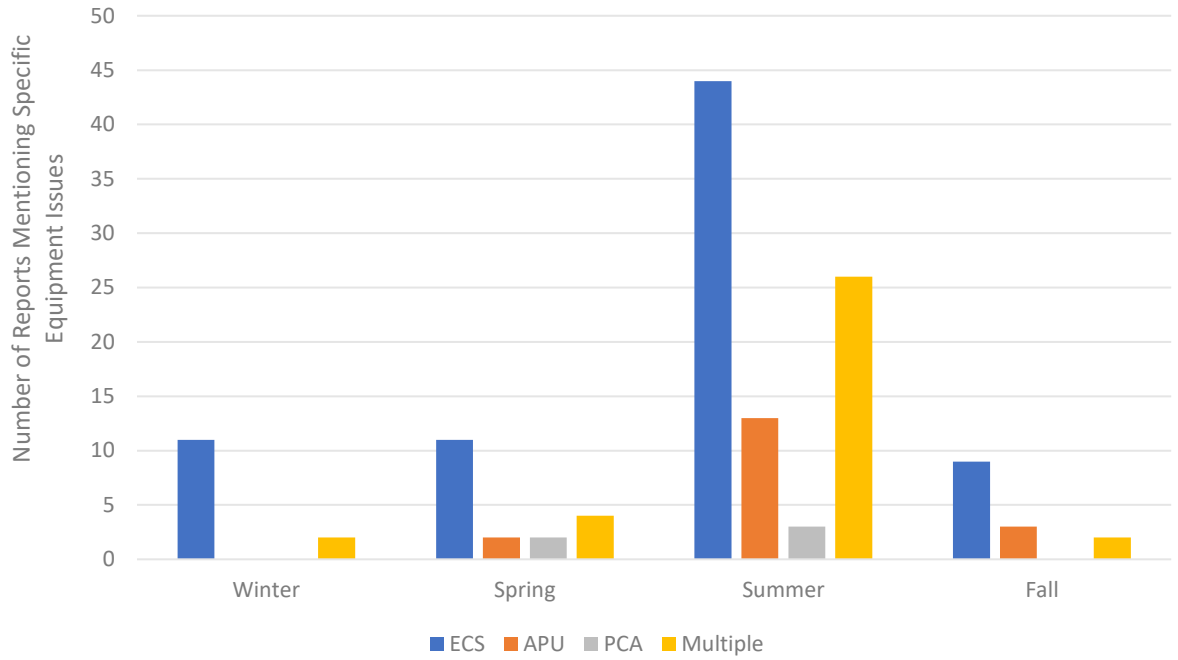

FIGURE 2-7 Frequency of equipment issues noted in NASA ASRS reports, stratified by season.
NOTES: Winter = December–February; Spring = March–May; Summer = June–August; Fall = September–November. APU = auxiliary power unit; ECS = environmental control system; PCA = preconditioned air.
SOURCE: Created with data from NASA (2025).

Challenges with Thermal Control During Flight

This section addresses the challenges that may arise with maintaining thermal control during flight. In some cases, the issues with aircraft systems described here can also impact thermal control during ground operations.

Air Conditioning Packs

Air conditioning pack issues (inoperable, deferred maintenance, or malfunction in flight) were reported in more than 50 percent of the NASA ASRS reports of cabin-temperature-related incidents for which a specific equipment issue was noted. Commercial aircraft used in Part 121 operations are equipped with a minimum of two air conditioning packs to condition the air supplied to the airplane cabin. This redundancy is a key safety feature; if one pack fails, the aircraft can continue to operate with the other. Depending on the aircraft model and the air

carrier's approved maintenance program, the FAA permits operation with a deferred[11] pack for up to 10 days (as specified in the master minimum equipment list, or MMEL);[12] if the pack is not repaired within that period, the aircraft must be removed from service. When a pack is inoperative, the remaining pack operates at a higher airflow setting, which may reduce overall cooling capacity on some models (FAA, 2023). Although simultaneous failure of both packs during flight is quite rare, several ASRS reports noted cases where aircraft were dispatched with an inoperative pack and the second pack malfunctioned in flight, resulting in an emergency that required rapid descent and landing due to a loss of cabin pressure and temperature control. Although uncommon, such scenarios underscore the risks associated with deferred maintenance of air conditioning packs, particularly during extreme ambient temperatures that may add additional workload to the remaining pack.

When an aircraft is deplaned and reboarded quickly in a hot climate, there may be insufficient time to connect PCA units or high-pressure ground carts at the gate, making it difficult to sufficiently cool the cabin. As a result, hot cabin temperatures can persist after takeoff. However, when ECS systems are functioning properly, the cabin typically cools to the setpoint in about 15 minutes or less, due to high air exchange rates and robust cooling capacity.

To ensure optimal performance and thermal control, aircraft manufacturers recommend that dedicated maintenance tasks for air conditioning packs be carried out prior to the start of the summer season (OEM, 2025). These tasks include cleaning the heat exchangers (clogging limits airflow and heat removal) and checking system components such as flow control valves and water drainage. Issues related to ECS performance of aging aircraft and maintenance programs are discussed in Box 2-1.

BOX 2-1
ECS Performance Degradation and Maintenance for Aging Aircraft

ECS performance degradation over time is an expected consequence of aircraft aging and harsh operating conditions and can result in reduced efficiency (A4A, 2026) even if the ECS remains functional (i.e., serviceable). Examples of factors that can contribute to decreased efficiency include filter clogging, leakages, and wear and tear of moving parts such as seals and bearings. Some aircraft manufacturers report taking ECS equipment degradation into account in system design, and all emphasize the importance of routine maintenance (e.g., heat exchanger cleaning, filter replacement) (OEM, 2025). As noted by one manufacturer, ECS components (with few exceptions such as filters) are generally not life-limited by design, meaning that their performance is not a function of age or flight hours. Rather, their functional lifetime is determined by their condition and the effectiveness of maintenance activities (including repair and replacement) to keep the system performing as designed (OEM, 2025). Thus, proper maintenance of the aircraft ECS is critical to ensuring adequate thermal control, particularly during extreme weather conditions.

[11] When a piece of equipment that needs repair is "deferred," this refers to deferred maintenance and means that for a specified period of time the aircraft can be operated without repairing the equipment.

[12] MMEL is an FAA-approved document that specifies which equipment can be inoperative for a flight, allowing operational flexibility while maintaining airworthiness (FAA, 2023). For example, if an aircraft's air conditioning pack fails, the aircraft MMEL allows for 10 days to repair the failed pack starting the day after failure. An FAA-approved air carrier's MEL is derived from the MMEL. Airlines track use maintenance tracking systems, maintenance control oversight, and daily MEL status reports to track days remaining (Pilot Institute, 2025).

Aircraft manufacturers provide recommendations on routine maintenance tasks to operators via an aircraft maintenance manual and may also issue service letters or bulletins. Airlines have dedicated departments that track airplane inflight and ground performance to ensure proper maintenance and airplane operation. These departments keep detailed records of any issues, including any maintenance conducted or needed. Additionally, many aircraft models have built in monitoring and diagnostic systems that monitor parameters of ECS performance in real time, alerting crew of possible degraded operational modes (e.g., blocked valves, sensor failures) that can inform troubleshooting and maintenance activities (OEM, 2025).

As the primary regulator for aviation safety, FAA establishes requirements for a continuous airworthiness maintenance program (FAA, 2016). A key element of such a program is the establishment of a continuing analysis and surveillance system (CASS), which air carriers are required to do under Title 14 Part 121, § 121.373. Air carriers use the CASS to monitor, analyze, and optimize the performance and effectiveness of their aircraft maintenance and inspection programs (FAA, 2016). A CASS can be used to identify trends, recurring defects, and systemic weaknesses and to guide the identification and implementation of corrective actions. A reliability program that has been accepted and authorized for use by FAA can fulfill some CASS requirements related to operational data collection, analysis, and corrective action (FAA, 2018).

Cabin Air Distribution

Optimizing air distribution in an aircraft cabin to provide a comfortable thermal environment for both sedentary passengers and active flight attendants, who have different thermal needs, is a significant challenge for ECS engineers. Achieving air distribution patterns that deliver cooler supply air through the aisles, maintain reasonable uniformity among passengers, and minimize drafts is also an important consideration in designing the aircraft air distribution system. These considerations apply to both inflight and ground operations.

A practical challenge arises when debris, dust, and other matter are deposited into the air supply ducting. For example, over time, the yellow hoses used to provide conditioned air from the PCA unit to the aircraft (see Figure 2-6) can deteriorate and shed small pieces of plastic, which may enter the aircraft air distribution system and interfere with airflow and optimal ECS functioning (NASEM, 2019). Addressing such issues requires replacing the PCA hose and cleaning the air distribution system to remove foreign debris and other accumulated matter. To minimize this risk, airlines may install metal screens on the airplane ground service intake. Periodic inspection and cleaning of the air distribution system, as needed, help identify issues (e.g., clogging, leakages) and ensure proper performance (OEM, 2025).

Simple operational measures can also improve ECS performance. For example, closing window shades and limiting the use of cabin electrical systems (such as IFE and galleys) can significantly reduce the heat load in the cabin. Additionally, the use of personal air outlets (on equipped aircraft) is encouraged to increase air movement in the vicinity of passengers and cabin crew, which enhances thermal comfort through localized cooling (OEM, 2025).

Cabin Air Recirculation

As described earlier in this chapter, the rates of cabin cooling and heating are also influenced by the aircraft's air recirculation systems. Recirculation fans contribute to thermal control in two ways: one, by increasing the effective air supply through the combination of

filtered recirculated air with conditioned pack air and, two, by promoting mixing within the cabin. However, as specified in the MMEL, aircraft are permitted to operate for a limited period—typically up to 10 days—with a recirculation fan inoperative, provided that certain conditions are met, such as proper functioning of the air-conditioning packs. Manufacturers recommend that replacement of recirculation fans be expedited when operating in high or low temperatures in order to ensure optimal thermal control and passenger comfort (OEM, 2025).

Challenges with Thermal Control During Ground Operations

This section discusses challenges unique to thermal control in aircraft during ground operations. As noted previously, issues with air conditioning packs, cabin air distribution, and recirculation systems can also impact thermal control on the ground, but these topics are not repeated here.

Aircraft time at the gate (turnaround time) can vary widely depending on aircraft size, type, route, airline type (e.g., regional, low cost),[13] and airport. Smaller aircraft with quick turnaround times may be parked at the gate for as little as 20 minutes, while larger passenger aircraft can remain parked at the gate for several hours. Unexpected delays can further extend turnaround times (NASEM, 2019; Wignall, 2022).

During ground operations, the ramp area[14] is often crowded with various types of ground support equipment and vehicles, including PCA units, baggage tugs, catering vehicles, fueling trucks, lavatory-servicing equipment, and deicing vehicles (NASEM, 2019). This high density of activity can contribute to ramp-traffic congestion, which is an important consideration for effective use of ground-based air conditioning systems.

The majority of hot cabin complaints occur while aircraft are on the ground (parked at the gate or on the taxiway), particularly during summer months (see Figure B-5 in Appendix B for supporting data). While on the ground, aircraft may become heat- or cold-soaked, further complicating thermal control. To provide a comfortable cabin temperature before boarding, preconditioning the aircraft (cooling or heating of the cabin) is recommended by manufacturers and airlines (A4A, 2026; OEM, 2025). The aircraft's APU or a PCA unit can be used for this purpose. When problems with these systems are not detected right away or require additional personnel (e.g., aircraft mechanics or ground crew) to be called to the aircraft to address the issue, exposures of cabin occupants to hot or cold temperatures may be extended.

Auxiliary Power Unit

Upon landing, the APU is typically activated by pilots when ambient temperatures exceed the capabilities of the PCA system, when the PCA is not adequately sized for the specific aircraft model, or when a PCA is unavailable (e.g., due to maintenance issues or remote parking locations). Interviews with airline and airport staff conducted during a previous National

[13] Different airline types may use different infrastructure during ground operations. For example, regional and value airlines may use airstairs for boarding instead of more expensive jetways, which can have implications for access to ground-based air conditioning systems used for cabin temperature control and reliance on APUs. For example, one value airline that responded to the committee's information request indicated that the APU is used 95 percent of the time for cabin temperature during ground operations (AVA, 2025).

[14] The ramp, also called an apron, is an area of the airport where planes park and are serviced (RDU, 2014).

Academies study found that APU usage is virtually continuous during periods when ambient temperatures at the ramp exceed PCA design limits—conditions that can persist for 3 months or more in some regions (NASEM, 2019). The importance of a functioning APU for maintaining thermal comfort under these circumstances is clear. Airlines may also direct pilots to use the APU during short ground times (turnarounds), typically when the servicing interval between flights is less than a specified threshold (e.g., 30 to 45 minutes). The FAA estimates that, on average, APUs are used for about 7 minutes per airplane turn—2 minutes upon arrival at the parking position and approximatively 5 minutes prior to pushback (NASEM, 2019). However, this average encompasses all flights and does not reflect the extended usage that may be required during extreme temperature conditions.

In some cases, APU-related challenges can arise due to malfunctions. The APU is included on the aircraft's MMEL, which allows an aircraft to be operated for an FAA-approved period (up to 10 days) without a functioning APU, provided certain conditions are met. These conditions may include the requirement that the engine backup AC power system is operational and that the flight remains within 180 minutes of a suitable airport (OEM, 2025). In other situations, the APU may be fully functional but not used. Reasons for non-use include the absence of pilots to operate the APU, fuel-saving initiatives, or, in some locations, prohibitions on APU use due to noise or environmental emissions concerns. Many airports—particularly those outside the United States—have enacted policies restricting APU operations to reduce noise and emissions from the APU turbine engine (NASEM, 2019).

Engines During Low Power Setting

When an aircraft is taxiing under its own power—often using a single engine to conserve fuel—the engines operate at a low power setting. At these low settings, the engines may not provide sufficient bleed air pressure to ensure full airflow to the cabin. As a result, the cabin may not receive adequate ventilation or temperature control solely from the engines during taxi. To address this, the APU is often operated during taxi to provide the necessary airflow for cabin comfort and environmental control (Ahmed et al., 2021; Mickeviciute, 2023).

Ground-Based Air Conditioning Systems at Airports

Many airports are equipped with ground-based systems, such as PCA units, to supply conditioned ventilation air to aircraft while they are parked at a gate. However, these systems are not always available for use (Heiple, 2025; NASEM, 2019). When ground-based systems are unavailable, the aircraft must rely solely on its APU or engines to provide the required air to the airplane ECS for thermal control. Quantitative data on the relative use of APUs and each type of PCA as sources of conditioned air supply during ground operations are not available (A4A, 2026).

Even when ground-based air conditioning systems are available, they may not always be used or may not function properly. The decision to connect and use PCA units is influenced by several operational considerations, including:

- **Fuel-saving initiatives:** Airlines may prioritize reducing fuel consumption by limiting the use of the APU.
- **Aircraft turnaround times:** Short ground times may lead ground staff to perceive that there is insufficient time to connect PCA units before the next flight.
- **PCA unit availability:** Equipment may be in use elsewhere, out of service, or otherwise unavailable.

- **Staffing and training:** Limited staff capacity, competing operational priorities, or insufficient training can delay or prevent proper PCA unit hookup (NASEM, 2019).

Equipment malfunctions, often resulting from maintenance problems, mishandling, or neglect, are another common challenge (Levenson, 2024). For example, kinked (depicted in Figure 2-8) or deteriorated hoses can significantly reduce the cooling capacity of PCA units (A4A, 2026). Hoses can become damaged by being continuously dragged across pavement or run over by ground support equipment vehicles on the ramp (NASEM, 2019). The resulting tears can give rise to air leaks. Some airports have upgraded their PCA hoses to hose reels (see Figure 2-9) or hose management systems that dispense the hose in a manner designed to minimize kinking and the risk of being run over. Regular inspection and maintenance are important to ensure that PCA units are in good working order.

FIGURE 2-8 Examples of kinked hoses connecting preconditioned air units to aircraft.
SOURCE: Scorsone (2025), used with permission from Air Line Pilots Association.

FIGURE 2-9 Example of a PCA hose reel.
SOURCE: iStock.com/Fabian Gysel.

Ground crews—whether airline or airport employees or third-party contractors—are responsible for operating ground-based air conditioning systems and ensuring their proper connection to the aircraft. These crews are critical actors in maintaining effective thermal control and overall aircraft operations. In addition to physically connecting and operating the equipment, ground crews communicate with pilots and airport staff regarding the status and functionality of PCA units. However, airport and airline stakeholders report that high turnover among ground crew employees is common. The frequent turnover can result in a workforce with less overall experience and limited familiarity with the proper operation of specialized equipment. One of the most frequently cited challenges to optimal system usage is the misuse of, and subsequent damage to, PCA units by users (NASEM, 2019). Such misuse—often stemming from inadequate training or lack of experience—can lead to equipment unavailability and operational disruptions.

Long delays in obtaining spare parts—whether due to low inventory or the discontinuation of component production—can contribute to system unavailability and hinder the use of PCA units. This issue is particularly pronounced at airports with aging PCA units and ground power equipment, where sourcing compatible parts may be especially challenging (NASEM, 2019).

A study from the Airport Cooperative Research Program of the National Academies Transportation Research Board identified both challenges and opportunities for improvements in the use of PCA units during ground operations. One suggested solution for addressing PCA unit usage challenges was the development and implementation of a real-time monitoring system to track the operational status of the gate equipment—including whether equipment is actively in use, faulty, undergoing maintenance, or idle. Such a system would provide valuable, actionable information to airport and airline operators, enabling more effective system optimization and improved management of the cabin thermal environment (NASEM, 2019).

Even when PCA units are available and functional, there may be inherent limitations in their cooling capacity, which can affect their ability to deliver the necessary volume of airflow at the required temperature. These limitations are often exacerbated on larger aircraft with higher passenger densities and during periods of hot and humid weather. One of the more frequently reported challenges to effective PCA unit usage—according to both airport and airline staff—occurs when ambient temperatures exceed the design standards of the PCA system (NASEM, 2019). In such cases, the PCA unit may be unable to sufficiently condition the aircraft cabin, whether the outside air is too hot or too cold for the system's capabilities. This underscores the importance of designing, sizing, and maintaining PCA units to accommodate typical climatic conditions (NASEM, 2019), taking into consideration changing temperature norms and the frequencies of extreme temperature events.

Specifications for PCA units are available through industry organizations (e.g., the International Air Transport Association's Air Handling Manual 974) and can inform both the design of equipment as well as requirements for procurement purposes. The provision by aircraft manufacturers of detailed specifications for PCA unit sizing for a given aircraft model—for example, through airport planning manuals (see, for instance, Boeing, 2024)—can also help airports and airlines procure PCA units that meet thermal control needs during ground operations.

SAE's Aircraft Ground Support Equipment committee is actively investigating potential improvements to PCA procedures and performance during ground operations. Its current efforts include the development of aircraft recommended practices documentation (ARP6986) that will address minimum performance requirements and design parameters for PCA units to guide PCA

manufacturers, the International Air Transport Association, and airline operators. Although this committee was unable to review the draft standard, the SAE website reports that it will cover performance and maintenance requirements for PCA filtration and hose assemblies and digital communication between PCA units and the aircraft cabin (SAE, 2026). Additionally, ARP6986 will address the interface installation requirements for a sensor unit that can be installed on aircraft to measure temperature, relative humidity, and other relevant parameters and provide real-time feedback to PCA units.

CONCLUDING REMARKS

In summary, this chapter has outlined the key factors influencing thermal control in the aircraft cabin both during ground operations and in flight, described the governing ECS design requirements and standards, detailed the configuration and operation of ECS components relevant to thermal management, and examined the role of ground-based air conditioning systems in maintaining cabin conditions during ground operations. The chapter also reviewed the primary challenges associated with temperature control across operational phases and highlighted airline and airport practices that promote effective thermal regulation. These considerations provide the foundation for the following conclusions:

Conclusion 2-1: In the vast majority of circumstances, aircraft ECS, as currently designed, can maintain comfortable cabin temperature both in flight and during ground operations when the ECS and APU are fully operational and used appropriately. During periods of extreme ambient temperatures, maintaining comfortable cabin temperatures during ground operations may require temporary operational adjustments, such as preconditioning the cabin, turning off IFE systems, and closing window shades.

Conclusion 2-2: The selection of conditioned air supply during ground operations is influenced by such factors as equipment availability, aircraft ground time, ambient conditions, and local constraints. Reliance on APUs and high-pressure ground air carts is generally less desirable than the use of PCA units because of higher fuel consumption, noise, maintenance impacts, and, in some settings, regulatory limitations. This underscores the importance of adequate PCA sizing for both airflow and cooling capacity as well as of the reliability and proper use of PCA when employed for thermal control.

Conclusion 2-3: Thermal issues may arise in flight when an ECS system component (e.g., air condition pack, bleed system) fails and the aircraft is dispatched in accordance with the air carrier's MEL. On the ground, cold or hot cabin temperatures can also occur when the APU is inoperative or not operated, either due to the absence of authorized operators or to restrictive airport rules that prevent its use. Additionally, when an aircraft is relying on a PCA unit, factors such as insufficient heating or cooling capacity, equipment outages, damaged hoses, or improper hookup can all contribute to inadequate cabin heating or cooling. Operational best practices can help address these common contributors to cabin temperature issues.

Conclusion 2-4: Allowances to operate aircraft with an inoperative APU or air conditioning pack in accordance with an air carrier's MEL are commonly described in

safety and complaint reports as contributing to challenges with hot or cold aircraft cabins, particularly during periods of extreme ambient temperatures.

Conclusion 2-5: Across both ground and in-flight phases, challenges related to excessively hot or cold cabin temperatures often reflect not a single failure, but a combination of environmental conditions, equipment limitations, and operational practices. Understanding these interacting factors is essential for identifying opportunities to prevent temperature-related health and safety impacts and for informing strategies to improve thermal management in aircraft cabins.

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3
Physiological, Cognitive, and Behavioral Effects Related to Thermal Exposure

This chapter reviews the potential physiological, cognitive, and behavioral effects of cabin air temperature on both passengers and flight attendants and discusses the factors that may modify these effects. Here, thermal exposure is defined as the cabin air temperature experienced during three primary phases of a flight: while an aircraft is parked at the gate, while operating under its own power such as when it is taxiing or parked away from the gate, and while in the air. In each of these scenarios, it should be acknowledged that passengers and flight attendants often face additional stressors, such as overcrowding, travel-related stress, sleep deprivation, and hunger. In addition to these considerations, flight attendant work includes stressful conditions such as schedule irregularity, continuously changing crewmember composition and dynamics, time zone changes, a confined work environment (the aircraft), elevated altitudes, turbulence, and noise (NRC, 2002; Ross, 2008). Flight attendants also must continually meet passenger needs, and they increasingly deal with unruly passenger behavior (FAA, n.d.; NASEM, 2025). Flight attendants often experience fatigue as a result of these conditions (see Box 3-1). This chapter focuses on the primary impacts of hot or cold cabin air temperatures on physiological, cognitive, and behavioral responses that influence health and safety. Where relevant, the chapter distinguishes between effects on passengers and on flight attendants.

The effects of hot or cold cabin air temperatures on physiological, cognitive, and behavioral responses are likely to differ between passengers and flight attendants. Passengers are generally sedentary and may be able to adjust their clothing for thermal comfort, depending on how they dressed for travel. Additionally, the passenger population is more heterogenous, likely with a wider range of underlying chronic diseases or disabilities—factors that can further modify the health and safety impacts of thermal exposures in the aircraft cabin. In contrast, flight attendants are required to perform low to moderate physical exertion while wearing a standardized uniform, limiting their ability to adapt to temperature change.

The risks associated with thermal exposure do not occur only at specific threshold temperatures; rather, they exist on a continuum. Personal and situational risk factors can worsen or alleviate the health and safety impacts of thermal exposures. These modifying factors—including age, health status, activity level, and clothing—are discussed throughout this chapter. Finally, it is worth emphasizing that the scientific evidence base specific to the health and safety effects of aircraft cabin temperatures is limited (see Chapter 5). While there is little reason to believe that the physiological effects of hot and cold cabin air temperatures are fundamentally different in aircraft than in other environments, the cognitive and behavioral responses may be amplified due to the elevated baseline stress levels commonly experienced in the enclosed, high-stress setting of air travel.

BOX 3-1

Flight Attendant Fatigue as an Aviation Safety Issue

Fatigue is a significant symptom of heat stress, yet it is challenging to measure and is defined in various ways. The Federal Aviation Administration (FAA) describes fatigue as "a condition characterized by increased discomfort with lessened capacity for work, reduced efficiency of accomplishment, loss of power or capacity to respond to stimulation, and is usually accompanied by a feeling of weariness and tiredness" (FAA, 2020). Fatigue reflects a decline in performance with continued exposure. Decreased cognitive capacity and increased variability in performance as a function of time on task are recognized characteristics of fatigue (FAA, 2010). In the scientific literature, fatigue has been defined as a psychophysiological condition characterized by a decreased motor or cognitive performance or an increased perception of effort—a multidimensional phenomenon in which temperature is acknowledged to play a role (Behrens et al., 2023).

In a questionnaire study of 9,180 flight attendants, 84 percent of respondents said they experienced fatigue while on duty (Avers et al., 2009). Among those who experienced fatigue, 60 percent reported that fatigue impacted their ability to respond to passenger needs, including both service- and safety-related tasks. Furthermore, 36 percent reported that their cabin safety performance (e.g., arming/disarming doors, verifying fastened seatbelts) was impacted, 34 percent noted reduced vigilance regarding cabin security, and 14 percent stated that preflight safety briefings were affected (Avers et al., 2009). High cabin temperatures were identified as a contributing factor to fatigue in this study. However, since fatigue can result from a variety of causes, the extent to which thermal exposures directly contributed to these reports remains unclear.

Given its impact on the performance of safety-critical duties by flight attendants, fatigue is recognized as an important aviation safety issue. FAA regulations described in 14 CFR § 121.467 address flight attendant duty period limitations and rest requirements, the intent of which is to minimize fatigue.

EFFECTS RELATED TO HEAT

Heat exposure can produce a range of physiological, cognitive, and behavioral effects, all of which may impact the health and safety of aircraft cabin occupants, both passengers and flight attendants. While these effects are described separately below, it is important to recognize that they often act in concert—physiological strain can influence cognitive performance and behavior, which in turn may affect safety outcomes. Numerous studies across diverse occupational settings have demonstrated that exposure to hot environments increases the risk of occupational injury as well as of unsafe work behavior (Ramsey et al.,1983; Spector et al., 2019; Varghese et al., 2018). This elevated risk is attributed to a combination of factors, including impaired concentration, reduced psychomotor performance, increased sweating and discomfort, heightened fatigue, diminished alertness, and altered behavior (Dillender, 2019; Park et al., 2021). These findings are highly relevant to the aircraft cabin environment, where both passengers and flight attendants may be exposed to elevated temperatures, particularly during ground operations.

A review of available data—including flight attendant complaints and incident reports (see Chapter 5)—shows that the majority of temperature-related complaints and safety issues arise from hot, rather than cold, cabin conditions. These incidents are especially prevalent when the aircraft is on the ground, such as when parked at the gate or during ramp operations. This pattern underscores both the importance of hot temperatures as a contributor to health and safety risks in the aircraft environment and the fact that ground operations represent a period of particular concern for thermal exposures.

Physiological Effects

Heat exposure contributes to heat stress, defined as the total heat load experienced by the body (Lim et al., 2020). This total heat load is determined by a combination of environmental conditions (temperature and humidity), clothing insulation, and the rate of internal (metabolic) heat production (Cramer et al., 2022). Notably, flight attendants—due to their active duties—typically have higher metabolic heat production than passengers, who are mostly sedentary. Elevated levels of heat stress increase the likelihood of developing heat strain, which is the body's physiological response to excessive heat load. Heat strain is characterized by elevations in core (internal) temperature (hyperthermia) and the activation of physiological mechanisms to maintain heat balance. It is the development of heat strain—not just heat stress—that underlies the potential health and safety impacts of heat exposure.

Heat strain may lead to a heat-related illness, which can range from mild clinical symptoms to severe, life-threatening conditions, such as heat stroke. Early signs and symptoms of heat strain include muscle weakness, dizziness, headaches, nausea, rapid breathing, and muscle cramps. These clinical manifestations result from physiological disturbances such as fluid and electrolyte imbalance, cardiovascular strain, and central nervous system activation as the body attempts to maintain heat balance under excessive thermal load. If heat strain is prolonged or sufficiently intense, it can progress to heat exhaustion, a severe but not immediately life-threatening condition characterized by elevated core temperature (typically less than 40ºC [104ºF]) and the inability of the cardiovascular system to adequately supply blood flow to vital organs (Casa et al., 2015; Cramer et al., 2022). Heat exhaustion may further progress to heat injury, which is defined as heat exhaustion with evidence of organ dysfunction and injury (Cramer et al., 2022). In the most severe circumstances, heat strain can lead to heat stroke, a life-threatening emergency that can be fatal if not recognized and treated promptly. Heat stroke is characterized by core temperature exceeding 40.5ºC (104.9ºF) and central nervous system dysfunction (such as confusion, seizures, or loss of consciousness) (Bouchama et al., 2022; Casa et al., 2015).

Under heat stress, the body activates physiological cooling mechanisms to prevent dangerous rises in core temperature. The primary cooling responses are:

- Cutaneous vasodilation: This increases blood flow to the skin, enhancing convective heat exchange with the environment.
- Sweating and evaporation: The evaporation of sweat is the main avenue for dissipating excess body heat.

Activation of these thermoregulatory responses leads to cardiovascular changes, including elevated heart rate, increased cardiac output, and altered blood volume distribution (Desai et al., 2023). These changes can challenge blood pressure regulation, even in healthy adults, and may manifest as dizziness or an increased likelihood of syncope (fainting) (Schlader

et al., 2016). Collectively, this physiological milieu increases the workload of the heart, thereby raising the risk of cardiovascular morbidity and mortality and aggravating existing chronic cardiovascular conditions (Desai et al., 2023). Importantly, cardiovascular strain (elevated heart rate and workload) can occur at lower levels of heat strain, before core temperatures reach thresholds associated with heat exhaustion, heat injury, or heat stroke (Cottle et al., 2023). Prolonged sweating without adequate fluid intake leads to dehydration—a state of reduced body water and blood volume—which further exacerbates cardiovascular strain (Ebi et al., 2021). In the aircraft environment, limited fluid intake (due to flight duration, access, or personal choices) can increase the risk of dehydration, even independent of heat stress, and may worsen the effects of heat exposure (Hashiguchi et al., 2013; Zubac et al., 2020). Excessive alcohol intake can exacerbate fluid loss under heat stress although moderate alcohol consumption does not meaningfully alter hydration (Morris et al., 2024).

Finally, even in the absence of heat illness, heat strain can lead to physiological fatigue (e.g., reduction in physical performance) (CDC, 2024). This fatigue results from cardiovascular strain and changes in both central and peripheral nervous system function (Chen et al., 2003; Wälde et al., 2024).

Cognitive Effects

Heat stress is known to increase perceptions of fatigue (Appukutti and Sharma, 2022; M. L. Chen et al., 2003; NIH, n.d.), which is an important consideration in the aircraft cabin environment (see Box 3-1). Beyond fatigue, heat stress can impair a range of cognitive processes including processing speed, memory, decision making, and concentration (NIH, n.d.). These impairments can diminish the ability of flight attendants to perform safety-critical and routine activities. The impact of heat stress on cognitive abilities and activity performance is likely to differ between passengers and flight attendants due to differences in their roles and activities.

For example, heat stress may impair the ability of flight attendants to efficiently recall safety routines or make timely decisions regarding passenger safety during emergencies such as extreme turbulence. Heat stress can also reduce concentration, distracting flight attendants from their primary duties such as monitoring the cabin, assisting passengers, or responding to urgent situations.

For passengers, heat stress may diminish the ability to follow or respond quickly to safety instructions or operational announcements, such as deplaning procedures, connecting gate information, or missed connection instructions. This, in turn, can increase the workload for flight attendants, who may need to provide additional guidance or assistance. However, the extent to which heat stress impacts cognition and subsequent performance in flight attendants versus passengers is difficult to estimate, given the limited available data specific to the aircraft cabin environment.

Although the findings are somewhat mixed (Schlader et al., 2015), multiple studies have identified associations between elevated ambient temperatures and cognitive impairment (Byun et al., 2024; Dupont et al., 2023; Krebs, 2024; Yin et al., 2024). Documented impairments include reduced accuracy in understanding or interpreting information, impaired performance on visual perception tasks, slower reaction times, difficulties concentrating, diminished processing speed, and overall cognitive decline (Chen et al., 2020; Dupont et al., 2023; Hancock et al., 2007; Yin et al., 2024). The degree of cognitive impact varies depending on such factors as the nature of the task, activity level, exposure duration, and the severity of the temperature.

Prolonged or more extreme heat exposures further exacerbate cognitive decline (Chen et al., 2020; Hancock et al., 2007; Yin et al., 2024).

Behavioral Effects

Heat stress has been shown to negatively affect emotional states (Li et al., 2021; Meidenbauer et al., 2024), leading to increased stress (Amasuomo and Amasuomo, 2016), anxiety, irritability, and anger (Fang et al., 2023; Li et al., 2021; Meidenbauer et al., 2024). Notably, these negative effects on mood occur even before any measurable increase in core body temperature (Gaoua et al., 2012; Meidenbauer et al., 2024). Heat stress–related increases in irritability and anger may contribute to aggressive behaviors and interpersonal conflict (Anderson, 2001; Choi et al., 2024). In some cases, heat-related aggression can arise from altered social perceptions, as individuals experiencing heat stress are more likely to perceive hostility from others (Anderson, 2001). Elevated temperatures can also amplify risky and impulsive behaviors, which may be further exacerbated by alcohol consumption. For example, research has linked hotter ambient temperatures to

- increased alcohol use (MacLean et al., 2024);
- higher rates of drug overdoses (Roy et al., 2022);
- more emergency department visits for self-harm behaviors (Nori-Sarma et al., 2022); and
- increased incidence of accidental injuries (Otte im Kampe et al., 2016).

These behavioral effects are particularly relevant in the aircraft cabin environment, where stress, close quarters, and a limited ability to escape discomfort may heighten the risk of disruptive or unsafe behaviors.

The effects of heat stress on impulsivity, aggression, and negative emotions may manifest as disruptive passenger behavior in the aircraft cabin (EASA, 2025; FAA, 2022). Both thermal discomfort and the negative emotional response it provokes are amplified when individuals are already in a high-stress situation (FAA, 2022), such as during air travel, which may increase the likelihood of disruptive or aggressive incidents among passengers already experiencing significant stress or anxiety. While there is no direct research demonstrating that travel-related stress or flight anxiety specifically worsens behavioral responses to heat stress in the aircraft cabin, this remains a plausible contributing factor. Additionally, prior work on heat stress shows that its effects on aggressive behaviors are intensified in situations where escape is not possible (Bell, 1992). Although there is no direct evidence that the inability to leave the cabin increases the risk of disruptive or aggressive passenger behavior, the confined environment of an aircraft likely contributes to this risk.

In 2021 the FAA sponsored a working group to recommend the development of and/or updates and improvements to de-escalation training for flight attendants (FAA, 2022). In its review of crewmember reports from the National Aeronautics and Space Administration's Aviation Safety Reporting System, the working group identified 67 reports with clear evidence of onboard misconduct. Among these reports, "cabin temperature" was cited as a trigger of passenger misconduct in four reports (6 percent) (FAA, 2022). The extent to which thermal discomfort leads to greater adverse behavioral effects in flight attendants versus passengers is difficult to estimate, given the limited data. However, available accounts support the idea that heat stress and discomfort can provoke emotional changes with direct or indirect implications for health and safety across both groups. For example, reports submitted through the Association of Flight Attendant's 2Hot2Cold app (see Chapter 5 and Appendix A) describe how hot cabin

environments led to passengers becoming "visibly upset, hot, and crying . . . had a minor anxiety attack due to the heat" and expressing "anger about heat and wanting to deplane but were unable to" (AFA, 2025). Similarly, several reports describe flight attendants who were extremely uncomfortable and upset about their inability to control the cabin environment or meaningfully cool down the airplane. Beyond emotional distress, fatigue is noted for both passengers and flight attendants. Some flight attendants reported that heat-related fatigue made it "very hard to fly in these situations" and described "confusion, stumbling . . . could not perform clearly or quickly in an emergency event" (AFA, 2025). Thus, exposure to heat and the inability to leave the hot environment appear to emotionally impact both groups, though the effects on safety may manifest differently between them—disruptive behaviors for passengers and impaired ability to perform safety-critical duties for flight attendants.

Implications for the Aircraft Cabin Environment

In summary, hot cabin temperatures sufficient to generate complaints are notably more common than those for cold temperatures, and these hot cabin conditions are especially likely to occur when the aircraft is on the ground, such as when parked at the gate or on the ramp, rather than during flight. Because flight attendants are typically much more physically active than passengers, their metabolic rate during work is approximately 1.5 to 2 times higher, although some adjustment of pace of work may be possible as flight attendants move about the cabin. Additionally, flight attendants have limited autonomy over clothing choices due to uniform requirements, which restrict their ability to use cooling behaviors such as removing layers. As a result, for any given cabin temperature, the level of heat stress experienced is likely to be higher in flight attendants than in passengers. By extension, compared with a passenger of the same age and underlying health status, a flight attendant is more likely to experience heat strain, such as an elevation in core temperature. In contrast to passengers who have to request beverages, however, flight attendants have ready access to cool water to help mitigate heat stress.

Numerous physiological, cognitive, and behavioral effects of hot air temperatures have been identified, and the likelihood and severity of these effects increase with magnitude of heat strain and are further worsened by prolonged exposure. Examples of these effects include cardiovascular strain, dehydration, fatigue, and, in extreme cases, heat illness. Even at less severe levels of heat stress, thermal discomfort is prevalent. This is important because thermal discomfort contributes to many of the cognitive and behavioral effects of hot temperatures, which often occur prior to any physiological manifestations. Notably, these cognitive and behavioral impacts are important in their own right, as they represent direct health concerns and have implications for safety through potential impairments in attention and decision making or increases in disruptive behaviors.

EFFECTS RELATED TO COLD

Like heat exposure, cold exposure can have physiological, cognitive, and behavioral effects, all of which have the potential to impact the health and safety of aircraft cabin occupants, including both passengers and flight attendants. However, an analysis of available datasets and incident reports (see Chapter 5) indicates that complaints and adverse events related to cold are much less frequent than those related to heat. This difference is likely explained by the powerful role of clothing and behavioral adaptation in mitigating the effects of cold; passengers and flight

attendants can add layers or use blankets to maintain comfort, making it easier to alleviate the health and safety impacts of a cold cabin environment.

Cold complaints can occur both on ground and in flight (see Figure B-7 in Appendix B). Even so, at temperatures typically experienced in aircraft cabins—outside of catastrophic equipment failures or emergencies—the effects of cold are more likely to impact thermal comfort than to challenge the physiological limits of thermoregulation. Accordingly, the physiological, cognitive, and behavioral effects of cold cabin air temperatures are described briefly below. Given the lower prevalence of cold-related complaints, the level of detail provided here is somewhat less than that for hot cabin air temperatures.

Physiological Effects

Exposure to cold environments contributes to cold stress, defined as the total cold load experienced by the body. In response, the body activates heat conservation and production mechanisms including:

- Cutaneous vasoconstriction: Blood flow to the extremities (hands and feet) is reduced to protect the central organs, increasing heat conservation.
- Increased metabolic heat production: The body generates additional heat through shivering and non-shivering thermogenesis (IOM, 1996).

Even mild cold stress can cause cold discomfort due to reductions in skin temperature in the extremities, primarily as a result of vasoconstriction. This systemic vasoconstriction response to even mild cold stress increases cardiac workload by elevating blood pressure (Wilson et al., 2007). As such, individuals with pre-existing cardiac conditions who are exposed to cold environments may face higher morbidity and mortality rates due to this additional cardiovascular stress (Ikäheimo, 2018).

Extremely cold air can compromise the respiratory system, particularly in individuals with chronic respiratory diseases such as asthma and chronic obstructive pulmonary disorder. Cold, dry air can irritate the airways, triggering bronchospasms that exacerbate chronic respiratory conditions. This can lead to clinical symptoms such as shortness of breath, coughing, and wheezing (D'Amato et al., 2018; Haman et al., 2022).

In the context of a cold aircraft cabin, exposures are unlikely to cause hypothermia (a fall in core body temperature). However, even mild cold exposure, especially when prolonged, can impair manual dexterity. This impairment is primarily due to reduced skin temperatures in the fingers, hands, and forearms (Chapman et al., 2025). Decreased dexterity can reduce motor coordination and movement speed, which, when experienced by flight attendants, may adversely impact the execution of service and vital safety tasks.

Cognitive Effects

While research on the cognitive effects of cold stress is more limited than for heat stress, available studies indicate that cold exposure can increase the risk of mental and neurological conditions (Byun et al., 2024). Experimental and field studies have documented that cold exposure can lead to decreased vigilance, impaired decision making, slowed reaction times, and reduced short-term memory (Donnan et al., 2021; Haman et al., 2022; Ramsey et al., 1983; Sun et al., 2022).

In extremely cold environments, additional consequences include reduced selective attention, diminished perceived judgment response speed, and further declines in short-term

memory compared with neutral conditions (Falla et al., 2021). The extent of cognitive impairment caused by cold stress depends on individual differences, the severity of cold exposure, and its duration (Falla et al., 2021).

Experimental studies have shown that exposure to 10°C (50°F) can result in decrements in memory (complex tasks), vigilance (complex tasks), reaction time (simple tasks), and decision making (complex tasks) (Falla et al., 2021; Taylor et al., 2016). Notably, cognitive impairments may persist up to 60 minutes into the recovery period, even after many physiological parameters have returned to normal (Falla et al., 2021). Difficulty maintaining attention has also been observed at relatively mild cold air temperatures, such as at 16°C (60.8°F) (Baniassadi et al., 2025).

Overall, attention, processing speed, executive function, and memory appear to be the cognitive domains most affected by cold exposure, with the severity and duration of cold stress playing key roles in the magnitude of the effect (Falla et al., 2021). Impairments can emerge within 30 to 120 minutes of exposure and can significantly affect these domains, although reasoning appears to remain intact (Falla et al., 2021). Such impairments may translate into tangible safety risks, with acute injury rates rising under both heat and cold exposure and being more sensitive to cold than to heat (Fogleman et al., 2005). However, findings across studies have not been entirely consistent for nonhypothermic cold exposures, where contrasting results have been reported for attention and memory (Palinkas, 2001). While cold stress may impair the cognitive function of both passengers and flight attendants, the impact may be especially important for flight attendants, who are responsible for passenger safety. It should also be noted that some passengers engage in cognitively demanding activities (e.g., working or reading) while flying, and these activities may also be affected by exposure to extreme cold.

Behavioral Effects

Uncomfortable cold air temperatures can worsen emotional states, including overall mood, vigilance, and tension (Lieberman et al., 2009). The evidence for these effects is considerably stronger for situations of extreme cold—especially when combined with other stressors or complex tasks—than it is for moderate cold exposures (Palinkas, 2001; Sun et al., 2022). Even after a 40-minute recovery period, cold exposure has been shown to result in feelings of confusion, bewilderment, anger, and reduced vitality (Sun et al., 2022). There is some preliminary evidence that cold discomfort may also lead to aggression (Morris et al., 2016), but very few studies have investigated these effects. Ultimately, while exposure to uncomfortably cold environments can lead to some cognitive, affective, and behavioral responses similar to those resulting from heat, the research supporting these effects is somewhat limited compared with research on the effects of heat.

Implications for the Aircraft Cabin Environment

In summary, while the prevalence of cold exposure sufficient to generate complaints is lower than that for hot cabin air temperatures (see Chapter 5), cold exposure can still have physiological, cognitive, and behavioral effects that may impact the health and safety of both passengers and flight attendants. Behavioral and cognitive challenges associated with cold exposure are most often related to thermal discomfort, which can arise even at mild cold temperatures and is exacerbated by longer durations of exposure, such as during long-haul flights (typically 7–12 hours in duration). Cold discomfort is more likely in passengers than in flight

attendants, as the latter typically sustain higher metabolic rates while performing their duties, which helps mitigate the effects of cold. Passengers generally have some opportunity to mitigate cold exposure through adaptive behaviors such as putting on additional layers of clothing, blankets, or accessories (e.g. scarves, gloves) or redirecting personal air outlets to reduce airflow, although the ability to increase metabolic heat production is limited by the constraints of seated travel. While hypothermia is unlikely under most scenarios, skin cooling on the fingers, hands, and forearms can impair dexterity. This may present a particular challenge for flight attendants, who rely on fine motor skills to perform service and safety-related tasks. Overall, even though cold-related complaints are less frequent and generally less severe than those related to heat, the potential for cold exposure to impair comfort, cognitive function, and task performance—especially during prolonged exposure—remains an important consideration for cabin safety and operations.

FACTORS THAT AFFECT RISKS FROM THERMAL EXPOSURE

Physiological responses to thermal exposure are influenced by multiple factors, including ambient humidity, physical activity level and metabolic rate, clothing, age (lifespan), and the presence of chronic medical conditions or disabilities (Table 3-1). While acclimatization and habituation are also important modifiers of thermal response in occupational settings with sustained exposure (Box 3-2), these factors are less relevant in the aircraft environment due to the intermittent and varied nature of air travel for both passengers and flight attendants. Within the aircraft cabin, modest elevations in carbon dioxide may interact with thermal stress to influence physiological responses. While some evidence indicates a minor amplification of central nervous system responses to heat under elevated carbon dioxide conditions, these effects are limited in magnitude and do not appear to impact subjective thermal perception or behavioral outcomes (Tu et al., 2021; Yang et al., 2026). Exposure duration is a key determinant of the health and safety impacts of thermal stress (Hancock et al., 2007). The longer the exposure, the greater the potential for negative health effects and the greater their associated severity. For example, a longer yet less extreme thermal environment may result in adverse health and safety effects that are equivalent to or greater than the effects of a shorter-duration exposure to more extreme thermal environments. This is particularly important in the context of potential extreme temperatures during ground delays, as regulations[1] require that passengers be allowed to deplane after 3 hours for domestic flights or 4 hours for international flights, as discussed in Chapter 1. Physiological responses to thermal exposures also vary based on multiple environmental and individual-level factors, thereby influencing safe temperature thresholds. The following section outlines these considerations, which are summarized in Table 3-1.

[1] See 14 CFR 259.4, Contingency Plan for Lengthy Tarmac Delays.

TABLE 3-1 Environmental and Personal Factors that Influence Risks from Thermal Exposures

	Cold Air Temperatures	Hot Air Temperatures
Humidity		
High humidity	Equivocal risk	Worsened risk
Low humidity	Equivocal risk	Lowered risk
Metabolic rate		
High metabolic rate	Lowered risk	Worsened risk
Low metabolic rate	Worsened risk	Lowered risk
Clothing		
Heavier clothing	Lowered risk	Worsened risk
Lighter clothing	Worsened risk	Lowered risk
Life stage		
Infants and children	Worsened risk	Worsened risk
Pregnant individuals (and fetus)	Equivocal risk	Worsened risk
Older adults	Worsened risk	Worsened risk
Chronic medical conditions & disabilities		
Cardiovascular diseases	Worsened risk	Worsened risk
Metabolic diseases	Worsened risk	Worsened risk
Respiratory diseases	Worsened risk	Worsened risk
Kidney diseases	Equivocal risk	Worsened risk
Neurological diseases and injuries	Worsened risk	Worsened risk
Certain prescription medications	Worsened risk	Worsened risk

Box 3-2
Acclimatization and Habituation

Heat acclimatization is a physiological adaptation that improves an individual's ability to tolerate heat stress through repeated exposures, partly by enhancing sweating response (CDC, 2026). The ability to acclimatize to heat varies widely among individuals. Heat acclimatization in an individual may be achieved by 2 continuous hours of heat stress exposure for 5 consecutive days, with maximal heat acclimation occurring over approximately 14 consecutive days of heat stress exposure (Jacklitsch et al., 2016). This adaptation declines when heat exposure stops (noticeable loss after 4 days, complete loss in 3 weeks) and may be insufficient for sudden increases in heat stress (Pandolf, 1998).

Cold habituation is a physiological and perceptual adaptation to repeated cold exposure that is not sufficient to reduce core temperature (Yurkevicius et al., 2021). This adaptation results in lower levels of cold-discomfort and can be induced in as few as five cold exposures

(Leppäluoto et al., 2001); however, unlike heat acclimatization, there is no consensus on an optimal protocol or schedule for inducing cold habituation. Cold habituation often occurs naturally during winter months in colder climates (Yurkevicius et al., 2021).

While there is evidence that heat acclimatization (Casa et al., 2015) and cold habituation (Yurkevicius et al., 2021) can modify the risk of adverse health and safety outcomes during exposure to hot or cold environments, respectively, the relevance of heat acclimatization and cold habituation in the context of the air cabin environment is unclear. Given the variability in routes among flight attendants and the ability to travel between climate regions within hours, it is difficult to determine who is heat acclimatized or cold habituated. Moreover, it is inaccurate to assume heat acclimatization or cold habituation status based solely on time of year (Jacklitsch et al., 2016).

Humidity

Humidity is the amount of water vapor in the air. High-absolute-humidity environments impair heat loss by impeding the evaporation of sweat from the skin. Therefore, increasing humidity levels can worsen heat stress, aggravate heat strain, and elevate the risk of adverse health outcomes (Baldwin et al., 2023).

Even though low humidity can compromise various bodily functions, including respiratory function and skin integrity (Baldwin et al., 2023), when considering the effects of humidity on people's physiological reactions to temperature in the aircraft cabin environment, it is primarily relevant to high-temperature conditions. Low humidity during a flight may contribute to dehydration during heat exposure by enhancing the rate of sweat evaporation. In cold environments, dehydration can also occur through increased respiratory water loss, as the gradient between the saturated air in the lungs and the lower water vapor pressure of ambient air drives greater moisture loss with each breath (IOM, 1996). This mechanism may be relevant during both short-duration flights (<3 hours) and especially during long-duration exposures (>13 hours), where cumulative respiratory water loss may contribute meaningfully to dehydration risk.

Physical Activity and Clothing

Heat is a byproduct of cellular respiration, and increased physical activity generates a greater amount of internal heat in proportion to the increase in metabolism (ACGIH, 2022). The metabolic rate associated with physical activity can be categorized as ranging from rest to light, moderate, heavy, and very heavy levels. During heat exposure, higher activity levels worsen heat stress because the body produces more internal heat, increasing heat strain and related health effects. During cold exposure, increased physical activity can help lessen cold stress, as the additional metabolic heat production helps maintain core body temperature.

Clothing provides insulation and contributes to heat stress by impeding heat dissipation to the surrounding environment (ACGIH, 2022). Clothing can be adjusted to maintain comfort in moderately warm environments. However, in a controlled office environment study of 12 individuals, Lan and colleagues (2020) found that even when individuals were allowed to adjust their clothing to achieve comfort, a moderately warm environment (27ºC [80.6ºF]) still resulted in some decrease in cognitive performance. Interestingly, the subjects did not adjust to the same level of thermal neutrality, with a 0.7-point higher average thermal sensation at 27ºC [80.6ºF] than at 23ºC (73.4ºF). In cold environments, clothing and accessories (e.g. scarves, gloves) can be beneficial since the insulation reduces heat loss to the surrounding environment (Blachowicz

et al., 2024). It is important to note that flight attendants are usually required to wear company-issued uniforms and follow strict grooming protocols when on duty. For instance, some airlines require flight attendants to wear blazers, scarves, berets, or hats during boarding. Uniform pieces are often made of wrinkle-resistant synthetic fibers. Characteristics of clothing fabric, including subjective attributes such as the feel of synthetic fibers, may contribute to thermal discomfort independent of temperature. Additionally, some airlines do not allow flight attendants to wear sweaters during food and beverage service, which can be problematic when the aircraft cabin is cold.

Aircraft seats also contribute to thermal insulation, particularly for passengers who remain seated for most of a flight. The effects of physical activity levels and insulation from clothing and aircraft seats are illustrated in Chapter 4 in the context of applying standards for thermal comfort and heat stress.

Susceptibility Across Populations

Susceptibility to the negative health and safety-related effects of extreme temperatures varies widely among different populations. Certain subgroups, such as infants and young children, older adults, pregnant individuals, and people with chronic medical conditions or disabilities as well as those with specific co-exposures or medication use, may have altered thermoregulatory capacity and thus face greater risks from thermal stress in the aircraft cabin environment. This section highlights key populations that are more vulnerable to the health and safety risks posed by thermal stress on aircraft; it is not intended to be comprehensive, but rather to illustrate the range of factors that can increase risk. Of note, though there is some evidence for lessened thermal comfort in cold temperatures in women (Vellei et al., 2025), the evidence for gender differences in heat discomfort, or health risks associated with being too hot or too cold, is relatively mixed and inconclusive (Kruger and Drach, 2017). Similarly, while body size and morphology may impact general comfort in a constricted space, and there is some evidence that perceptions of thermal comfort can be modestly impacted by body size (Zhou et al., 2023), there is little to no evidence that this meaningfully translates to modifications in health risks from heat or cold. Accordingly, gender differences and effects of body size are not discussed further.

The lack of studies specifically examining physiological responses to thermal stress among susceptible groups during air travel limits the committee's ability to determine the extent to which these factors may influence safe temperature thresholds. Therefore, it is prudent that airline crewmembers receive training to identify individuals who may be at greater risk of thermal stress, be able to recognize relevant signs and symptoms, and have access to interventions that address the unique needs of these subpopulations whenever possible (discussed further in Chapter 6).

Infants and Children

Although understanding and recognition of the health-related impacts of extreme temperature exposures in children is growing, there are currently no studies that have specifically attempted to establish causal relationships between air temperatures and negative health outcomes in pediatric populations. This gap is due in part to ethical barriers, since such studies would require exposing young children, who cannot provide informed consent, to potentially harmful physiological limits. Despite the paucity of direct evidence, observational studies in

infants and children have examined associations between extreme ambient temperature environments and health. These findings can help inform pediatric considerations for this report.

Numerous studies have highlighted the vulnerability of children, particularly infants, to adverse thermal conditions at both high and low extreme temperatures (Lakhoo et al., 2022). Both Basagaña et al. (2011) and Basu and Ostro (2008) investigated the association between extreme heat exposure and infant mortality, finding an increased risk of mortality with higher temperatures. These findings have been reinforced by case-crossover studies conducted during heatwaves in various geographic settings, which have consistently demonstrated elevated risks for infants and young children (Basu et al., 2015; Fouillet et al., 2006; Schinasi et al., 2020; Son et al., 2017). Temperature-related mortality risks vary considerably with age (Lakhoo et al., 2022). Infants are at the greatest risk of mortality from cold exposures, while for heat exposures mortality risk peaks in children aged 1–4 years old (Silveira et al., 2025). Beyond mortality, exposure to high temperatures is also associated with increased all-cause morbidity for infants and neonates (Lakhoo et al., 2022). These findings underscore the critical need for increased attention to extreme thermal exposures and the unique risks they pose for pediatric populations.

Symptoms of heat or cold stress in pediatric populations often present differently than in adults, and this is further complicated by the fact that children are inherently reliant on their caretakers to identify, report, and address these signs and symptoms (van de Kamp and Daanen, 2025). Diagnostic complexity is increased by the nonspecific nature of symptoms related to temperature exposures, which may overlap with a variety of other stressors commonly encountered during air travel, such as lack of sleep, ear pressure, concurrent illness, family stress, or the unfamiliar environment of flying.

Infants and children under 4 years of age are uniquely vulnerable to extreme ambient temperatures due to the immaturity of their thermoregulatory systems, which limits their ability to effectively regulate body temperature. Several other factors contribute to this vulnerability:

- Larger body surface area relative to body mass: This increases heat exchange with the environment, making infants and young children more susceptible to both heat gain and heat loss, with this effect being most pronounced in infants.
- Higher thresholds for sweating and lower sweat rates: Young children often have a reduced ability to dissipate heat through sweating, which is the primary mechanism for cooling the body.
- Comparatively higher metabolic rates: This leads to greater internal heat production for a given level of activity or exposure.
- Immature autonomic and cardiopulmonary regulation: Infants and young children have less mature heart rate and thermoregulatory responses to temperature stress. Cold exposure may precipitate bradycardia, whereas heat stress more commonly results in tachycardia. For infants especially, cardiac output is heavily dependent on heart rate because stroke volume is relatively constrained; thus, temperature-related cardiovascular stress in this group may more quickly overwhelm compensatory mechanisms and lead to decompensation (Saikia and Mahanta, 2019).

These physiological characteristics place infants and young children at heightened risk for heat strain under the same environmental conditions that might be tolerated by older children or adults (van de Kamp and Daanen, 2025). Among this heterogenous population, infants represent the highest-risk subgroup because of their limited physiological reserves and the potential for increased risk related to prematurity or other underlying conditions. This risk of heat strain may

be further exacerbated in infants and children under 2 years old who sit in an adult's lap instead of their own seat for the duration of a flight—something the FAA permits for this age range—due to conductive heat transfer between the child and the caregiver. Conversely, this process may support thermal stability in cooler environments.

Heat illness–related symptoms in infants and children may present as changes in sleep patterns, poor feeding, lethargy, skin changes (such as decreased skin turgor or flushing), tachypnea, reduced tear production, or decreased urine output as reflected by fewer wet diapers (Berger et al. 2023; Xu et al. 2012). In addition, extreme heat has been associated with an increased prevalence of ear infections, electrolyte disturbances, gastrointestinal illness, and respiratory symptoms (particularly in children with asthma) (Basu et al., 2012; Bernstein et al., 2022; Lakhoo et al., 2022; Sheffield et al., 2018; Soneja et al., 2016; Uibel et al., 2022). While the cognitive impact of extreme temperature exposures in younger age groups is more difficult to characterize, studies in older children (10–18 years) have demonstrated reduced concentration and slower cognitive processing in extreme heat conditions (Park, 2022; Wargocki et al., 2019).

In cold environments, the larger relative body surface area of infants and young children exacerbates heat loss, increasing the child's vulnerability to cold stress (van de Kamp and Daanen, 2025). Health risks associated with cold temperatures are particularly significant for newborns and infants, who are at increased risk of hypothermia even under moderate cold exposure (Dang et al., 2023; Lei, 2023). The effects of cold exposure in children may present with symptoms similar to heat stress, including fussiness, lethargy, changes in skin color, and poor feeding (Schimelpfenig and Jacobsen, 2022). Hypothermia also increases the risk of infection, respiratory distress, and metabolic disturbances such as hypoglycemia (Lei, 2023).

Pregnant Individuals

Pregnant individuals present unique considerations when exposed to extreme ambient temperatures. Pregnancy induces several protective physiological adaptations to help mitigate the negative effects of heat exposure, including a lower core temperature, increased plasma volume, and a lower threshold for sweating to enhance heat dissipation (Samuels et al., 2022). But while the ability of pregnant individuals to thermoregulate during heat exposure generally remains intact (Smallcombe et al., 2021), the physiological adaptations can be overwhelmed under certain conditions, potentially posing health risks to both the pregnant individual and the developing fetus (Meltzer et al., 2024).

Numerous studies have demonstrated that high ambient temperatures are associated with negative maternal and fetal outcomes, including, but not limited to, stillbirth, low birthweight, pre-eclampsia, and gestational diabetes (Chersich et al., 2020; Lakhoo et al., 2025; Yang et al., 2022). Animal studies have further shown that extreme heat conditions can decrease uterine–placental blood flow, which is particularly concerning for the developing fetus, as fetal oxygen and nutrient supply is entirely dependent on maternal circulation (Cowell et al., 2023).

Studies examining the effects of low ambient temperatures and maternal–fetal health outcomes have found an increased risk of pre-term birth, low birthweight, and stillbirth (Basagaña et al., 2011; Ruan et al., 2023). These adverse outcomes are more pronounced at the extreme ends of the temperature spectrum and when exposures occur during the third trimester. However, the overall risk of pregnancy complications appears to be greater with extreme heat than with extreme cold (Basagaña et al., 2011; Ruan et al., 2023).

Older Adults

As adults age, physiological changes that reduce their bodies' ability to regulate temperature cause them to become more vulnerable to temperature extremes (Van Someren, 2007). This vulnerability is further compounded by the increased likelihood of underlying health conditions, disabilities, or the use of medications that interfere with temperature regulation. For example, older adults have a diminished capacity to increase skin blood flow and tend to sweat less during heat stress, resulting in a greater magnitude of heat strain for a given level of heat exposure compared with younger adults (Cottle et al., 2024). Furthermore, older adults are more susceptible to heat-related illness, such as heat exhaustion and heat stroke, due to the high prevalence of chronic conditions (e.g., diabetes, thyroid disorders, Parkinson's disease, arthritis) (Coon and Low, 2018; Kenny et al., 2010; Zhang et al., 2026) and the use of medications that impair thermoregulation in this population (Fastl et al., 2024).

Older adults have a reduced cutaneous thermal sensitivity and a diminished subjective perception of temperature, which increases their vulnerability to cold environments. The cutaneous vasoconstriction response to cold—an important mechanism for conserving body heat—is impaired in older adults compared with younger individuals, likely due in part to reduced skin vasomotor sensitivity to sympathetic stimulation (Greaney et al., 2015). Additionally, the cold-induced rise in metabolic rate, which normally helps protect against hypothermia, is attenuated with age (DeGroot and Kenney, 2007). Both central and peripheral components seem to contribute to these age-related changes in thermoregulatory effector function (Byun et al. 2024). Cold exposure has also been shown to decrease physical performance measures in older adults (Lindemann et al., 2014).

Heat and cold stress have been associated with impaired cognitive ability in older adults (Baniassadi et al., 2025; Byun et al., 2024; Dolcini et al., 2020; Muller et al., 2012), although there is some inconsistency in the literature (Schlader et al., 2016).

It is important to note that older adults, including those in the oldest cohorts, are common aircraft passengers. Many flight attendants can also be considered older workers, typically defined as over 65 years of age, though some definitions start at age 55. In the United States there is no upper age limit for flight attendants. Middle-aged (age 40–64 years) and older (more than 65 years old) flight attendants may experience slightly reduced thermoregulatory abilities (Leach et al., 2024). Furthermore, flight attendant crews may include both younger and older workers, and younger flight attendants may not always be aware when their older teammates are experiencing thermal duress during communications or duty handoffs.

Chronic Medical Conditions and Disabilities

Several chronic medical conditions can impact how an individual responds to hot or cold cabin air temperatures. Table 3-2 lists several common chronic medical conditions and disabilities and their effects on vulnerability to hot or cold cabin air temperatures. The conditions discussed were selected based on their relatively high prevalence in the general population, their known physiological effects on thermoregulation, and their potential to affect aircraft cabin occupants. It should be noted that this is not a comprehensive summary of the impact of all chronic medical conditions and disabilities on thermoregulation. For a more comprehensive discussion, readers are referred to a recent review by Cramer and colleagues (2022). Moreover, the comparative importance of these conditions relative to other factors in determining risk during exposure to thermal extremes is largely unknown.

Hearing loss warrants separate consideration because the mechanism of concern differs. Elevated temperature, humidity, and sweat can degrade hearing assistive devices, including hearing aids and cochlear implant sound processors, through corrosion and the moisture-related failure of electronic components (Asikainen et al., 2025; Yadav et al., 2021). For passengers and crew who rely on these devices, degraded performance may impair the ability to hear safety announcements or emergency commands. Other disability-related medical equipment may be similarly affected by cabin thermal conditions.

In addition to specific conditions, several prescription drugs can impact the thermoregulatory response to heat and cold exposure. For example, anticholinergic medications can limit sweating, thereby reducing the body's ability to dissipate heat. Diuretics can indirectly increase the likelihood of heat strain by promoting dehydration. Moreover, dopaminergic medications may further impair thermoregulation.

TABLE 3-2 Examples of Common Chronic Medical Conditions and Disabilities that Influence Risks from Thermal Exposures

Chronic Condition Category	Example Condition(s) of Relevance	Potential Effects on Risks from Thermal Exposures
Cardiovascular diseases	Coronary artery disease	Increased risk of a heart attack from, for example, increased heart rate during heat stress or cold-induced elevations in blood pressure (Barry et al., 2024; Hess et al., 2009).
Metabolic diseases	Diabetes	Increased risk of heat strain or hypothermia during heat or cold stress, respectively, due to thermoregulatory impairment associated with metabolic diseases (Cramer et al., 2022; Kenny, 2016). Impaired regulation of blood sugar for people with diabetes (Cramer et al., 2022).
Kidney diseases	Chronic kidney disease	Reduction in kidney function in proportion to the magnitude of heat strain and potential for acute kidney injury in extreme conditions (Chapman et al., 2021; Zhang et al., 2024).
Respiratory diseases	Asthma, chronic obstructive pulmonary disorder	Aggravation of respiratory conditions with exposure to hot air (McCormack et al., 2016) or cold dry air (Donaldson et al., 1999).
Neurological diseases and injuries	Parkinson's disease, multiple sclerosis, spinal cord injury	Increased risk of heat strain or hypothermia due to impaired thermoregulation in both heat and cold stress conditions (Coon and Low, 2018; Davis et al., 2018; Frohman et al., 2013; Handrakis et al., 2017).

CONCLUDING REMARKS

The goals of this chapter were to outline the health and safety effects of air temperature as they may impact passengers and flight attendants in the aircraft cabin and to present the factors that modify these effects. While research specific to aircraft cabin environments is limited, available evidence suggests that the physiological, cognitive, and behavioral effects of thermal exposure in the cabin are likely similar to those observed in other settings. However, these cognitive and behavioral effects may be amplified, as compared with other environments, by the unique characteristics of the aircraft environment, such as an enclosed space, a limited ability to escape discomfort, and the presence of additional stressors. This chapter described the physiological, cognitive, and behavioral effects of both hot and cold cabin air temperatures and discussed how these factors may contribute to the development of fatigue. Special attention was given to modifying factors such as age, underlying health conditions, activity level, clothing, and medication use, all of which can influence individual susceptibility to thermal stress. A synopsis of the findings is depicted in Figure 3-1.

There are two key takeaways from this chapter based on the research described. First, perceptual perturbations (e.g., discomfort) occur at less severe deviations in air temperatures than do the more profound physiological responses associated with heat strain and physical health-related medical conditions. The evidence base for these psychological impacts is smaller than that for physiological effects and the associated health risks of hyperthermia, and these psychological effects appear to be more influenced by context and individual differences. In particular, research on the cognitive and behavioral effects of discomfort is primarily based on individual studies, whereas the evidence for physiological impacts is bolstered by systematic reviews and authoritative reports from such organizations as the National Institute for Occupational Safety and Health. Nevertheless, these impacts are important to note: inferential evidence suggests that increasing discomfort is associated with alterations in perceived well-being, decision making, irritability, heightened perceptions of fatigue, and other behavioral manifestations. In the aircraft cabin environment, these changes may manifest as impairments in decision-making abilities, increased fatigue, and passenger disruptions or aggression, which may have direct or downstream effects on safety. Thus, while discomfort on its own may not be a major concern, protecting against the proximal cognitive and behavioral effects arising from discomfort is of vital importance to ensuring the health and safety of passengers and crewmembers alike.

Second, the risks associated with extreme air temperatures are modified by numerous factors, including duration of exposure, age, personal health characteristics, physical activity level, and other environmental factors, such as humidity and air movement. As a result, the health and safety impacts of cabin air temperatures are numerous, multifactorial, and heterogeneously distributed across both passengers and flight attendants. These considerations provide the foundation for the following conclusions.

> *Conclusion 3-1: Health issues associated with extreme heat and cold in aircraft cabins are relatively rare. Thermal discomfort, both hot and cold, occurs at less extreme temperatures than those associated with heat stress or cold stress and may have important behavioral and cognitive effects with implications for safety-related factors such as decision-making abilities, flight attendant fatigue, and passenger disruptions or aggression. Protecting*

against the proximal cognitive and behavioral effects arising from discomfort is therefore of vital importance to ensuring the health and safety of passengers and crewmembers.

Conclusion 3-2: In addition to air temperature, other environmental factors (such as humidity and air movement) as well as characteristics of the flight attendants and passengers will affect thermal comfort and alter risk for adverse impacts of hot or cold cabin temperatures. Relevant characteristics of crew and passengers include, but are not limited to, pregnancy, age (both young children/infants and older adults), and certain medical conditions and disabilities.

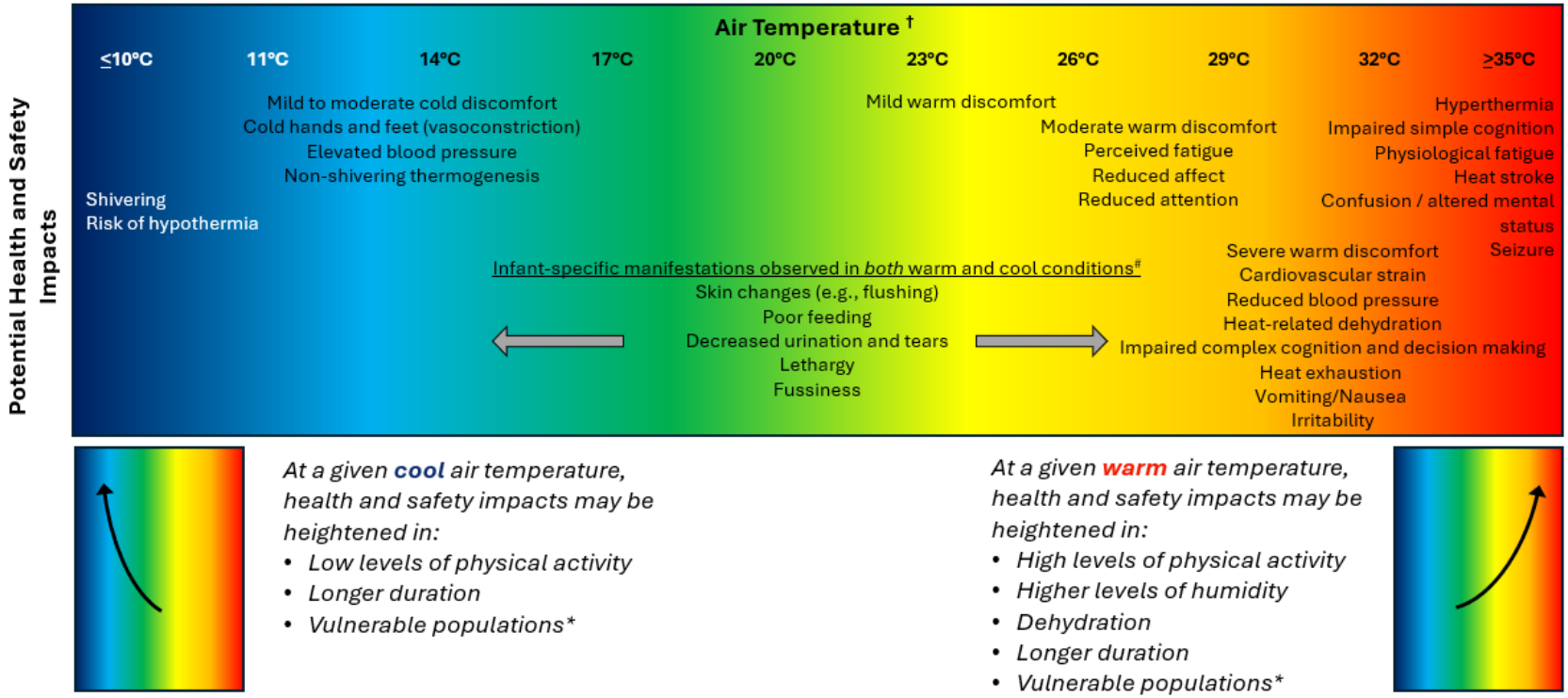

FIGURE 3-1 Expected physiological, cognitive, and behavioral effects across the temperature spectrum.
†The stated air temperatures are general guidelines. The potential health and safety impacts exist on a continuum and are modified by multiple factors (see chapter text).
*Identified vulnerable populations include infants and young children, older adults, and people who are pregnant, taking certain medications, or with medical conditions that have primary or secondary effects on behavioral or autonomic thermoregulation.
#Infant-specific manifestations are highlighted separately but may occur across the full temperature spectrum. There is currently insufficient evidence to define temperature-specific thresholds for onset.

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4
Applying Standards and Guidelines for Thermal Comfort and Heat and Cold Stress to Aircraft Cabin Occupants

The committee was charged with reviewing the evidence on the health and safety impacts of cabin temperatures and assessing the applicability and feasibility of applying existing standards on air temperatures and humidity levels to ensure the health and safety of cabin occupants. Chapter 3 described health and safety risks resulting from the physiological, cognitive, and behavioral effects of exposure to hot and cold temperatures. As described in that chapter, health and safety impacts of thermal exposures can result not only from heat and cold stress, but also from thermal discomfort, which, in an aircraft setting, may impair cognitive processes essential to performing flight attendants' safety critical duties and contribute to unruly passenger behavior. Building on that foundation, this chapter identifies cabin temperature and humidity levels at which discomfort, heat stress, or cold stress may be expected, using established thermal comfort, cold stress, and heat stress standards and guidelines[1] applied in the unique context of commercial aircraft.

A central concept in this chapter is the use of thermal response zones—defined for the purposes of this report as ranges of temperature and humidity that correspond to comfort, discomfort, or physiological stress. By comparing available cabin temperature and humidity data with these combined thresholds, the committee provides a framework for assessing the potential health and safety impacts of reported conditions (see Chapter 5).

This chapter begins with a summary of key thermal comfort and heat/cold stress standards and guidelines, including their scientific basis and limitations. It then describes how these standards and guidelines were applied to classify cabin thermal conditions into different thermal response zones, with supporting tables and figures. The temperature criteria from the aircraft-specific Standard 161 of the American National Standards Institute and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE), *Air Quality within Commercial Aircraft* (ANSI/ASHRAE, 2023a)—detailed in Chapter 2), are examined in relation to these thermal response zones. The chapter ends with a discussion of how such factors as activity level, clothing, humidity, and local cooling via personal air outlets influence the thresholds for comfort and thermal stress and the implications for the existing standards to ensure the safety and health of cabin occupants (discussed further in Chapter 6). This approach provides an objective basis for evaluating whether measured or reported cabin conditions are likely to pose health and safety risks, and it informed the committee's subsequent findings and recommendations.

[1] For the purposes of this report, the use of the terms "standard" and "guideline" in reference to specific documents reflects the nomenclature used by the bodies that developed the documents. This terminology is not intended to indicate whether compliance is mandatory or voluntary.

THERMAL COMFORT STANDARDS

The committee's assessment of the applicability of temperature and humidity standards was not limited to those specifically developed for aircraft settings (e.g., ANSI/ASHRAE Standard 161-2023). The study scope was broad and also encompassed thermal standards for enclosed environments intended for public occupancy in general. Two widely used thermal comfort standards developed for the general population in any indoor space are:

- ANSI/ASHRAE Standard 55-2023, *Thermal Environmental Conditions for Human Occupancy* (ANIS/ASHRAE, 2023b); and
- Standard 7730:2025 of the International Organization for Standardization (ISO), *Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria* (ISO, 2025).

Both standards are intended to define indoor environmental conditions under which most occupants are expected to experience thermal comfort.[2] In both, the determination of thermal comfort was based on a model developed by Fanger (Charles, 2003). This model estimates how people are likely to perceive their thermal environment by considering a combination of environmental and personal factors, including air temperature, air movement, clothing insulation, and activity level. The primary metric used to assess the suitability of an environment for thermal comfort in this model is the predicted mean vote (PMV), which predicts the average thermal sensation of a large group of people exposed to the same environment (Fanger, 1982). The PMV is described in detail in the following section.

The Fanger Thermal Comfort Model

The Fanger thermal comfort model (Fanger model) estimates thermal comfort by applying an energy balance approach to the human body in a given environment (see below). Specifically, the model compares:

- Required heat loss for a given metabolic activity (i.e., the amount of heat the body must dissipate to maintain thermal equilibrium at a comfortable skin temperature and sweat rate), and
- Actual heat loss that would occur in the specific environment, considering air temperature, radiant temperature, humidity, air movement, clothing insulation, and activity level, with the body at the desired temperature and sweat rate for that activity level for the average adult (Charles, 2003).

The difference between these two values represents the thermal strain experienced by the body. Experimental data linking this thermal strain to individuals' reported thermal sensation were used to develop the PMV index. The PMV represents the average comfort response of a group of occupants exposed to the same environmental conditions.

The Fanger model is based primarily on a major laboratory study involving 1,600 college-age research participants who were exposed to a variety of environmental conditions and activities (Rohles, 1971). While the initial study population consisted of college-age adults, subsequent research validated the model in a broader adult population (Van Hoof, 2008).

[2] Another widely referenced standard, EN 16798-1:2019, *Energy Performance of Buildings* (CEN, 2019), also includes thermal comfort requirements for indoor environments; however, because its comfort criteria are based on ISO Standard 7730:2025 (ISO, 2025), it is not reviewed separately here.

Subjective thermal comfort in these studies was evaluated using a discrete 7-point scale, as shown in Table 4-1.

TABLE 4-1 Subjective Thermal Comfort Scale

Descriptor	Value
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

The PMV index predicts the mean value of the 7-point thermal sensation scale for a large group of people under the same environmental conditions (ISO, 2025). This provides a quantitative basis for defining thermal comfort zones in such standards as ANSI/ASHRAE Standard 55-2023 (ANSI/ASHRAE, 2023b) and ISO Standard 7730:2025 (ISO, 2025).

The PMV was calculated as the average thermal sensation reported by study participants exposed to a range of preselected environmental conditions. The thermal environment was characterized using six key factors (ANSI/ASHRAE, 2023b; ISO, 2025):

- Air temperature: The temperature of the air surrounding the occupant.
- Radiant temperature: A weighted average temperature of surrounding surfaces (e.g., walls, windows, and ceilings), which affects heat exchange by radiation.
- Air humidity: The amount of moisture in the air, influencing evaporative heat loss.
- Air speed: The velocity of air movement, which can enhance heat loss through convection and evaporation (Cramer et al., 2022).[3]
- Clothing insulation: The thermal resistance of clothing, typically measured in "clo" units. 1 clo = 0. 155 $m^2 \cdot °C/W$ and corresponds approximately to the clothing insulation provided when wearing a typical men's two-piece business suit. 0 clo corresponds to a person wearing no clothing.
- Metabolic activity: The rate of energy expenditure by the occupant, typically measured in metabolic equivalent of task (MET) units.

By systematically varying these factors, the Fanger model predicts the average thermal sensation (PMV) for a group, enabling the establishment of comfort criteria that can be applied to a wide range of indoor environments, including, with appropriate adjustments and caveats, the aircraft cabin.

It is important to distinguish between the two temperature parameters—air temperature and radiant temperature. In indoor environments, including aircraft cabins, air temperature and

[3] Convection is the transfer of heat between the skin and the surrounding air as air moves away from the skin. Evaporation is the vaporization of moisture (e.g., sweat) from the skin surface into the external environment (Cramer et al., 2022).

radiant temperature are approximately equally important in determining the rate of heat exchange between a person and his or her surroundings. As a result, both play a critical role in determining thermal comfort and heat or cold stress. It is the combination of these two temperatures, rather than air temperature alone, that drives an individual's perception of an environment as warm, cold, or comfortable (see Chapter 9 [*Thermal Comfort*] of ASHRAE, 2025).

For some applications, the term "operative temperature" is used. Operative temperature is a theoretical construct used to simplify calculations involving how a person experiences temperature in an enclosed space (ANSI/ASHRAE, 2023b). The simplifying assumption is that the temperature is uniform across the entire enclosure, and then the *operative temperature* is defined as the temperature that would make a uniform enclosed space feel the same to an occupant as the actual, real-world space with its non-uniform air temperature and radiant temperature. In practice, operative temperature is calculated as a weighted average of the air temperature and radiant temperature. Thus, when describing an environment as hot or cold, it is technically the operative temperature that best represents the thermal experience, not just the air temperature. In many indoor settings, air and radiant temperature are similar, but differences can occur. For example, in cold weather, exterior walls or windows may be cooler than the interior air, lowering the mean radiant temperature. After a rapid change in air temperature, interior surfaces may warm up or cool down more slowly than the surrounding air, creating a temporary mismatch. These distinctions are particularly relevant in the aircraft cabins, where rapid changes in environmental conditions can occur and where both air and surface temperatures contribute to occupants' thermal comfort and physiological responses.

Over the more than 50 years since the Fanger model was first developed, its reliability and applicability have been extensively evaluated in a wide range of thermal comfort studies (Van Hoof, 2008). These studies have encompassed diverse geographics, ethnic groups, age groups, and indoor environments. Across these varied contexts, the Fanger model has consistently proven to be a robust and reliable basis for predicting thermally comfortable conditions in enclosed, air-conditioned environments.

For any given thermal environment, individuals may experience different levels of subjective comfort. Within a large group, responses can span the entire 7-point thermal sensation scale even when all are wearing the same clothing and are engaged in the same activity in the same environment (Van Hoof, 2008). The PMV index represents the average response of the group and is not intended to predict the response of any specific individual. To address this variability, the concept of predicted percent dissatisfied (PPD) was introduced. In this framework, individuals who report thermal sensations of +1 (slightly warm), 0 (neutral), or -1 (slightly cool) on the 7-point scale are considered satisfied with the thermal environment, while those selecting other values are considered dissatisfied. Fanger established a correlation between PMV and the percentage of dissatisfied occupants, allowing the model to predict the PPD as a function of PMV (Charles, 2003).

While the Fanger model has proven to be a reliable means for evaluating thermal environments, it is not without limitations. The following section discusses some of the limitations that may be particularly relevant for cabin crew and passengers in aircraft.

Limitations of the Fanger Model in the Context of Aircraft Settings

The Fanger model is based on laboratory experiments that used healthy adult subjects across a wide range of ages (Van Hoof, 2008). As a result, it does not necessarily apply to

infants, children, and those who are ill, infirm, or who have physical disabilities or medical conditions that affect thermoregulation.

The Fanger model is based on steady-state exposure (Van Hoof, 2008). Most of the data used to develop the model were collected after 3 hours of constant exposure to a given environment. This may not accurately reflect responses to rapidly changing thermal conditions in aircraft, such as those that can occur during boarding, taxiing, or ground delays. Additionally, the model does not account for the effects of prior thermal exposure (e.g., entering a warm cabin from a cold outdoor environment).

The Fanger model assumes that all sweat generated is fully evaporated and does not address the level of skin wettedness required to achieve this evaporation. Skin wettedness, which refers to the subjective perception of moisture on skin, is an important factor for warm thermal discomfort (ASHRAE, 2025). As a result, the model may not accurately reflect the effects of humidity, particularly during periods of elevated activity in warm and humid environments.

In summary, the Fanger model remains a reliable means of identifying indoor conditioned spaces likely to elicit a high level of thermal comfort under steady-state conditions (Van Hoof, 2008). However, it is not intended to address extreme conditions or associated cold or heat stress, and its applicability is limited in scenarios involving rapid environmental changes, high humidity, or vulnerable populations. Despite these limitations, it continues to serve as a valuable tool and is the specific resource referenced by the thermal comfort standards considered in this report.

Comparison of ANSI/ASHRAE Standard 55-2023 and ISO Standard 7730:2025

Both ANSI/ASHRAE Standard 55-2023 and ISO Standard 7730:2025 use the Fanger model as the primary basis for evaluating indoor environments for thermal comfort (ANSI/ASHRAE, 2023b; ISO, 2025). However, there are important differences in how each standard applies the model and defines the comfort zone. ANSI/ASHRAE Standard 55-2023 defines the comfort zone as the range where the PMV is between -0.5 and +0.5 ($-0.5 < PMV < +0.5$). This corresponds to a maximum PPD of 10 percent. By contrast, ISO Standard 7730:2025 introduces three classes of comfort environments:

Class A: $-0.2 < PMV < +0.2$
Class B: $-0.5 < PMV < +0.5$
Class C: $-0.7 < PMV < +0.7$

The comfort range specified in ANSI/ASHRAE Standard 55-2023 aligns with Class B in ISO Standard 7730:2025. While ISO Standard 7730:2025 provides detailed information on the parameter limits for each class, it does not prescribe which class should be used for a given application, leaving the decision to the user. This flexibility can be advantageous but also introduces ambiguity when applying the standard to nontraditional environments, such as aircraft cabins.

Both standards are based on the Fanger model's steady state assumption, developed from data collected after 3 hours of constant exposure and activity (Van Hoof, 2008). However, they differ in how they address non-steady state conditions. ANSI/ASHRAE Standard 55-2023 requires a minimum 15-minute averaging period for non-steady-state conditions and notes that prior exposure (and presumably prior activity) can affect comfort perceptions in a new environment for up to 1 hour (ANSI/ASHRAE, 2023b). ISO Standard 7730:2025 also specifies steady-state conditions but sets explicit limits on the rate of environmental change for the

standard to be applicable (ISO, 2025). It addresses step changes (such as entering a new environment) by stating that step increases in operative temperature have an immediate impact on thermal sensation, and the PMV calculation for the new environment applies immediately. For negative step changes in operative temperature, the initial thermal sensation response overshoots before gradually approaching the steady-state response over about 30 minutes.

These differences highlight the need for careful interpretation when applying either standard to environments with rapidly changing conditions or varying activity levels, as commonly encountered in aircraft cabins. The lack of explicit guidance on which comfort class to use and the steady-state assumptions underlying both standards may limit their direct applicability to the dynamic and heterogeneous conditions present in aircraft cabin operations.

Considerations for Applying Thermal Comfort Standards

In addition to overall thermal sensation, several other factors can contribute to thermal discomfort in an indoor environment. These include

- vertical temperature stratification (temperature differences between floor and ceiling);
- radiant asymmetry (uneven temperatures of surrounding surfaces);
- localized drafts; and
- excessive air speed.

Both ANSI/ASHRAE Standard 55-2023 and ISO Standard 7730:2025 address these factors in detail (ANSI/ASHRAE, 2023b; ISO, 2025). While this chapter focuses on the use of these standards to establish overall thermal limits, it is important to recognize that these additional factors may also influence thermal comfort and should be addressed when applying the standards to aircraft cabins.

A critical step in applying either standard is determining the appropriate values for clothing insulation and activity level (metabolic rate) for the occupants. This can be particularly challenging in environments like aircraft cabins, where occupants have varying activity levels (flight attendants are often active, while passengers are typically sedentary) and where clothing choices vary. Passengers may wear a wide range of clothing, while flight attendants may be required to wear uniforms. Both standards provide guidance and tables for estimating clothing insulation and metabolic rate. If the specific clothing worn is known (e.g., uniforms), clothing insulation can be estimated with reasonable accuracy. For the general public, such as passengers, the diversity of clothing makes it difficult to assign a precise value for clothing insulation. Similarly, metabolic rate can be estimated accurately for sedentary activities (such as seated passengers). However, for active individuals such as flight attendants, metabolic rate may vary significantly across flight phases and duties, making it more difficult to determine a representative value.

In summary, while thermal comfort standards provide a valuable framework for assessing environmental conditions, their application in aircraft cabins requires adaptation that involves careful consideration of the variability in clothing and activity among occupants as well as of other environmental factors that may influence thermal comfort.

HEAT STRESS GUIDELINES AND STANDARDS

American Conference of Governmental Industrial Hygienists Heat Stress and Strain Guideline

The American Conference of Governmental Industrial Hygienists (ACGIH) develops guidelines for safe levels of workplace exposure to various chemical and physical stressors, including heat and cold (ACGIH, 2022, 2026). Like ANSI/ASHRAE and ISO standards, ACGIH guidelines are not legally enforceable unless adopted by regulatory authorities such as the Occupational Safety and Health Administration (OSHA) or the Federal Aviation Administration (FAA). ACGIH has developed guidelines for threshold limiting values (TLVs) and action limits (ALs) for occupational exposure to hot environments (ACGIH, 2022). The TLVs are "based on the ability of most healthy hydrated acclimatized workers to maintain thermal equilibrium" (ACGIH, 2022). In contrast, the ALs are intended to represent "conditions where most healthy unacclimatized workers can achieve thermal equilibrium" (ACGIH, 2022). For a description of heat acclimatization, see Box 3-2 in Chapter 3.

When environmental conditions exceed the TLVs or ALs, meaning that thermal equilibrium cannot be sustained, the risk of heat exhaustion or heat stroke increases. It is important to note that TLVs and ALs pertain strictly to thermal safety. The guideline also points out that increasing heat stress may lead to "an increased likelihood of errors in judgement, acute injury, and adverse incidents" (ACGIH, 2022), but these additional risks are not considered in establishing the recommended limits.

The ACGIH heat stress and strain guideline uses the wet bulb globe temperature (WBGT) as a comprehensive measure of the thermal environment (ACGIH, 2022). The WBGT is specifically designed to assess heat stress. It incorporates the combined effects of air temperature, thermal radiation (measured by a black globe thermometer), air speed, and ambient humidity.

The WBGT is the wet-bulb globe temperature for indoor applications composed of the naturally aspirated wet-bulb temperature exposed to the ambient environment (T_{nwb}) and the temperature of a black globe exposed to the ambient environment (T_g) (ACGIH, 2022). For indoor applications, the WBGT is calculated as:

$$WBGT = 0.7\ T_{nwb} + 0.3\ T_g$$

where

T_{nwb} = naturally aspirated wet-bulb temperature (°C)

T_g = black globe temperature (°C)

To establish safe exposure limits, the ACGIH provides equations for the WBGT TLV and AL as a function of metabolic rate:

$$TLV_{WBGT} = 56.7 - 11.5 \log_{10}(M)$$

$$AL_{WBGT} = 60.0 - 14.1 \log_{10}(M)$$

where

TLV_{WBGT} is the WBGT threshold limit value (°C)

AL_{WBGT} is the WBGT action limit (°C)

M is the metabolic rate (watts)

These equations allow practitioners to determine the maximum safe WBGT for a given level of physical activity, supporting effective heat stress management in occupational and specialized environments such as aircraft cabins.

Some instruments used to measure the WBGT employ a naturally aspirated wet bulb thermometer and a globe thermometer. However, because the naturally aspirated wet-bulb instrument can be cumbersome to use in practice, most modern WBGT instruments instead measure air temperature, air speed, relative humidity, and globe temperature and then use empirical relationships to calculate the natural wet-bulb temperature (T_{nwb}). For occupational heat stress assessment, 1-hour time-weighted averages of environmental conditions are required.

The TLV and AL values generated by the above WBGT equations are further adjusted for clothing insulation. For typical clothing worn in aircraft cabins, these adjustments are minimal. Example clothing adjustment values are shown in Table 4-2.

TABLE 4-2 WBGT Adjustment Values for Clothing

Clothing	*Adjustment to WBGT (°C)*
Short sleeves and short pants	+1
Long sleeve shirt and long pants	0
Cloth (woven) coverall over underwear	0
Double layer clothing	-3

NOTE: Higher WBGT can be tolerated with lighter clothing, while heavier clothing decreases the tolerable WBGT.

SOURCE: Adapted from ACGIH (2022); Bernard et al., 2017. ©2017 National Institute of Occupational Safety and Health. CC BY-NC-ND.

The ACGIH guideline provides recommendations for establishing heat stress management programs when the AL is exceeded. Since flight attendants and passengers are generally not expected to be heat-acclimatized, the ALs are likely the most appropriate limits for application in aircraft cabin environments.

Other Heat Stress Guidelines and Standards

The National Institute for Occupational Safety and Health (NIOSH) provides guidance for heat exposure in the workplace (Jacklitsch et al., 2016), and OSHA has used this guidance to inform its proposed rulemaking for heat injury and illness prevention in both outdoor and indoor work settings,[4] as discussed in Chapter 1. Similarly, ISO 7243:2017, *Ergonomics of the Thermal Environment, Assessment of Heat Stress Using the WBGT (Wet Bulb Globe Temperature) Index* (ISO, 2017), provides guidance on heat stress. Both the NIOSH guidance and ISO Standard 7243:2017 closely follow the ACGIH guideline (Jacklitsch et al., 2016; Parsons, 2006), so they are not reviewed separately here. All these guidelines specify exposure limits in terms of the WBGT.

The committee also considered ISO 7933:2023, *Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Heat Stress Using Calculation of the Predicted Heat Strain*, which provides an analytically intensive approach for estimating outcomes such as temperature and sweat rate (ISO, 2023). However, ISO 7933:2023 generally requires detailed input parameters and expert interpretation. In contrast, the ACGIH method—and by extension NIOSH and ISO 7243:2017—offers a more readily practical framework for

[4] 89 FR 70698, *Heat Injury and Illness Prevention in Outdoor and Indoor Work Settings*.

evaluating heat stress risk using easily obtainable measurements.[5] For these reasons, the committee determined that the ACGIH approach was the best method for defining heat stress boundaries, while acknowledging that ISO 7933:2023 represents a reasonable alternative.

COLD STRESS STANDARDS

Cold stress guidance differs significantly from heat stress guidance. In cold environments, appropriate clothing can protect a healthy individual from cold stress, even under conditions far colder than those typically encountered in a passenger aircraft cabin. As a result, guidelines for cold conditions generally focus on determining the clothing insulation required for a given temperature exposure and on protecting exposed skin from frostbite, rather than on defining environmental temperature limits for comfort.

ISO Standard 11079:2007, *Ergonomics of the Thermal Environment—Determination and Interpretation of Cold Stress when Using Required Clothing Insulation (IREQ) and Local Cooling Effects*, provides a method for assessing the required clothing insulation, IREQ, as a function of environmental conditions (ISO, 2007). The standard defines two different values of IREQ:

- Neutral IREQ: The clothing insulation required to minimize body cooling during extended exposure.
- Minimum IREQ: The insulation value that allows some significant body cooling but prevents the body from cooling beyond a safe point. With minimum IREQ, excessive cooling of extremities may still occur during prolonged exposure (ISO, 2007).

ISO Standard 11079:2007 does not specifically address thermal comfort. However, it is reasonable to associate the neutral IREQ value with minimal overall thermal discomfort and the minimum IREQ value with a significant level of overall cold discomfort. The standard is intended for environments at or below 10°C (50°F). Based on available data (see Chapter 5), such cold conditions are rare in aircraft cabins and account for only a very small portion of the thermal environment complaints reviewed by this committee.

APPLICATION OF THERMAL COMFORT AND HEAT AND COLD STRESS STANDARDS AND GUIDELINES FOR AIRCRAFT CABIN SETTINGS

Thermal comfort standards, cold stress standards, and heat stress guidelines can be used to classify thermal conditions into "thermal response zones" ranging from comfort to discomfort and physiological stress. The committee's approach had two main objectives:

1. Provide a basis for comparing the limits established in the aircraft-specific standard, ANSI/ASHRAE Standard 161-2023 (discussed in Chapter 2), with the comfort, discomfort, and stress zones defined by other relevant standards and guidelines (ASHRAE, 2023a). This comparison is discussed later in this chapter.
2. Use these same zones to evaluate measured temperature and humidity conditions from a sampling of flights, determining whether such conditions are likely to

[5] Notably, FAA's Aviation Safety Thermal Stress Prevention Program, applicable to FAA aviation safety employees, applies the ACGIH method to the assessment of heat hazards (FAA, 2022).

result in thermal discomfort or thermal stress. These comparisons are presented in Chapter 5.

It is important to note that thermal response varies considerably among individuals. The standards and guidelines applied here are intended to represent average responses for healthy adults and may not reflect the experience of every individual. For the purposes of this analysis, thermal conditions were categorized into the following zones:

- Cold stress: Conditions sufficiently cold to raise health concerns.
- Cold discomfort: Conditions that some or most people will find uncomfortably cold but that typically would not pose a health risk to a healthy adult.
- Comfortable: Conditions that most people would find acceptable.
- Hot discomfort: Conditions that some or most people will find uncomfortably warm but that typically would not pose a health risk to a healthy adult.
- Heat stress: Conditions sufficiently warm to raise health concerns.

To define the boundaries between these zones, the committee used the objective criteria provided by the referenced standards and guidelines. However, it should be recognized that there is some inherent arbitrariness in setting these boundaries, and the transition from one zone to another is gradual rather than abrupt. Finally, it is also important to emphasize that thermal discomfort—even when not reaching the level of heat or cold stress—can still have physiological, cognitive, and behavioral effects that pose safety risks, as discussed in Chapter 3.

All of the standards and guidelines that the committee used to establish the boundaries are typically intended for land-based application. The question then arises as to whether it is reasonable to use them to establish boundaries for aircraft applications. From a physical environment perspective, a key difference between an aircraft cabin environment and a land-based enclosed environment is the high altitude of the aircraft during much of a typical flight. However, modern aircraft use pressurized cabins that maintain the air pressure equivalent to a surface elevation no higher than 8,000 feet (2428 meters) elevation. The term cabin altitude is typically used to describe cabin pressure where cabin altitude is defined as the surface elevation that has an atmospheric pressure equal to the pressure in the cabin. Typical cabin altitude during cruise ranges from 6,000 to 8,000 feet (1,828 to 2,428 meters). Neither ANSI/ASHRAE Standard 55-2023 nor ISO Standard 7730:2025 states specifically that it applies to aircraft, but neither standard has provisions that would exclude application to aircraft. ANSI/ASHRAE Standard 55 states in its scope that it is applicable to elevations up to 10,000 feet or 3,000 meters, which exceeds the range of cabin altitudes. ISO Standard 7730:2025 does not have a similar statement in its scope, and there is no mention of limits of elevation or ambient air pressure in the standard. Similarly, neither the ACGIH heat stress and strain guidelines nor ISO Standard 11079:2007 states that it is applicable to aircraft, but neither has any provisions which would exclude aircraft application. Given this lack of elevation limitation in the standards and guidelines and the fact that cabin altitudes fall within the range of elevations that the standards and guidelines would be used for with land-based applications, it is reasonable to apply them to aircraft cabins. It should be kept in mind that the purpose of the calculated boundaries is not to determine whether given cabin conditions comply with the various standards and guidelines but rather to provide an objective means to establish cabin conditions in which thermal comfort, thermal discomfort, and thermal stress may be expected.

Calculation of Comfort and Heat and Cold Stress Zones

Calculations based on ANSI/ASHRAE Standard 55-2023 or ISO Standard 7730:2025 can be used to establish a thermal comfort zone for specific activity levels and clothing insulation (ANSI/ASHRAE, 2023b; ISO, 2025). While both standards are based on the Fanger model, they implement certain aspects differently, particularly regarding the effect of body movement on effective air speed and clothing insulation (Tartarini and Schiavon, 2025). These differences can lead to variations in the PMV values for some conditions, especially at higher activity levels. However, for comfort conditions defined by PMV values between –0.5 and +0.5, the resulting temperature ranges are generally similar.

The PMV range used as the comfort criteria in ANSI/ASHRAE Standard 55-2023 is equivalent to Class B in ISO Standard 7730:2025. One distinction is that ANSI/ASHRAE Standard 55-2023 uses operative temperature (a weighted average of air and radiant temperature), while ISO Standard 7730:2025 requires separate inputs for air temperature and radiant temperature. For simplicity and consistency, the comfort ranges used in this report are based on ISO Standard 7730:2025. The committee used a thermal comfort tool developed by the Center for the Built Environment (Tartarini et al., 2020) under ASHRAE sponsorship, which calculates PMV according to both standards. For the analyses and figures presented in this chapter, the ISO Standard 7730:2025 implementation with PMV limits of +0.5 and –0.5 was used to define the comfort zone boundaries.

The ACGIH WBGT ALs were used to establish the lower temperature boundary for the heat stress zone, based on specific activity and clothing values. To determine the combinations of relative humidity and temperature that correspond to specified WBGT values, an empirical WBGT calculator was used (Perry, 2025). Because WBGT is a measured index and there is no universally accepted mathematical formula linking WBGT to its underlying parameters, these estimates should be interpreted as approximations rather than exact values. Importantly, the ACGIH guidelines state that the ALs calculated using the formulae provided underestimate exposure at both high humidity and low humidity. The guidelines do not provide any specific guidance as to what constitutes a high or low humidity or how the ALs should be modified to account for this underestimate. The data for thermal conditions in aircraft reviewed did not include any high humidity conditions, and the temperatures at low humidity were all well below the ALs (see Chapter 5). Thus, this limitation at high and low humidity was not a factor in making assessments of the data. However, these limitations should be recognized if the boundaries calculated are applied in other settings.

For cold stress, ISO Standard 11079:2007 was used to define the cold stress zone by calculating the minimum required clothing insulation (minimum IREQ) (ISO, 2007). The air temperature value was adjusted until the minimum required insulation matched the specified clothing insulation. Since the online tool referenced in the standard is no longer available, an alternative tool developed by Lund University (Lund University, 2022) was used for these calculations (see Appendix A for details). ISO Standard 11079:2007 recommends that it not be applied for conditions warmer than 10°C (50°F), and the online tool does not allow calculations above this threshold (ISO, 2007). As a result, it was not feasible to establish cold stress boundaries for lighter clothing and lower activity levels. However, even though these boundaries could not be explicitly calculated, they do exist and would occur at temperatures above 10°C (50°F).

For all calculations, regardless of the standard used, the radiant temperature was set equal to the air temperature. Thus, the temperature input into the calculations should be considered the

operative temperature. In most cases, air temperature and radiant temperature are expected to be very similar in an aircraft cabin. However, exceptions can occur under the following conditions:

- If a *heat-soaked* aircraft (exposed to high ambient temperatures) is boarded while still cooling, the interior surfaces may remain warmer than the cabin air, resulting in a radiant temperature higher than the air temperature.
- Conversely, in a *cold-soaked* aircraft (exposed to low ambient temperatures), the radiant temperature may be lower than the air temperature while the cabin is warming up.

Additionally, the close proximity of passengers in an aircraft cabin means that the radiant temperature that the passengers experience will be increased above the air temperature due to the presence of the other warm bodies, and the more crowded the aircraft, the greater the impact. No data were found to quantify this effect, however. Where applicable, solar radiation was set to zero. While solar radiation external to the aircraft may well affect the thermal conditions within the aircraft, occupants of the aircraft are exposed directly to minimal solar radiation, and it is generally not a significant factor in the heat exchange between them and their surroundings. More detailed descriptions of the calculation methods for each standard or guideline can be found in Appendix A.

The regions between the upper comfort limit and the onset of heat stress are labeled as "hot discomfort," while regions between the lower comfort limit and the onset of cold stress are labeled as "cold discomfort." It is important to recognize that the transitions from comfort to discomfort and from discomfort to stress are gradual and continuous, rather than abrupt. For example, the experience of discomfort just above the comfort limit can be quite different from the experience just below the threshold for heat or cold stress. These thermal response zones are intended to be broadly applicable to healthy adults. However, individual responses can vary considerably, and a given person may experience discomfort or stress at different thresholds than the average. Additionally, these zones may not be applicable for certain vulnerable populations, such as older adults, infants and young children, or individuals with health conditions that affect thermoregulation.

To determine the comfort limits and ALs, it is necessary to specify both the metabolic rate and the clothing insulation for the occupants. Anecdotal evidence suggests that many instances of hot cabin conditions occur during ground operations, particularly during and after boarding (see Chapter 5 and Appendix B). To reflect realistic conditions across different phases of flight, the committee considered six case scenarios that capture the potential variability in both clothing insulation (typical, warm, light) and activity levels (busy, light) that may be encountered by flight attendants and passengers (see Table 4-3). While passengers are primarily expected to be sedentary after boarding, the scenarios for flight attendants include both moderate and light activity levels to account for the range of duties performed during a flight. Details on the estimation of metabolic rates for these scenarios are provided in Appendix A.

TABLE 4-3 Clothing and Metabolic Rate Values for Case Scenarios Used to Calculate Comfort Limits and Thermal Stress Limits

Case[a]	Case Scenario Description	Clothing Insulation (clo)[b]	Metabolic Rate (MET)[c]
1	Busy flight attendant, **typical** clothing	0.6	2.3
2	Seated passenger or flight attendant, **typical** clothing	0.6	1.2
3	Busy flight attendant, **warm** clothing	1.0	2.3
4	Seated passenger or flight attendant, **warm** clothing	1.0	1.2
5	Busy flight attendant, **light** clothing	0.4	2.3
6	Seated passenger or flight attendant, **light** clothing	0.4	1.2

[a] For all cases, it is assumed that radiant temperature equals air temperature and air speed equals 0.2 m/s, representing aircraft cabin conditions without personal air outlets operating.
[b] Clothing insulation also includes the insulation provided by the seat for the 1.2-MET activity as it is presumed to apply to a seated individual. The contribution of aircraft seat insulation varies depending on clothing worn (Wu et al., 2016) and occupant posture but could be up to 0.2 clo for case 2. At 2.3-MET activity, the person is not likely to be seated, and seat insulation is not a factor.
[c] The process used by the committee for estimating different possible metabolic rates for flight attendants and passengers is described in Appendix A.

Thermal Response Zones Across Case Scenarios for the Aircraft Cabin[6]

Figures 4-1 and 4-2 illustrate thermal response zones—specifically, comfort, hot and cold discomfort, and heat and cold stress—based on the application of the relevant standards and guidelines for two representative cases:

- Case 1: Busy flight attendant, typical clothing (0.6 clo, 2.3 MET).
- Case 2: Seated passenger or flight attendant, typical clothing (0.6 clo, 1.2 MET).

The curvilinear boundaries of the zones in the figures reflect the influence of humidity on thermal comfort and stress. Also shown on the graphs are the target temperature ranges and upper limits from ANSI/ASHRAE Standard 161:2023 (ANSI/ASHRAE, 2023a), providing a context for how the standard aligns with human comfort and safety. This standard defines three operative temperature ranges for aircraft cabins (see Table 2-1 in Chapter 2):

1. Target range: Applies both in flight and on the ground.
2. Extended upper limit: Increases the allowable upper temperature limit and applies in-flight regardless of in-flight entertainment (IFE) operation as well as on the ground when IFE is not operating.
3. Extended ground operation upper limit (with IFE): Further increases the upper temperature limit but only for ground operations when all IFE systems are operating.

[6] The graphs included in this section of the report are intended solely to illustrate how existing standards and guidelines might be used to assess the suitability of cabin thermal environments. The cited standards and guidelines are complex and incorporate many factors. Simplifications, approximations, and assumptions were made in generating these graph templates, which are not intended for design or evaluation purposes. For detailed design or compliance assessments, readers should consult the original standards and guidelines referenced in this report.

There is no extension of the allowable range to temperatures below the target range. Importantly, the temperature specifications in the standard do not account for humidity variation and are intended to apply at all humidity levels. It should be noted that there is no physiological basis for allowing higher upper temperature limits when IFE is operating. These extensions likely reflect operational constraints associated with ground operations and IFE use rather than differences in human thermal response.

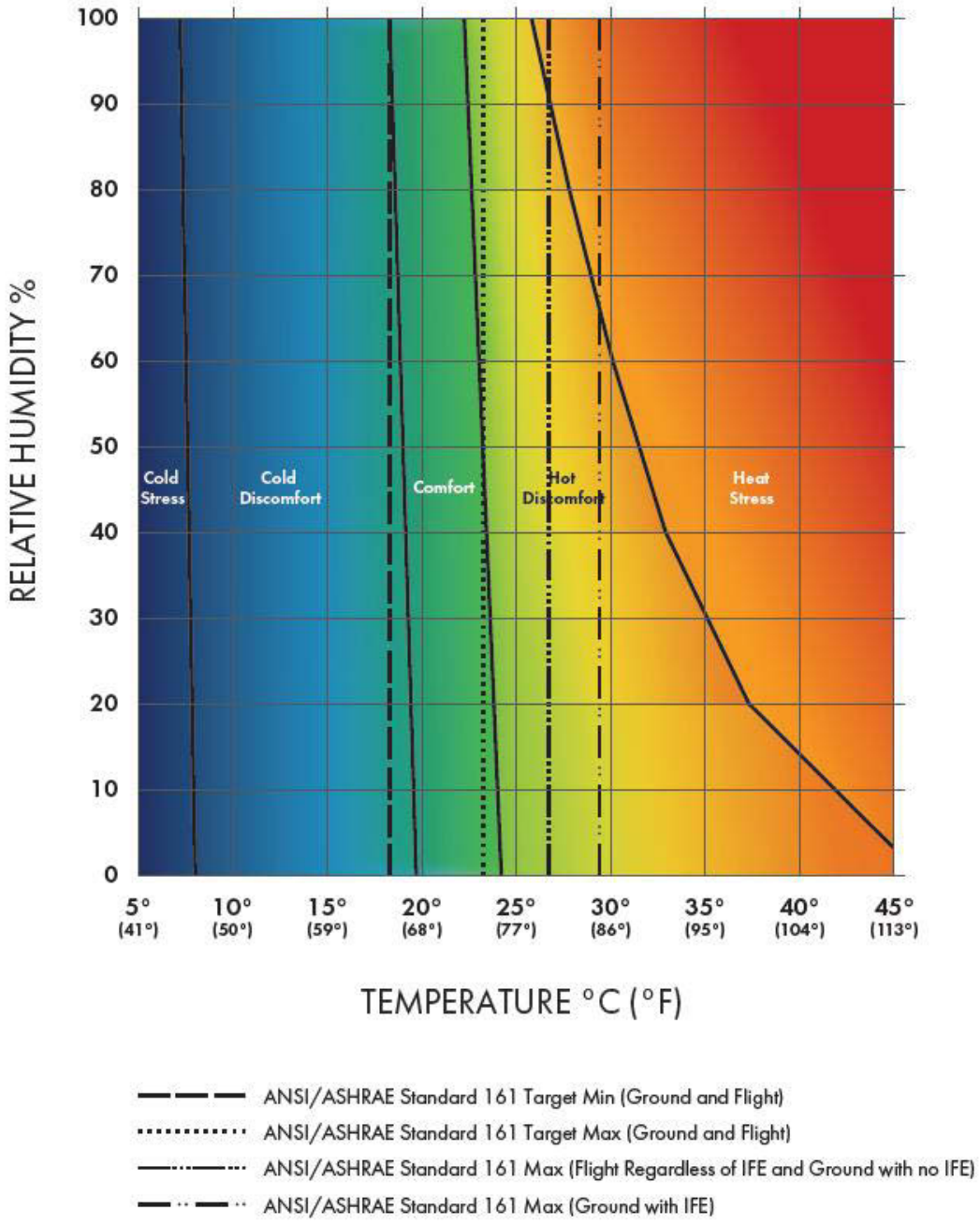

FIGURE 4-1 Thermal response zones from application of thermal comfort and heat and cold stress standards and guidelines for Case 1—busy flight attendant and typical clothing (2.3 MET; 0.6 clo).

NOTES: The green comfort zone is bounded by the upper and lower limits from application of the ISO 7730:2025 thermal comfort standard. The red heat stress zone is bounded by the action limits from the ACGIH guideline. Importantly, the action limits may underestimate exposure at high and low humidity and the boundaries should not be applied outside the scope of this study. The yellow hot discomfort zone is defined as the space between the comfort and heat stress zones. Similarly, the upper limit for the dark blue cold stress zone is defined by the application of ISO Standard 11079:2007, and the light blue cold discomfort zone is defined as the space between the cold stress and comfort zones. ANSI/ASHRAE Standard 161:2023 target and extended limits are overlaid for comparison. Curvilinear zone boundaries are due to the large influence of humidity when addressing heat stress. Shading indicates that the transitions from comfort to discomfort and from discomfort to stress are gradual and continuous rather than abrupt, and it reflects the variation in individual-level tolerances. Exposure duration is not depicted, but effects are not instantaneous; the potential for negative health effects and greater severity increases with longer durations of exposure. IFE = in-flight entertainment.

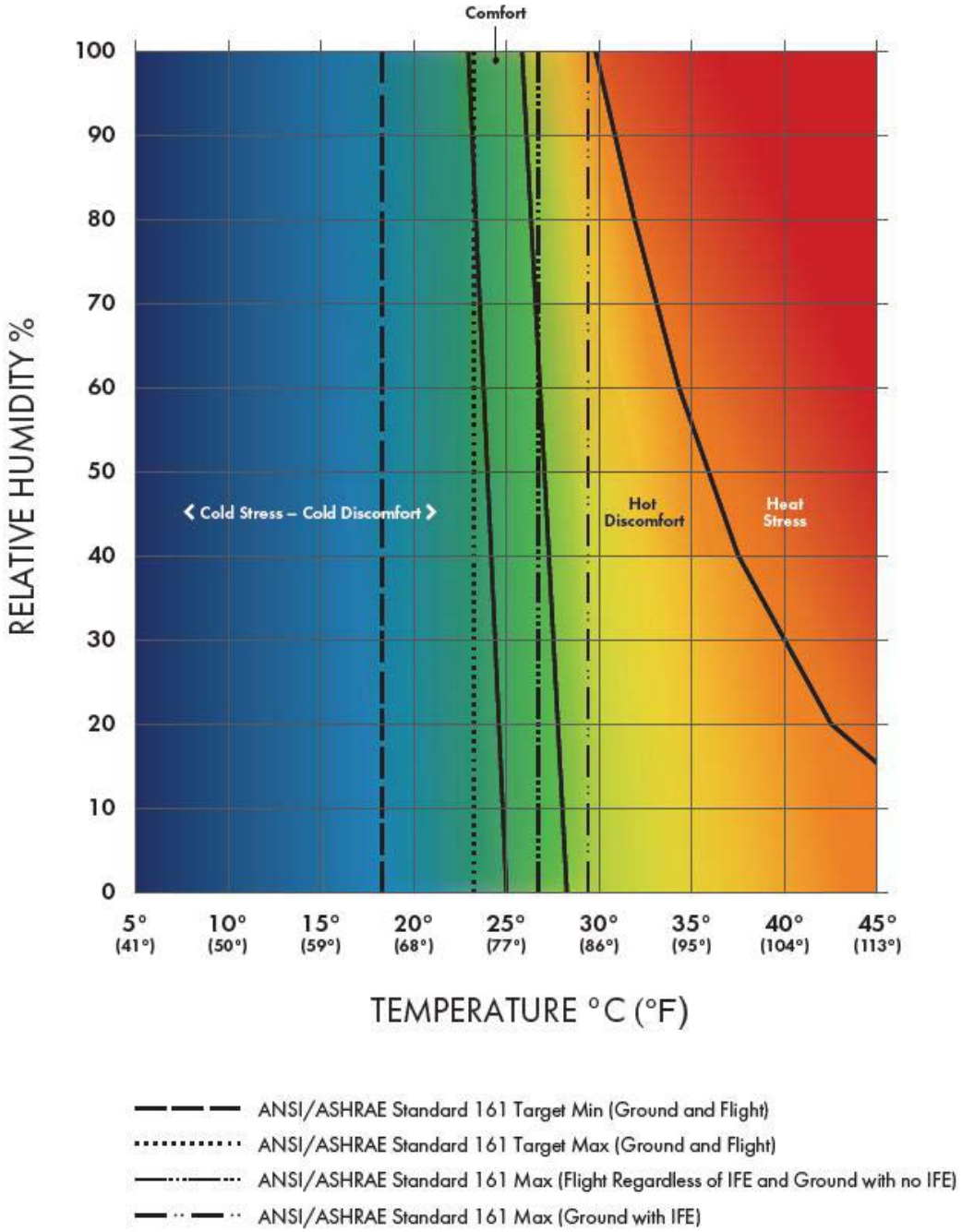

FIGURE 4-2 Thermal response zones from application of thermal comfort and heat and cold stress standards and guidelines for Case 2—seated passenger or flight attendant and typical clothing (1.2 MET, 0.6 clo).

NOTES: The boundary between cold stress and cold discomfort could not be precisely defined as it is above 10°C (50°F), the upper limit of ISO Standard 11079:2007. The lower range of the blue zone is in the cold stress zone, and the upper range of the blue zone is in the cold discomfort zone. The green comfort zone is bounded by the upper and lower limits from application of the thermal comfort standard. The red heat stress zone is bounded by the action limits from the ACGIH guideline. Curvilinear zone boundaries are due to the large influence of humidity when addressing heat stress. Importantly, the action limits may underestimate exposure at high and low

humidity, and the boundaries should not be applied outside the scope of this study. The yellow hot discomfort zone is defined as the space between the comfort and heat stress zones. The ANSI/ASHRAE Standard 161-2023 target and extended limits are overlaid for comparison. Shading indicates that the transitions from comfort to discomfort and from discomfort to stress are gradual and continuous rather than abrupt, and it reflects the variation in individual-level tolerances. Exposure duration is not depicted, but effects are not instantaneous; the potential for negative health effects and greater severity increases with longer durations of exposure. IFE = in-flight entertainment.

For higher activity levels (e.g., Case 1, busy flight attendants), the ANSI/ASHRAE Standard 161-2023 target temperature range is generally consistent with the comfort zone calculated using established thermal comfort standards (ISO Standard 7730:2025). This means that for active flight attendants, the recommended temperatures in ANSI/ASHRAE Standard 161-2023 are likely to provide acceptable thermal comfort under most conditions. The extended allowable temperature of 26.7°C (80°F) in ANSI/ASHRAE Standard 161-2023 for both inflight operations and ground operations without IFE aligns reasonably well with the upper comfort limit when activity levels are lower (e.g., Case 2, seated passengers or inactive flight attendants). However, at the lower end of the ANSI/ASHRAE Standard 161-2023 target range, there is potential for considerable cold discomfort among sedentary occupants. This is because the comfort zone for low-activity individuals shifts upward, making them more susceptible to feeling cold at temperatures that might be comfortable for more active individuals.

Complaint and safety data related to cabin temperatures (see Chapter 5) indicate that the vast majority of reports concern heat-related discomfort rather than cold, at least in terms of overall thermal sensation. This suggests that, in practice, hot cabins are a more frequent and pressing concern for both passengers and cabin crew, while cold discomfort—though possible, especially at the lower end of the standard's range—is less commonly reported.

At lower to medium relative humidities, the calculated comfort ranges for both active and sedentary occupants are well below the ACGIH occupational ALs for heat stress. This provides a substantial safety margin: temperatures can exceed the upper comfort limit somewhat before reaching levels associated with undue heat exposure risk for healthy unacclimatized workers.

However, as relative humidity increases, the upper comfort limit and ACGIH AL begin to converge. This convergence is concerning because the Fanger model (on which thermal comfort standards are based) is less reliable at high humidity and elevated activity. As a result, the "comfort" zone may extend to conditions that are tolerable for healthy workers but could be quite uncomfortable, or even unsafe, for aircraft cabin occupants, particularly for vulnerable groups such as infants, young children, older adults, or those with compromised health.

This issue is especially relevant for the extended upper temperature limits allowed by ANSI/ASHRAE Standard 161-2023 during ground operations with IFE operating (i.e., 29.4°C/85°F). At high humidity, these limits may fall within or near the heat stress zone for active flight attendants and approach it even at lower activity levels. It is important to note that relative humidity—which cannot be controlled on aircraft in the same manner as temperature—is typically quite low during flight (see Chapter 5), so these concerns are most acute during ground operations, especially in hot, humid climates or when ventilation systems are not fully operational.

Figures 4-1 and 4-2 illustrate that the extended temperature limits permitted by ANSI/ASHRAE Standard 161-2023 may not be appropriate if low humidity is not maintained

during ground operations. At higher humidity, the safety margin narrows and the risk of heat stress increases, even at temperatures that would otherwise be considered acceptable. Real-world temperature and humidity data during aircraft boarding phases relative to the thermal response zones are presented in Chapter 5 (see Figure 5-9).

Compensatory Effects of Clothing and Local Cooling on Thermal Comfort

Figures 4-1 and 4-2 illustrate the challenge of providing cabin conditions that are comfortable for the full range of activity levels encountered in an aircraft. As shown in Figure 4-3, the comfort zones for Case 1 (high activity, such as a busy flight attendant) and Case 2 (low activity, such as a seated passenger) barely overlap. This means that only a very narrow range of temperatures is likely to be generally acceptable for both groups. Even within these designated comfort zones, individual differences—such as personal sensitivity, health status, or clothing choices—mean that some occupants will still experience discomfort, feeling either too hot or too cold. This lack of overlap highlights the importance of compensatory strategies that enable behavioral responses, such as clothing adjustments or the use of localized cooling mechanisms (e.g., personal air outlets), to help accommodate the diverse thermal needs of both cabin crew and passengers and lessen the risk of heat or cold strain. While cabin occupants may not always have control over clothing or local air ventilation, without such measures it is nearly impossible to maintain a single cabin temperature that ensures comfort for everyone on board.

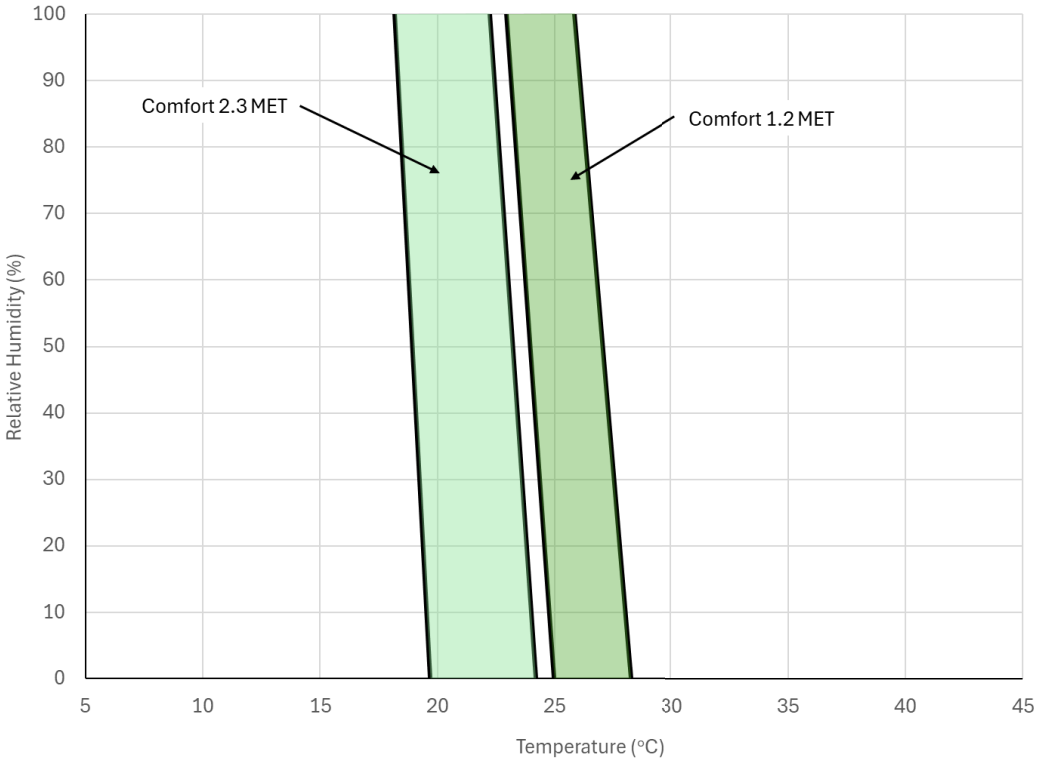

FIGURE 4-3 Comparison of comfort zones for Case 1 (high activity, 2.3 MET) and Case 2 (low activity, 1.2 MET).

Compensatory Effects of Clothing

Clothing is an important factor to consider in the aircraft cabin environment, given the variety of garments and resulting insulation that individuals might wear on a given flight. For example, on a flight from a cold to a warm environment, some people may dress for the originating colder climate, while others may dress for the warmer destination. Additionally, clothing choices are sometimes made for reasons other than thermal comfort. Still, the ability to individually adapt clothing is a powerful means to improve thermal comfort, as individuals can adjust their clothing—to some extent—according to their activity level and thermal preference. There are limits to how much clothing can be removed (especially in public settings), but generally there are fewer limits to how much can be added. Thus, clothing options are more effective for mitigating cold discomfort than for mitigating warm discomfort.

Figure 4-4 demonstrates both the challenge and the opportunity associated with variation in clothing. On the one hand, it is difficult to specify a single set of thermal conditions that is suitable for the wide range of clothing insulation people might wear on a given flight. On the other hand, individuals can achieve comfort across a wide range of thermal conditions if they are willing and able to adapt their clothing as needed. For example, the comfort zones for Case Scenario 3 (high activity, warm clothing) and Case Scenario 6 (low activity, cool clothing) do not overlap at all, making it impossible to find a common temperature that would be widely acceptable to both groups. Conversely, Case 4 (low activity, warm clothing) and Case 5 (high activity, cool clothing) overlap almost perfectly, showing that clothing flexibility and choices can allow acceptable common thermal conditions for a wide range of activities. In summary, clothing adjustments can allow a wide range of temperatures to be acceptable for a given activity level.

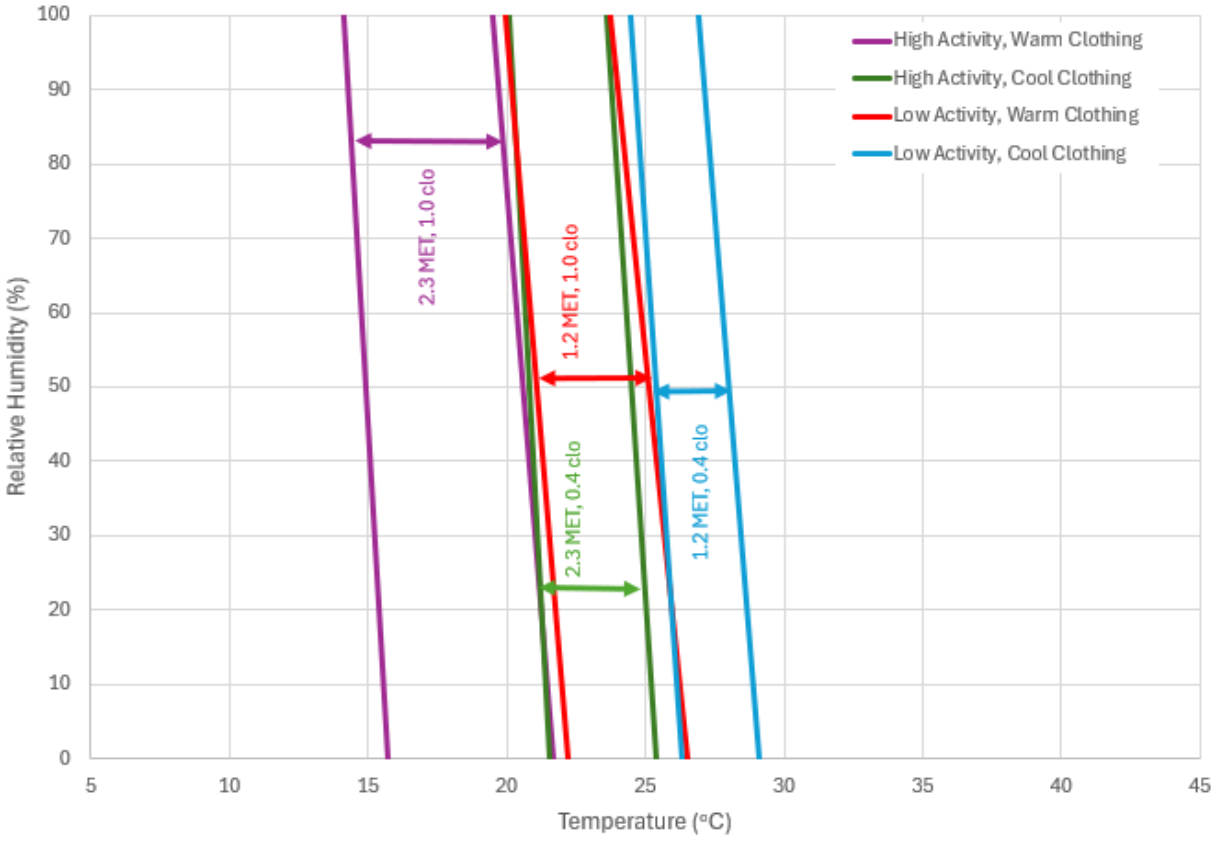

FIGURE 4-4 Comfort zones for case scenarios 3 through 6 involving different activity and clothing insulation levels, demonstrating how the two factors can offset each other.
NOTES: Case scenarios are described in Table 4-3. Upper and lower limits for comfort zones were derived from applying the thermal comfort standard, ISO Standard 7730:2025, while varying activity and clothing level inputs. Comfort zone for the high activity (2.3 MET) with cool clothing case (0.4 clo) case (green lines) overlaps nearly completely with the comfort zone for the low activity (1.2 MET) with warm clothing (1 clo) case (red lines).

Compensatory Local Cooling Effects Through Use of Personal Air Outlets

As described in Chapter 2, many aircraft are equipped with personal air outlets[7] located above each passenger seat. Personal air outlets are an airline-selectable option and are more prevalent on standard-body (single-aisle) aircraft than on wide-body (dual-aisle) aircraft. Passengers can independently control both the flow rate and direction of air from their personal air outlets. This localized airflow can provide a cooling effect due to its elevated velocity. When the air from the personal air outlets is supplied from the environmental control system mix manifold, it is typically cooler than the surrounding cabin air, providing an additional cooling benefit. Personal air outlets are a required feature under ANSI/ASHRAE Standard 161-2023 for flight attendant work and seating areas (ASHRAE, 2023a).

This localized cooling allows a degree of individual thermal control (adaptive behavioral response) and can mitigate sensations of excessive warmth as well as of hot discomfort and heat stress. Accordingly, the presence of personal air outlets in an aircraft cabin is expected to result in a modest upward adjustment of the upper limits of both the comfort zone and the hot discomfort zone depicted in Figure 4-2 for passengers who choose to use them.

Du et al. (2017) conducted experiments to quantify the effect of personal air outlets on thermal sensation at airflow rates ranging from 0.67 to 1.45 L/s (1.4 to 3.0 cfm). At the highest flow rates, the researchers observed a reduction in overall thermal sensation of approximately 0.5 to 0.65 on the same scale as used for PMV, with smaller reductions at lower flow rates. In these experiments, the temperature of the air emitted from the personal air outlet was the same as the cabin air temperature. Air supplied at a temperature lower than the cabin air would be expected to provide a greater cooling effect. Given that the ±0.5 PMV (1-vote range) comfort zone is approximately 4–5°C (7–9°F), as shown in Figure 4-3, the observed reduction in thermal sensation with personal air outlets in the study by Du et al. could correspond to a shift of about one-half this amount, roughly 2–3°C (3.5–4.5°F) in the thermal zones depicted in Figure 4-2.

This benefit, however, is accompanied by increased localized air velocity directed toward the upper body, which may not be well tolerated by all occupants. Both ANSI/ASHRAE Standard 55-2023 and ISO Standard 7730:2025 provide guidance on acceptable limits for localized elevated air speeds to address potential discomfort.

Rankin et al. (2000) conducted a large-scale passenger comfort study which included 3,630 completed passenger surveys across six different aircraft models. One objective of the study was to assess both the perceived importance of personal air outlets and their actual use. Among respondents on aircraft equipped with personal air outlets, 72 percent (724 of 1006 respondents) reported using them during the flight, indicating that personal air outlets are widely valued by passengers. Using a 7-point importance scale (1 = not important, 7 = extremely important), respondents rated personal air outlets an average importance of 5.7 on standard-body

[7] Sometimes called gaspers or gasper vents.

aircraft and 4.9 on wide-body aircraft. Because personal air outlets are not installed on all aircraft, no adjustments were made in this report to the comfort and discomfort zones to explicitly account for their effects. Nevertheless, the combined findings of these studies indicate that personal air outlets can improve thermal sensation under warm cabin conditions, are frequently used when available, and are widely perceived by passengers as important. As such, personal air outlets represent a meaningful, though limited, means of improving thermal comfort and mitigating hot discomfort and heat stress.

CONCLUDING REMARKS

In summary, this chapter reviewed existing thermal comfort and heat/cold stress standards and guidelines and demonstrated an approach for applying them to the aircraft cabin environment. This analysis highlighted the significant impacts of humidity, activity level, clothing, and local cooling mechanisms on thermal comfort and risk and illustrated how these factors interact to shape the thermal experience of both passengers and flight attendants. By establishing thermal comfort and stress zones for various scenarios, the chapter provided a framework for evaluating the adequacy of existing standards, such as ANSI/ASHRAE Standard 161-2023, in protecting the health and safety of aircraft cabin occupants. The findings presented in this chapter inform the committee's charge to assess the applicability of existing standards for ensuring occupant health and safety (discussed further in Chapter 6) and provide the foundation for the following conclusions:

Conclusion 4-1: Thermal comfort standards may not accurately reflect the impact of humidity at higher activity levels, particularly with respect to hot discomfort. This limitation may result in underestimating the risk of thermal discomfort for active occupants in humid conditions.

Conclusion 4-2: The lack of inclusion of humidity effects in ANSI/ASHRAE Standard 161-2023 may restrict its applicability to situations where humidity is low, such as during flight. The temperature criteria in the standard may not accurately reflect comfort requirements where humidity or activity levels may be elevated, such as during ground operations.

Conclusion 4-3: The lower limits of the ANSI/ASHRAE Standard 161-2023 target temperature range may result in substantial cold discomfort for sedentary occupants. Conversely, the special exemption and higher upper temperature limits in ANSI/ASHRAE Standard 161-2023, when all IFE are operating during ground operations, may result in substantial hot discomfort and, potentially, heat stress if cabin humidity is high.

Conclusion 4-4: Clothing can help mitigate discomfort associated with both cool or warm conditions, providing individual control and allowing occupants to better manage their personal thermal comfort. However, there may be limits to the compensatory effects of clothing adjustments on thermal stress.

Conclusion 4-5: Personal air outlets have the potential to improve thermal comfort, modestly expand the comfort zone, and provide some mitigation of hot discomfort. Their installation and use in aircraft provides a means for reducing the effects of excessively warm cabin temperatures.

Conclusion 4-6: Given human variability, the range of activities of aircraft occupants, and limitations on clothing selection for thermal comfort, there is no one set of thermal conditions that all cabin occupants will find comfortable regardless of the effectiveness of aircraft thermal control systems. However, guidelines can be developed that would meet the needs of the large majority of the cabin occupants and mitigate health and safety risks.

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5
Evidence on Health and Safety Impacts of Cabin Temperatures

The committee was charged with assessing the health and safety impacts of temperatures in the passenger cabins of airlines operating under a Part 121 certificate of the Federal Aviation Administration (FAA). Chapter 3 reviewed evidence on the physiological, cognitive, and behavioral effects of cabin temperature exposure, drawing on a broader literature concerning the health and safety impacts of thermal exposures. Importantly, Chapter 3 highlighted key vulnerabilities to temperature effects that vary by age, underlying health conditions, and metabolic rate. Chapter 4 illustrated the application of standards and guidelines on thermal comfort and heat and cold stress to identify cabin temperature and humidity levels at which discomfort and health and safety effects associated with heat and cold stress may be expected. In that discussion it was noted that cabin crew, who are generally more active across all phases of flight, may be at increased risk from temperature exposure compared with the more sedentary passengers. This chapter builds on that foundation by examining the available empirical evidence concerning the impacts of cabin temperature on health and safety, and it concludes with recommendations for future data collection that could enable more reliable assessment of these effects.

Ideally, the committee would have identified a large, national study (e.g., a large-scale survey or medical record analyses of passengers and flight attendants) designed to provide evidence on the health and safety impacts of cabin temperatures. However, a review of published and "gray"[1] literature revealed very limited direct evidence on how cabin temperature—and the related factor of humidity—affect health and safety. The scant direct evidence and the limitations of such evidence are reviewed at the start of this chapter. The chapter further examines indirect evidence of cabin-temperature-related health and safety impacts. In the absence of strong direct evidence from large, systematic studies, data from smaller studies, case reports, and incident summaries still provide useful insights. The committee therefore adopted an approach that integrated data from multiple sources by breaking the problem down into the following key questions which guided the committee's review of the indirect evidence:

- To what extent are passengers and flight attendants exposed to cabin temperatures that are beyond the expected thermal comfort range across all flight phases (e.g., boarding/deplaning, taxiing, and inflight)?
- What are the health and safety impacts of experiencing such temperature exposures?

The empirical evidence reviewed in this chapter is derived from a range of sources, summarized in Table 5-1, including peer-reviewed journal articles (both primary research and literature reviews), government reports, and databases maintained by agencies such as the

[1] Gray literature is defined as the broad category of data or information sources (e.g., government and industry reports) not found in typical peer-reviewed published journals (NIH, n.d.).

Occupational Safety and Health Administration (OSHA) and the Department of Transportation (DOT) as well as U.S. airlines, labor unions, and aviation medical consultation organizations. Some reporting systems were developed specifically to capture cabin temperature issues (e.g., the Association of Flight Attendants' [AFA's] 2Hot2Cold app and the Association of Professional Flight Attendants' [APFA's] hot cabin reporting system), while others—such as the National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS)—focus more broadly on aviation safety. Additional details on these data sources are provided in Appendix A.

TABLE 5-1 Characteristics of Evidence Sources Used by the Committee

Data source	Purpose	Cabin temperature data included?	Cabin humidity data included?	Health and safety outcomes included?	Key limitations
Published research studies	Characterize typical flight conditions and, in some cases, link conditions to thermal comfort	Yes	Most	Only 1 study identified	Relies on convenience sampling; nonrandomized and nongeneralizable; small sample sizes limit detection of rare events.
NASA Aviation Safety Reporting System	Collects voluntarily submitted aviation safety incident/situation reports to enable deficiencies and discrepancies to be remedied by appropriate authorities	Sometimes	No	Sometimes	Voluntary self reporting; inconsistent detail; temperature measurement methods not always known; data not known to be representative of typical flights.
Flight attendant union reporting systems (2Hot2Cold, APFA Hot Cabin Reporting System)	Union-maintained systems for collecting voluntary reports from flight attendants and other cabin occupants on instances of hot or cold cabins to aid union advocacy efforts	Yes	No	Sometimes	Voluntary self reporting; inconsistent detail; subjective determination of what constitutes too hot or too cold; temperature measurement methods unknown; data not known to be representative of typical flights.

DIRECT EVIDENCE OF TEMPERATURE IMPACTS ON HEALTH AND SAFETY OF CABIN OCCUPANTS

Evidence from Research Studies

The committee identified only one study—a collaborative effort among the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the FAA, Boeing, Batelle, and Harvard University (see Box 5-1)—that examined the relationship between cabin thermal conditions (temperature and humidity) and self-reported health outcomes (Battelle, 2018; Lordo et al., 2023). This study found a significant positive association between higher temperatures and several reported symptoms, including back and shoulder pain or stiffness, dry and irritated eyes, ear pain or pressure, nasal congestion, and general discomfort. Conversely, colder temperatures were associated with increased reports of runny nose, sneezing, and dry or irritated throat (Battelle, 2018; Lordo et al., 2023).

Passengers who reported being not "in good health" overall were more likely to experience discomfort and related symptoms (Rankin et al., 2000). This finding highlights a key vulnerability: individuals with compromised health appear more susceptible to temperature-related discomfort—a concern amplified by the aging U.S. population, which faces higher rates of chronic conditions that impair temperature regulation (as discussed in Chapter 3).

BOX 5-1
ASHRAE Research Project 1262

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Airliner Cabin Environmental Research (ACER) Program developed research project RP-1262, which was co-sponsored by the Federal Aviation Administration (FAA), Boeing, and ASHRAE. The project examined environmental conditions and cabin air contaminants across three airlines operating eight aircraft models, comparing these conditions to existing standards and other indoor environments. The goal was to update design performance standards to better protect passenger and crewmember health and safety—a concern originally raised in a 2002 National Academies report (NRC, 2002).

ASHRAE RP-1262 examined temperature and humidity in the aircraft cabin during 80 of 130 flights, along with other environmental conditions and flight characteristics (e.g., duration and flight paths) in relation to the comfort and health of the passengers and crewmembers (Lordo et al., 2023). Batelle developed and evaluated measurement protocols and conducted inflight measurements for ASHRAE, working in collaboration with Harvard University ACER researchers. In addition, Batelle surveyed 6,135 passengers and 1,232 cabin (flight attendants) and flight deck crewmembers on comfort, health, and safety effects aboard 129 flights (Battelle, 2018).

Temperature was continuously measured during the 80 flights using sensors placed in the middle of economy class, away from side walls (aisle or middle seats), across all aircraft models despite design variations that could affect localized temperatures (e.g., galleys). Measurements began after the aircraft ascended to 10,000 ft and ended at 10,000 ft during descent, meaning that conditions at the gate or on the runway were not captured in relation to passenger or crewmember health and safety.

Interpretating the findings from ASHRAE RP-1262 requires taking into account several limitations. First, self-reported health and comfort were collected only from participants aged 18 years and older, excluding infants, children, and adolescents. Second, symptoms related to temperature and humidity during boarding or while on the runway were not captured (surveys were not distributed until the flight was underway). No objective physiological measures—such as heart rate, breathing rate, blood pressure, oxygen saturation, or cognitive function—were recorded. Other FAA-supported studies conducted by the Airliner Cabin Environmental Research Program–National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment independent of the ASHRAE RP-1262 project incorporated physiological measures showing significant health changes in vulnerable and older passengers, including arrythmias and oxygen desaturation linked to environmental stressors such as cabin pressures, even when the symptoms were not reported (McNeely and Watson, 2011). These findings underscore the fact that health consequences are not always apparent.

Evidence from Aviation Industry Reporting Systems

Additional direct evidence on the health and safety impacts of cabin temperatures comes from aviation industry reporting systems, such as the NASA ASRS and data collected through the 2Hot2Cold app. Self-reported health outcome data from these sources are largely limited to symptom descriptions (e.g., nausea, lightheadedness, dehydration), and many minor events likely go unreported. The durations of exposure to cabin temperatures that resulted in health symptoms are generally not reported. There is no predetermined threshold to prompt reporting through these systems. In the absence of an apparent temperature-related illness, injury, or safety event, reporting relies on a subjective determination of whether cabin temperatures are too hot or cold. Crewmember awareness of cabin-temperature-related issues and reporting systems may influence the likelihood of reporting. Additionally, while tools like the 2Hot2Cold app were designed to be used at any time, the committee learned that flight attendants would need to use off-duty (unpaid) time to submit reports (temperature-related or otherwise) to systems such as ASRS, which may have disincentivized reporting. As noted in Appendix A, airlines also maintain their own reporting systems that may include health and safety events, but the committee did not have access to those data.

NASA ASRS Data

Table 5-2 summarizes the physical, cognitive, and behavioral effects of cabin temperature exposure described in NASA ASRS reports. Because reports of extreme cold were rare, most symptoms listed relate to heat exposure, although the committee did hear during a public meeting an anecdotal account of possible frostbite from exposure of a flight attendant to localized cold conditions (Heiple, 2025). Of the more than 500 unique reports captured from iterative keyword searches of ASRS reports from Part 121 air carrier operations submitted from 1988 to 2026 (see Appendix A), 154 temperature-related reports were identified and analyzed, yielding 13 cases (8.4 percent) in which medical attention was sought,[2] supporting media reports (Cook, 2017; Fingert, 2025; Grant and Sweeney, 2023) that serious temperature-related health impacts, while uncommon, do occur. Safety concerns are further suggested by behavioral issues

[2] The numbers of incidents requiring medical attention are likely higher than reported here, given descriptions of serious symptoms (e.g., seizure, loss of consciousness) in reports for which no mention of medical attention was noted.

(unruliness) and cognitive symptoms (e.g., distraction from duties, procedural errors) noted in ASRS reports. While most cognitive effects were reported by members of the flight crew, similar effects on flight attendants' cognition and performance of duties are likely, as noted in Chapter 3.

TABLE 5-2 Physical, Cognitive, and Behavioral Symptoms Reported in NASA ASRS Reports

Symptom Category/Type	Number of Reports (N=154)[a]	Percentage of Reports (%)
Physical Symptoms		
Heat illness/heat stress	19	12.3
Nausea/vomiting	13	8.4
Difficulty breathing	10	6.5
Lightheadedness/dizziness	14	9.1
Fatigue	8	5.2
Loss of consciousness/ unresponsiveness	8	5.2
Headache	3	1.9
Seizure	2	1.3
Dehydration	2	1.3
Chest pains	1	0.6
Fever	1	0.6
Cognitive Symptoms		
Distraction from duties/procedural errors	7[b]	4.5
Behavioral Symptoms		
Emotional distress (e.g., crying, panic)	7	4.5
Irritability/anger	16	10.4
Unruliness (e.g., verbal aggression towards cabin crew, threats)	9	5.8

[a] Numbers in this column do not sum to the total number of committee-identified NASA ASRS reports citing cabin temperature issues (N = 154) because many reports (83) did not include mention of symptoms from temperature exposures, and some reports included symptoms that fall into multiple categories.

[b] Of the seven reports of cognitive symptoms that affected performance of duties, all seven involved the flight crew, and one of those also involved flight attendants.

SOURCE: Created with data from NASA (2025).

AFA 2Hot2Cold Data

Medical or first aid was provided in 4.5 percent of 3,883 relevant 2Hot2Cold reports, with more extreme temperatures associated with greater risk (see Figure 5-1). For example, 8.8 percent of reports involving cabin temperatures of 40°C (100°F) or more required medical aid. In contrast, there were no reports indicating the provision of medical aid for temperatures between 15 and 20°C (70–79°F). The involvement of medical attention may lead to crew distractions, flight delays, or aircraft diversions for occurrences during flight.

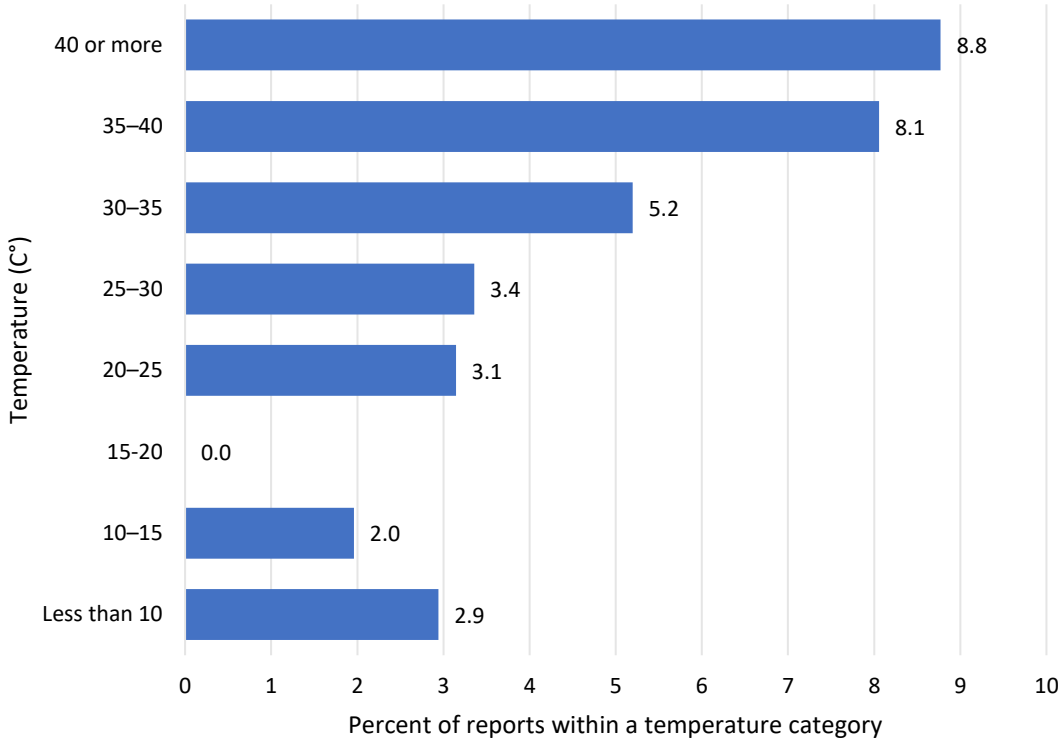

FIGURE 5-1 Percentage of 2Hot2Cold reports within each temperature category indicating the provision of medical or first aid.
NOTES: The 2Hot2Cold dataset received by the committee included a field for "Medical or First Aid Provided?" that was used to calculate the percentage of reports for which provision of medical or first aid was noted. For 796 reports the provision of medical or first aid was marked as unknown; these reports were omitted from analysis, leaving 3,883 reports for analysis. Reports are only submitted when there is an issue, and the need for medical aid may be more likely to result in reports than extreme temperatures alone. Thus, these results are likely to overstate the frequency of reports among flights overall. It is possible for multiple reports to be submitted for a single flight, so these counts are not identical to the number of flights involved. As an example of how to read the temperature ranges, 20–25 represents those temperatures that were at least 20°C (68°F) and below 25°C (77°F) with no rounding.
SOURCE: Created with data from AFA (2025).

Summary and Synthesis

In summary, evidence from aviation industry reporting systems suggests that health and safety concerns related to cabin temperature exposures are more serious than those captured in the ASHRAE RP-1262 study, which reported associations with only minor health issues (e.g., shoulder pain or stiffness, eye irritation, nasal congestion) (Lordo et al., 2023). The comparison of evidence sources is limited by the fact that the ASHRAE RP-1262 study focused only on inflight conditions, in contrast to aviation industry reporting systems, which include data on inflight and on-ground occurrences. The absence of information on measurement methods, humidity levels, and duration of exposure limits the inferences that can be drawn from data from incident reporting systems like NASA ASRS and 2Hot2Cold.

INDIRECT EVIDENCE OF TEMPERATURE IMPACTS ON HEALTH AND SAFETY OF CABIN OCCUPANTS

Because direct evidence linking cabin temperature exposure to health and safety outcomes is limited in both quantity and scope, this section examines indirect evidence to assess potential impacts. The analysis draws on available data for cabin temperature and humidity and, where possible, compares these real-world conditions with thermal discomfort or heat and cold stress zones defined by established thermal comfort and stress standards and guidelines (see Chapter 4).

Summary of Evidence from Cabin Temperature and Humidity Data

Data from Research Studies

A limited number of studies have measured and reported aircraft cabin temperature and humidity conditions. In addition to peer-reviewed articles, the committee identified several relevant reports from research studies in the gray literature.[3] Table 5-3 summarizes the temperature and humidity ranges reported across these studies,[4] while Table 5-4 compares the sources that include individual temperature and humidity measurements that could be further reviewed. Comparisons in both tables should be interpreted cautiously, as study protocols were not standardized. For instance, instrumentation varied widely, from inexpensive temperature–hygrometer sensors to sophisticated climate devices. Many data were collected on convenience flights, while other studies aimed for a more representative mix. Some sources recorded conditions only at specific points in a flight (e.g., after boarding and 1 hour after takeoff), whereas others collected continuous measurements throughout the flight. Most measurements were taken during flight, with the exception of the study by Nicholls and Vink (2025), which also captured boarding conditions. In many cases, temperature and humidity were secondary parameters within broader studies focused on air contaminants (e.g., carbon dioxide, carbon monoxide, ozone, volatile organic compounds, particulate matter) or ventilation performance rather than primary endpoints.

Summary data from published research studies

Despite the aforementioned limitations, the data from published research studies provide a reasonable picture of typical cabin conditions. Mean temperatures generally fall between 23ºC and 25ºC (73.4ºF and 77ºF), with extremes reaching 30–32ºC (86–90ºF) on the warm side and 17–18ºC (63–64ºF) on the cool side. Studies with larger sample sizes report wider ranges, as

[3] Nearly half of the studies collected data from air carriers based outside the United States (i.e., not operating under an FAA Part 121 certificate). However, this information was not consistently reported. Given the limited availability of cabin temperature and humidity data and the fact that the same commercial aircraft models are used by both domestic and international air carriers, the committee chose not to exclude studies based on whether they involved Part 121 operators. Studies that simulated flight conditions were excluded from the committee's analysis of cabin temperature and humidity data.

[4] The article by Wang and colleagues (2024) referenced in Table 5-3 is a review paper that summarizes data from 19 studies that measured cabin temperature and 20 studies that measured relative humidity. Summary data for the primary studies included in that review can be found in Table B-1 in Appendix B.

expected. Humidity levels drop sharply after takeoff and remain low during flight, typically in the 10 to 20 percent range.

TABLE 5-3 Summary of Cabin Temperature and Humidity Data from Published Studies

Study	Number of Flights	Mean Temperature across all Flights (°C [°F])	Minimum Temperature (°C [°F])	Maximum Temperature (°C [°F])	Mean and/or Range of Relative Humidity (%)
Wang et al. (2024) (review article)[a]	252 (temperature measurements) / 273 (relative humidity measurements)	23.7 (74.7)	20.6 (69.1)[b]	25.2 (77.4)[b]	18.4 11.6–43.6
Cui et al. (2017)	10	NR	23.0 (73.4) (lowest average among individual flights)	26.6 (79.9) (highest average among individual flights)	15.4–20.8
Gameiro da Silva et al. (2023)	25	NR	22.7 (72.9) (lowest average among individual flights)	29.3 (84.7) (highest average among individual flights)	23.3–37.6
Nicholls and Vink (2025) (boarding)	143	23.5 (74.3)	16.7 (62.0) (across all flights)	30.2 (86.4) (across all flights)	36.4 10–82
Nicholls and Vink (2025) (in-flight)	143	24.5 (76.1)	17.8 (64.0) (across all flights)	31.3 (88.4) (across all flights)	20 9–59
EASA (2017) (bleed air)	12	24 (75.2)	21 (69.8) (across all flights)	28 (82.4) (across all flights)	13 5–28
EASA (2017) (electric compressor)	8	21 (69.8)	18 (64.4) (across all flights)	24 (75.2) (across all flights)	18 10–43
Battelle (2018) (ASHRAE RP-1262)	80	24.4 (75.9)	19.2 (66.6) (lowest median across all flights)	31.3 (88.3) (highest median across all flights)	10.7 1.7–41.2

NOTE: NR = not reported.

[a] Wang and colleagues (2024) reviewed 54 studies on in-flight aircraft cabin environmental factors and identified 19 studies (covering a total of 252 flights) that measured cabin temperature and 20 studies (for a total of 273 flights) that measured relative humidity. The reported statistics reflect aggregated data across all applicable flights. As a review article, these figures depend on the data reported in the original

studies. Summary data for the primary studies included in the review can be found in Table B-1 in Appendix B.

[b] Minimum and maximum values represent averages across flights (which the authors categorized by aircraft type), not the absolute extreme observed across all flights.

Data from studies from which individual temperature and humidity measurements are available

Beyond the summary statistics published in peer-reviewed and gray literature, the committee obtained linked raw cabin temperature and humidity data from the following three sources:

1. Nicholls and Vink (2025) publication appendix;
2. ASHRAE RP-1262 (Lordo et al., 2023) project dataset; and
3. ACER program data (unpublished).

Combined, these datasets—referred to as Nicholls and Vink, ASHRAE 1262, and ACER, respectively—provide inflight temperature and humidity data for 379 flights, offering a broad cross-section of conditions routinely encountered in aircraft cabins. Key characteristics of the datasets are summarized in Table 5-4. In addition to providing data used to characterize distributions of cabin temperature and humidity, these datasets were used in the comparison of cabin conditions with thermal discomfort and heat and cold stress zones as described later in this chapter. As emphasized in Chapter 4, humidity plays a critical role in thermal response, particularly in zones of warm discomfort and heat stress. Therefore, mapping cabin conditions to thermal response zones requires simultaneous temperature and humidity measurements.

TABLE 5-4 Summary of Datasets with Raw Cabin Temperature and Humidity Data

Dataset	Number of Flights with Temperature and Humidity Measurements (Total Flights)	Flight Sampling Method	Instrumentation	Data Collection Timing
Nicholls and Vink	101 (143)	Convenience	Inexpensive, consumer-grade	After boarding and 1 hour after takeoff
ASHRAE 1262	68 (80)	Designed to capture a range of flight conditions	Laboratory-grade	Continuous while altitude ≥ 10,000 ft
ACER	210 (210)	Convenience	Mixed prototypes	Continuous with variable start time

The Nicholls and Vink study employed a well-defined measurement methodology. Cabin temperature and humidity measurements were recorded at two points: upon passenger boarding (once seated) and again 1 hour after takeoff. Measurements were taken using a small temperature and humidity sensor placed on the passenger tray table. Flights were selected by convenience—data were collected on flights taken by project personnel and volunteers—rather than through independent sampling. The device used for these measurements was an inexpensive, consumer-

grade device. Given the challenges of accurately measuring humidity (Ma et al., 2023), these low-cost devices likely represent a limitation of the Nicholls and Vink dataset. The device manufacturer's specifications reported on the online retail site provided in correspondence with the authors (Vink, 2025) are ±1ºC and ±5 percent relative humidity, with operating ranges of –50 to +70 ºC (-58 to 158°F) and 10–90 percent relative humidity. The study methods did not include calibration or verification of sensor accuracy (Vink, 2025). In total, boarding measurements were collected on 113 flights and 1-hour measurements on 101 flights. The study methods provide no information regarding the timeframe for data collection, but correspondence from the authors indicated that data were collected between June 1, 2022, and March 1, 2023 (Vink, 2025). The dates of individual flights are unknown. In contrast to the other datasets used in the committee's analyses and importantly for a study including data on ground operations, the study by Nicholls and Vink included ambient temperature (but not humidity) data for each of the flights for which cabin temperature and/or humidity measurements were taken. Exterior temperatures varied from -31.1°C to 32.2°C (-24°F to 90°F). Boarding temperatures varied across a smaller range (16.7°C to 30.2°C [62.0°F to 86.6°F]) but were correlated with exterior temperatures (r = .448) (Nicholls and Vink, 2025).

The ASHRAE RP-1262 project, described in Box 5-1, collected data on flights intentionally selected to capture a range of flight conditions (flight lengths, longitude ranges, season) rather than a random sample. Consistent measurement protocols were established and adhered to throughout the study.. Instruments were located in an unoccupied seat reserved for this purpose near the middle of the economy section. A key limitation of this dataset is that all measurements were taken only after the aircraft reached 10,000 feet and before descending below that altitude, excluding conditions during boarding and taxiing. Once activated, instruments recorded temperature and humidity measurements every minute. In total, temperature and humidity data were reported for 62 flights.

The ACER dataset was developed through a project aimed at creating a compact instrument package capable of measuring and recording multiple environmental variables—including air temperature, relative humidity, and cabin pressure—while being portable enough to carry on any flight without special accommodations (Chen et al., 2010). Several instrument prototypes were built and tested during the project. Data were collected on flights of convenience by project personnel, colleagues, and volunteers. Due to the developmental nature of the project, measurement protocols varied: some recordings began during boarding, others shortly before takeoff, and some only after reaching altitudes above 10,000 feet. Although records did not specify the exact timing of instrument activation, flight versus ground operation can be distinguished using cabin pressure data. Instrument placement also varied, including being placed on tray tables, hanging outside the seatback pockets, or sitting inside seatback pockets. Once activated, the instruments recorded data continuously until they were turned off. Sensor calibration was conducted and verified for selected instruments by an independent lab, though validation focused primarily on cabin pressure and CO_2 concentration measurements rather than temperature and humidity (Cao et. al., 2019). In total, data were collected and archived for 210 flights.

The Nicholls and Vink in-flight data were collected 1 hour into each flight. Because neither the ASHRAE 1262 nor ACER data collections recorded the time when data collection began, it was not possible to identify the 1-hour point for comparison. However, continuous data collection in the ACER and ASHRAE 1262 datasets indicate that cabin conditions typically stabilize after takeoff and climb-out, with minimal variation during cruise. To provide a

consistent reference point across datasets, measurements from the top of descent—identified by the onset of increasing cabin pressure and, when available, data on changes in altitude—were used to represent in-flight conditions in the ACER and ASHRAE 1262 datasets. An analysis of the longitudinal measurements for a subset of flights (see Appendix B) suggests that the temperatures used in the assessments are representative of an extended exposure and are not the result of short fluctuations in cabin conditions.

Figure 5-2 presents a comparative overview of inflight temperature and humidity distributions across these datasets, grouped into four humidity ranges. All three datasets show similar temperature patterns, dominated by the 20–30°C (68–86°F) range, with fewer than 10 percent of flights outside this range. The ACER dataset features a slightly higher mean temperature (25.7°C, or 78°F) than Nicholls and Vink or, ASHRAE 1262, which had means of 24.5°C and 24.9°C, respectively (76°F and 77°F), and than other published datasets (see Tables 5-3 and B-1). This small difference may reflect different instruments or instrument placement practices—some ACER devices were positioned inside the seatback pocket where localized heating could occur.

Relative humidity patterns for the inflight data differ more noticeably. The ASHRAE 1262 dataset is concentrated in the very low range (less than 15 percent, with an average of 9 percent), while ACER data are more evenly distributed in the low humidity range (less than 30 percent, with an average of 16 percent), similar to published datasets (see Tables 5-3 and B-1). Only the Nicholls and Vink dataset includes some midrange humidity values (30–60 percent), though the average was 20 percent. Given the challenges of accurately measuring low humidity, these differences between the datasets likely reflect instrumentation accuracy limitations. Proper calibration of sensors is essential for accurate humidity measurements (Schellenberg 2002). None of the reports or publications for the studies associated with these three datasets documented calibration or verification of the accuracy of the humidity sensors used. Some of the data in the datasets appear to be unrealistically low (e.g., less than 5 percent relative humidity). Nevertheless, it is clear from the data collected in these three studies that relative humidity in aircraft during flight is typically low, mostly below 30 percent relative humidity and often below 15 percent.

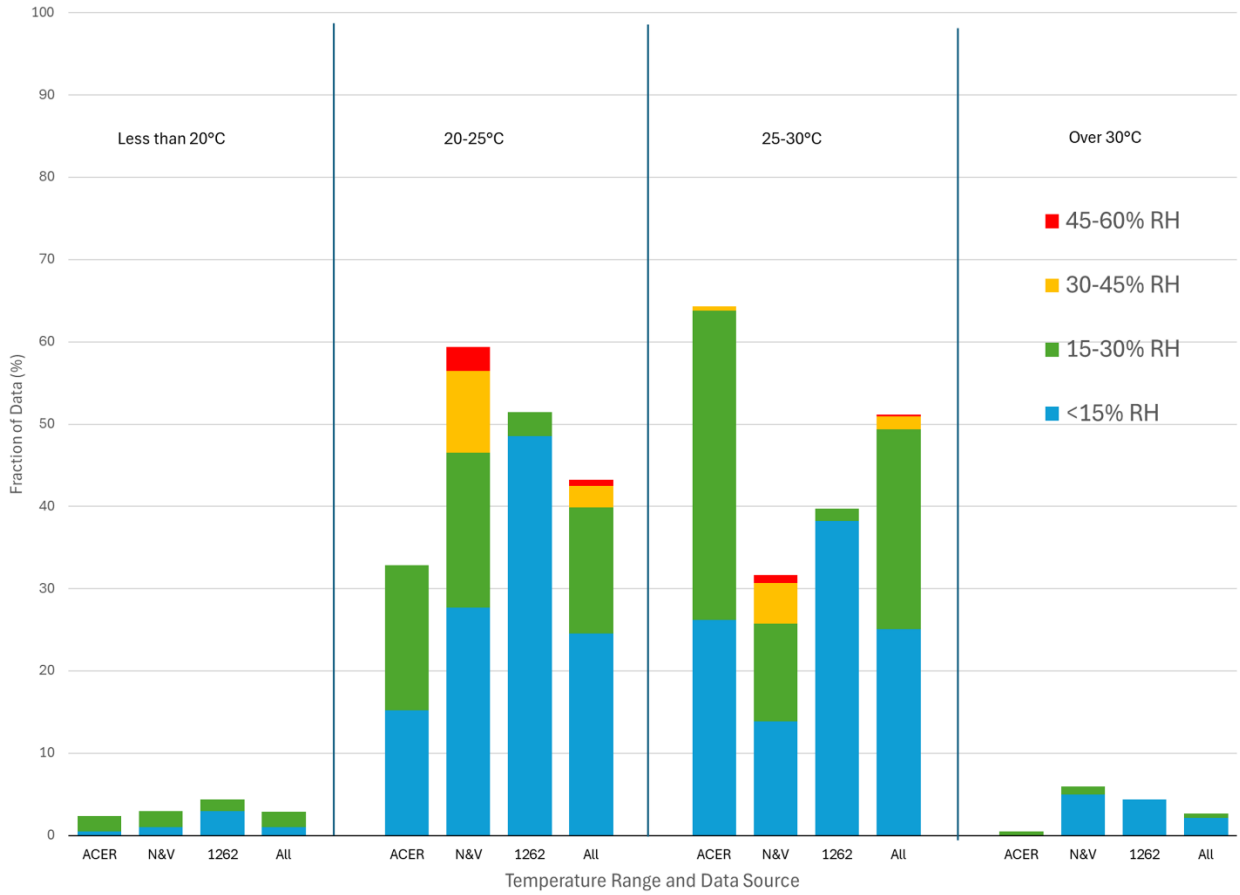

FIGURE 5-2 Distribution of inflight temperature and humidity data from three independent datasets (Nicholls and Vink, ACER, ASHRAE 1262).
NOTE: RH = relative humidity; N&V = Nicholls and Vink; 1262 = ASHRAE-1262.
SOURCES: Created with data from ACER (2025), ASHRAE (2026), and Nicholls and Vink (2025).

Data from Aviation Industry Reporting Systems

Data from aviation health and safety and complaint reporting systems, understandably not random, present a markedly different picture from published research data (see Figure 5-3). More than half of the 84 NASA ASRS reports that reported cabin temperatures (out of 154 total reports) cite temperatures of 35ºC (95ºF) or higher, with approximately 13 percent reporting temperatures at or above 40ºC (104ºF). Data from the 2Hot2Cold app (4,679 relevant reports, all but 4 of which included temperature values) and the AFPA Hot Cabin reporting system (352 reports with 261 including temperature values) show an intermediate range, with the majority of reports toward the warmer end of cabin temperatures, falling between 25ºC (77ºF) and 35ºC (95ºF).[5] Corresponding humidity data are not available from these sources; however, it is

[5] The vast majority of reports from these systems concern heat-related cabin temperature issues. In fact, only approximately 5 percent of the relevant NASA ASRS reports identified by the committee involved cold cabin conditions.

reasonable to assume that humidity could be elevated at higher temperatures during ground operations when ventilation systems are shut off (Horstman, 2025).

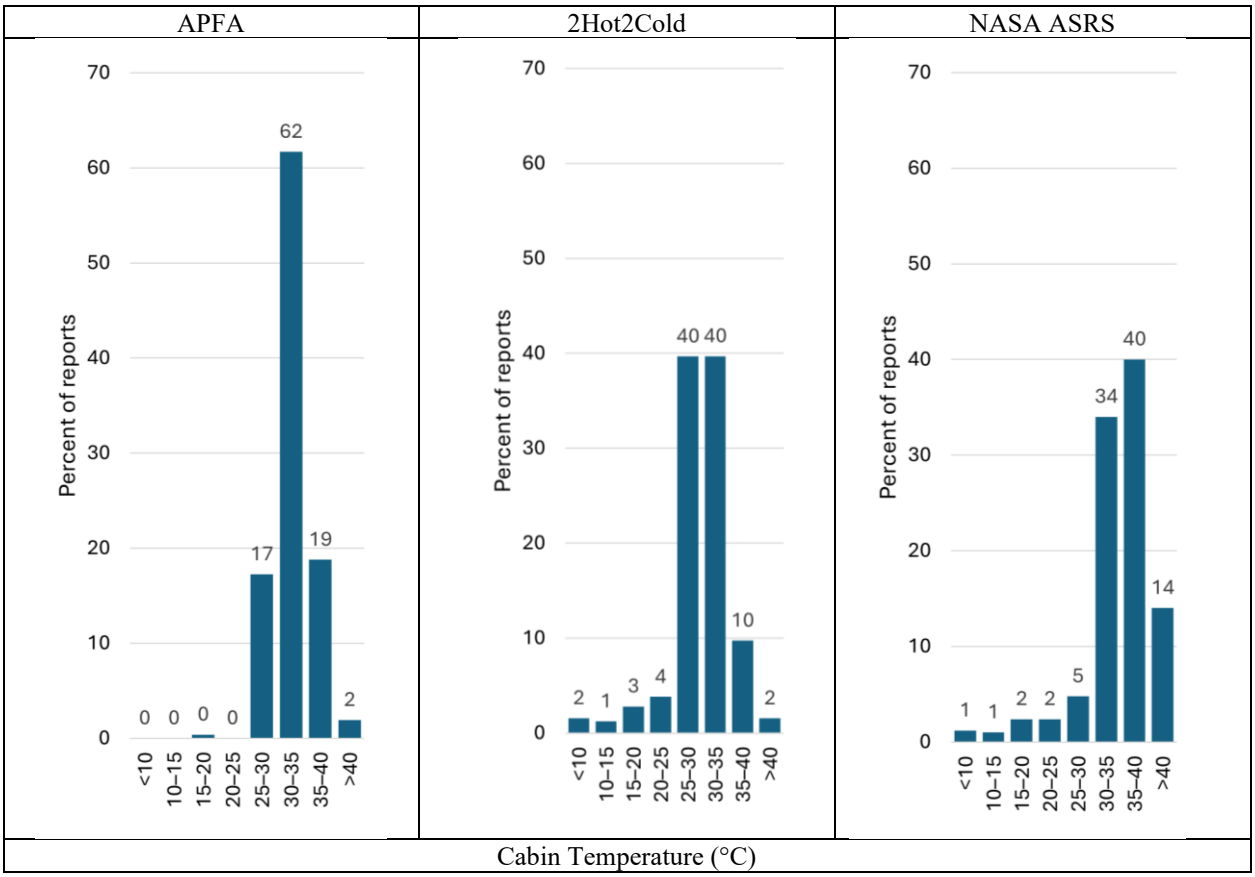

FIGURE 5-3 Percentage of reports from aviation industry reporting systems citing cabin temperature issues, categorized by temperature range and data source.
SOURCE: Created with data from AFA (2025), APFA (2025), and NASA (2025).

Differences in reported temperatures across these systems reflect the different objectives and methods for the reporting systems. NASA ASRS reports are primarily submitted to document safety concerns and are typically generated only in such cases. In contrast, reports from the 2Hot2Cold app and the AFPA Hot Cabin system are better characterized as complaint data, submitted when flight attendants or other cabin occupants perceive conditions as excessively hot (or cold). These reports may or may not be intended to signal a safety issue. Characteristics of these different data sources (including years of available data) are summarized in Table A-2 in Appendix A. Contextualization of the aviation industry reporting data relative to the total number of flights estimated to have occurred over the respective reporting periods is provided later in this chapter (see section on Assessing the Magnitude of the Problem).

Figures 5-4 and 5-5 compare the 2Hot2Cold and NASA ASRS reports with inflight and ground temperature data from ACER, ASHRAE 1262, and Nicholls and Vink. Figure 5-4 compares inflight temperatures from all three data sources with the complaint reports, while Figure 5-5 contrasts only Nicholls and Vink on-ground temperatures with those reports. There is

an evident distinction between the more typical cabin conditions and the extremes that trigger complaints or safety reports.

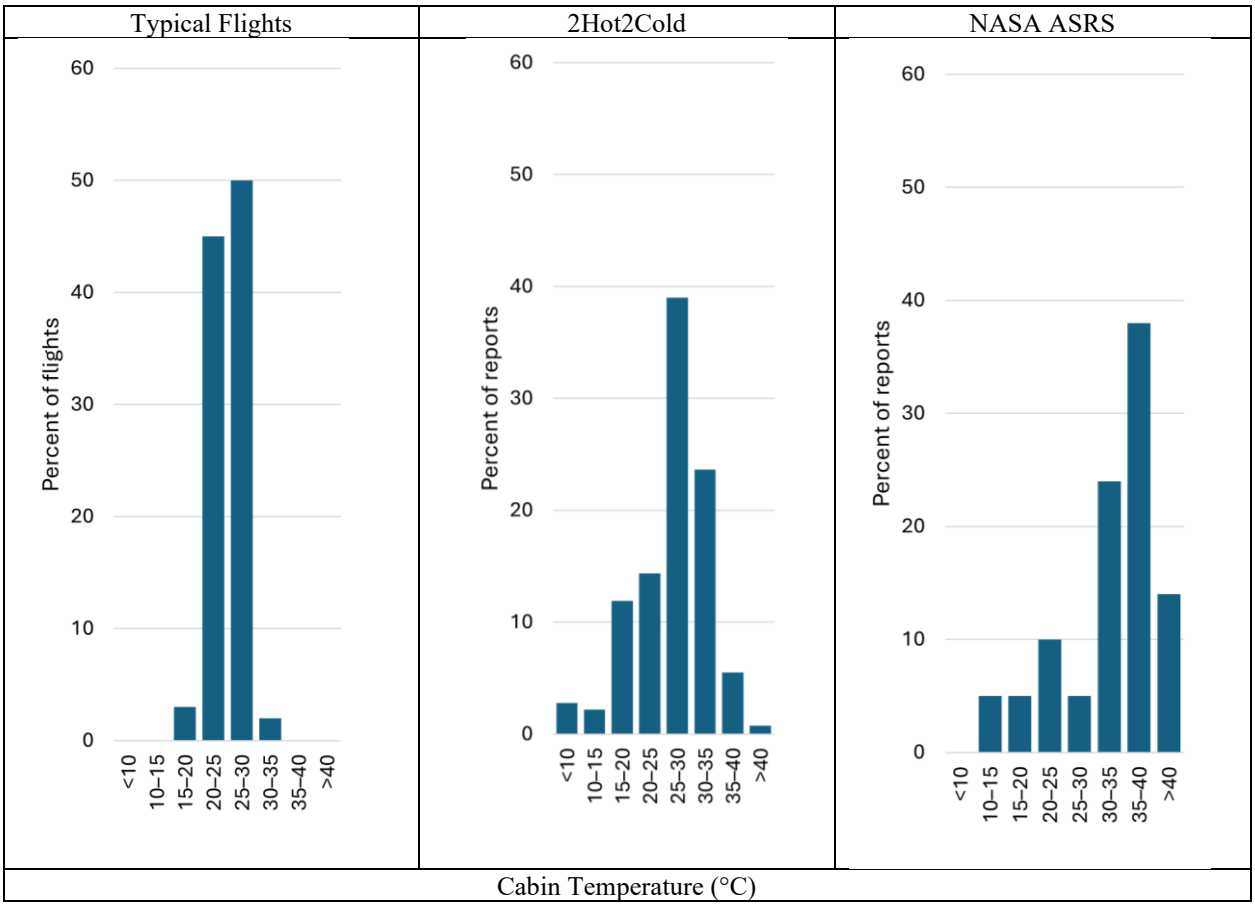

FIGURE 5-4 Comparison of the distributions of in-flight cabin temperatures observed/reported during typical flights, 2Hot2Cold reports, and NASA ASRS reports.
NOTES: Each panel shows the percentage of observations within a dataset falling into 5°C temperature intervals; percentages sum to 100 percent within each dataset. Complaint and health and safety reports show more extreme conditions than those observed in typical flights from research studies (i.e., data from ACER, ASHRAE-1262 and Nicholls and Vink), particularly on the hot side.
SOURCE: Created with data from ACER (2025), AFA (2025), ASHRAE (2026), NASA (2025), and Nicholls and Vink (2025).

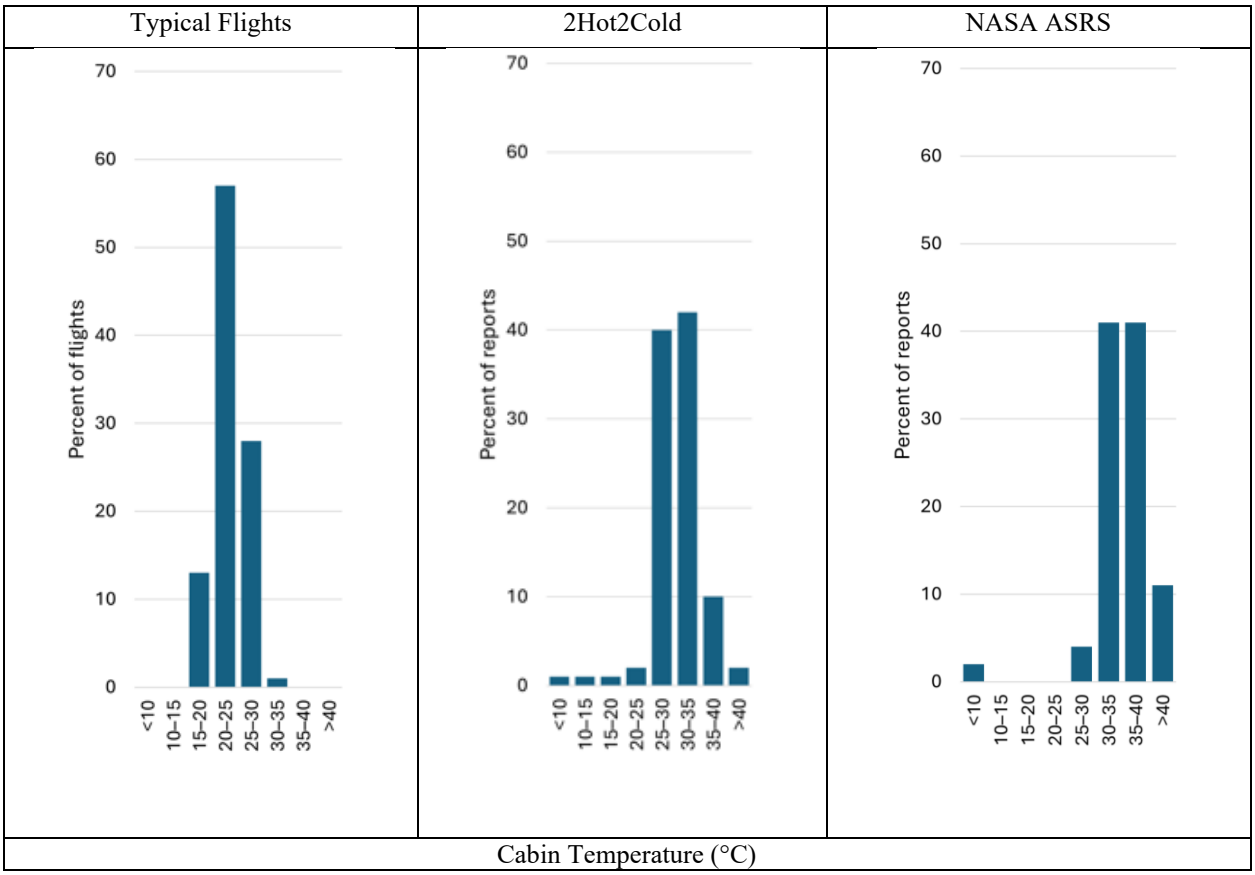

FIGURE 5-5 Comparison of the distributions of on-ground cabin temperatures observed during typical flights (from Nicholls and Vink study), 2Hot2Cold reports, and NASA ASRS reports.
NOTES: Each panel shows the percentage of observations within a dataset falling into 5°C temperature intervals; percentages sum to 100 percent within each dataset. Data illustrate the gap between routine boarding conditions and the extreme temperatures associated with reported incidents. Nicholls and Vink (2025) was the only available source of on-ground cabin temperatures.
SOURCE: Created with data from AFA (2025), NASA (2025), and Nicholls and Vink (2025).

Mapping Cabin Temperature and Humidity Data to Thermal Zones Based on Thermal Comfort and Heat and Cold Stress Standards and Guidelines

To explore the available indirect evidence linking cabin temperature and humidity levels to health and safety outcomes, the committee overlaid measured cabin conditions from the Nicholls and Vink, ACER, and ASHRAE RP-1262 datasets onto the thermal response zones that were prepared and described in Chapter 4. These zones represent ranges of environmental conditions associated with comfort, discomfort, and heat or cold stress for typical low and moderate activity levels. Similar methods have been used by others to interpret cabin temperature and humidity data in the context of limits from thermal comfort standards (Gameiro da Silva et al., 2023; Haghighat et al., 1999), although the committee is unaware of any such comparisons that have also incorporated heat and cold stress limits.

To orient readers, Figure 5-6 introduces the thermal zones alone that were developed in Chapter 4. Figures 5-7, 5-8, and 5-9 incorporate data points from the datasets with linked cabin

temperature and humidity measurements. The curvilinear zone boundaries in these figures reflect the effects of humidity on thermal comfort and stress. This visual framework enables comparison of measured cabin conditions with zones that influence physiological, cognitive, and behavioral responses (see Chapter 3). For the mappings, in-flight data from all three datasets (Nicholls and Vink, ACER, and ASHRAE RP-1262) were combined in Figures 5-7 and 5-8. The Nicholls and Vink on-ground measurements collected from 113 flights before departure from the gate were mapped separately (Figure 5-9).

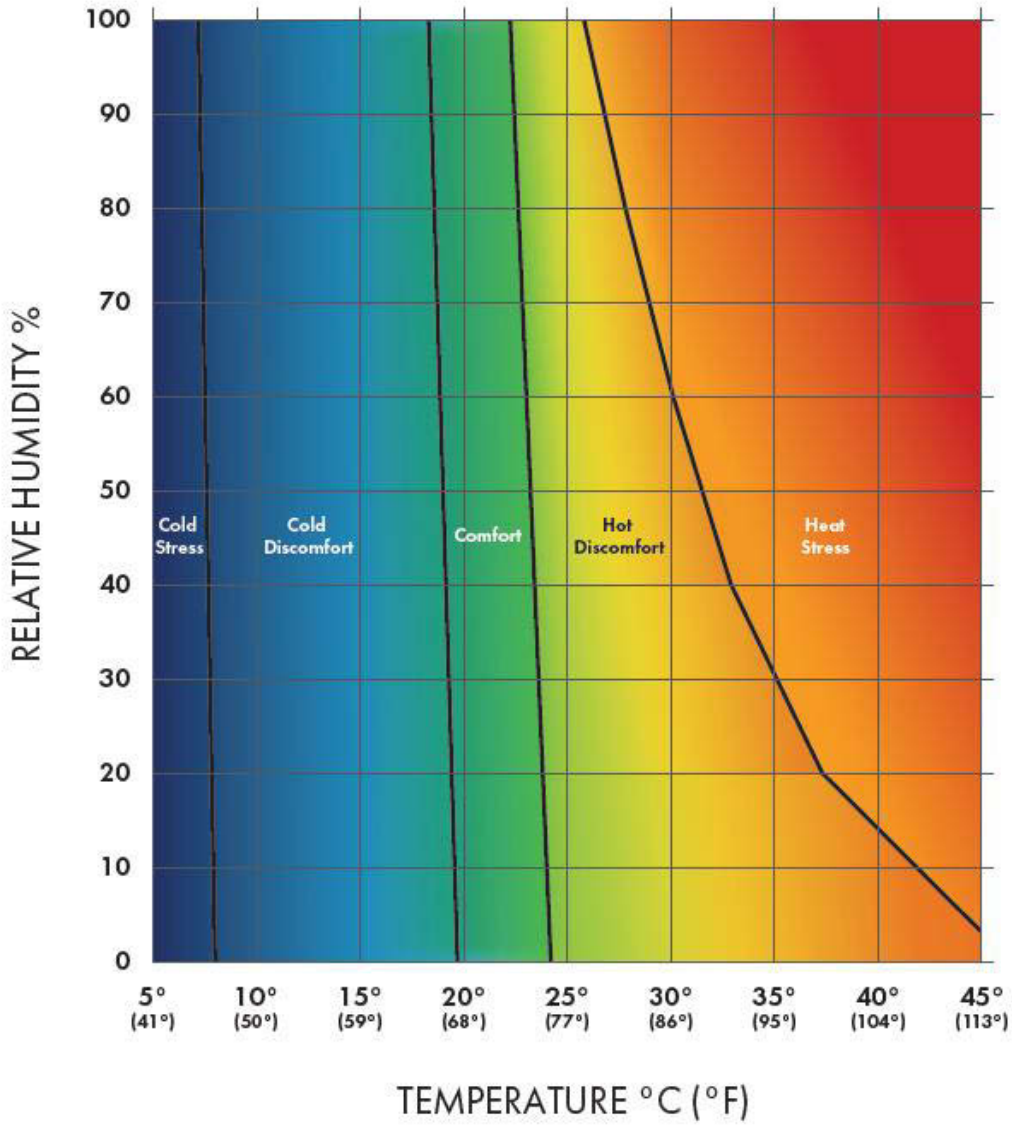

FIGURE 5-6 Thermal response zones from the application of thermal comfort and heat and cold stress standards and guidelines for a scenario involving an active flight attendant wearing typical clothing (2.3 MET, 0.6 clo).
NOTES: The green comfort zone is bounded by the upper and lower limits from the application of the thermal comfort standard (Standard 7730:2025 of the International Organization for Standardization [ISO]). The red heat stress zone is bounded by the action limits from the ACGIH (American Conference of Governmental Industrial Hygienists) heat stress and strain guideline

(applies to unacclimatized workers). Curvilinear zone boundaries are due to the large influence of humidity when addressing heat stress. Importantly, the action limits may underestimate exposure at high and low humidity, and the boundaries should not be applied outside the scope of this study. The yellow hot discomfort zone is defined as the space between the comfort and heat stress zones. Similarly, the upper limit for the dark blue cold stress zone is defined by the application of ISO Standard 11079:2007, and the light blue cold discomfort zone is defined as the space between the cold stress and comfort zones. Shading indicates that the transitions from comfort to discomfort and from discomfort to stress are gradual and continuous, rather than abrupt, and it reflects the variation in individual-level tolerances. Exposure duration is not depicted, but the effects are not instantaneous; the potential for negative health effects and greater severity increases with longer durations of exposure.

Given the effects of metabolic activity level on thermal comfort, it is instructive to view the measured flight conditions considering the range of activities encountered by flight attendants and by passengers. Figures 5-7 and 5-8 illustrate how measured cabin conditions compare to thermal comfort and stress zones. The figures depict the same cabin temperature and humidity data, but the thermal response zones differ, reflecting two different activity levels described in Chapter 4:

- Case scenario 1: Active flight attendant—representing a moderate activity level and typical clothing (2.3 MET, 0.6 clo)
- Case scenario 2: Seated passenger or flight attendant—representing a low activity level and typical clothing (1.2 MET, 0.60 clo)

Case scenario 1 with 2.3-MET activity level is intended to represent the condition of the sustained activity of a busy flight attendant. Typically, flight attendant activities will be well below this level for much of a flight, especially longer flights. For this scenario (Figure 5-7), conditions from the three data systems fall primarily within the warm discomfort zone, with few observations near cold discomfort and none within heat stress or cold stress zones. This pattern reflects the higher metabolic load of active flight attendants, which increases susceptibility to warm discomfort even at moderate cabin temperatures.

For case scenario 2 (Figure 5-8), the pattern is reversed. More data points fall within the cool discomfort zone, with some approaching cold stress thresholds, while conditions on the warm side remain well below heat stress levels. These differences underscore the challenge of maintaining thermal comfort for both active cabin crew and sedentary passengers in the same environment.

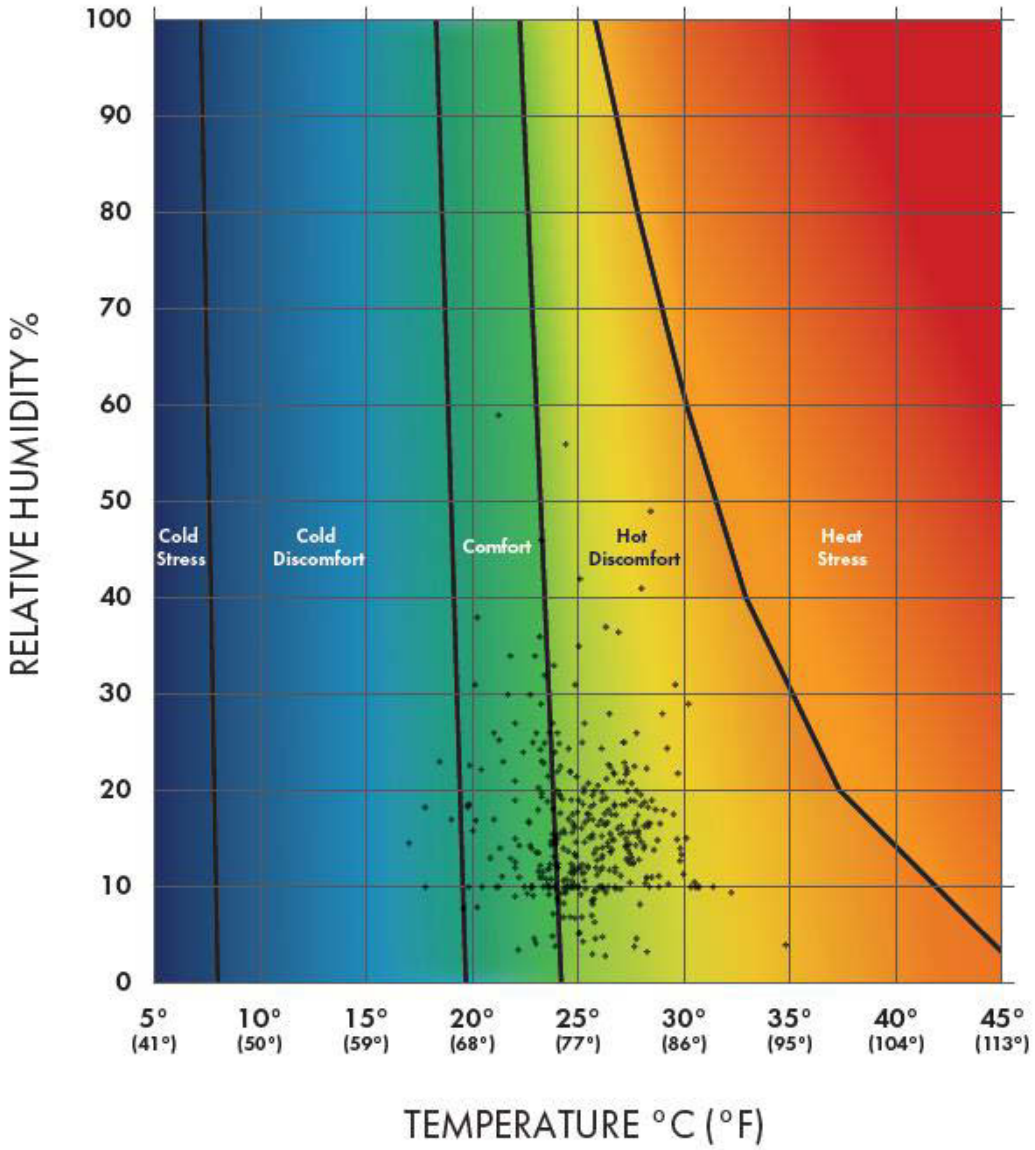

FIGURE 5-7 Comparison of in-flight cabin temperature and humidity data from three independent datasets (Nicholls and Vink, ACER, ASHRAE 1262) overlaid on thermal response zones for case scenario 1—active flight attendants in typical clothing (2.3 MET, 0.6 clo). NOTES: Colored zones represent thermal comfort and stress ranges; + symbols indicate data points for observed inflight cabin conditions. Measurements from the top of descent—identified by the onset of increasing cabin pressure and, when available, data on changes in altitude—were used to represent in-flight conditions in the ACER and ASHRAE 1262 datasets. Most conditions fall within the warm discomfort zone, with none in heat stress or cold stress zones. Shading indicates that the transitions from comfort to discomfort and from discomfort to stress are gradual and continuous, rather than abrupt, and it reflects the variation in individual-level tolerances. Importantly, the methods used to generate the boundaries may underestimate exposure at high and low humidity, and the boundaries should not be applied outside the scope of this study. Exposure duration is not depicted, but the effects are not instantaneous; the potential for negative health effects and greater severity increases with longer durations of exposure.

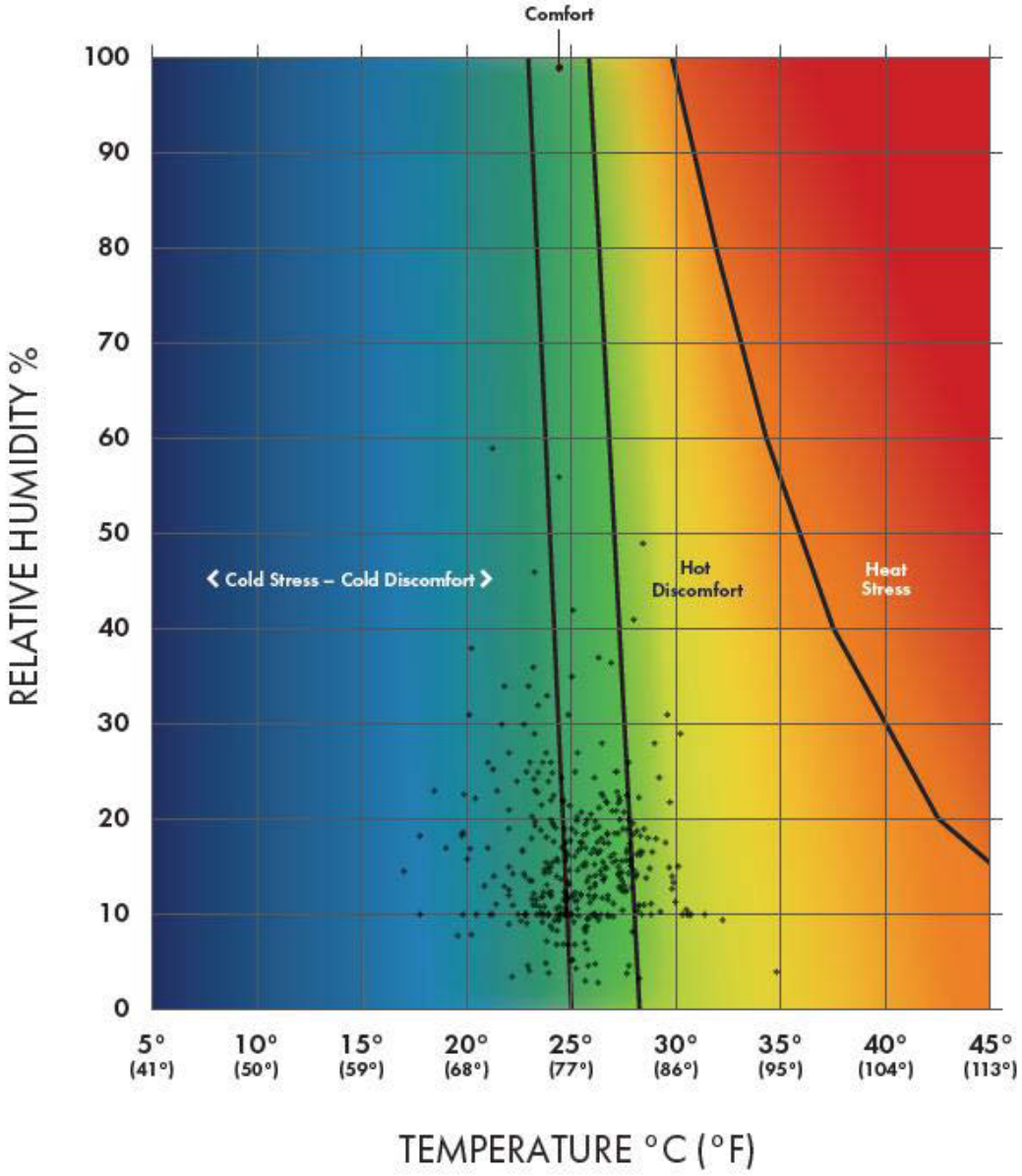

FIGURE 5-8 Comparison of in-flight data from three independent datasets (Nicholls and Vink, ACER, ASHRAE 1262) overlaid on thermal response zones for case scenario 2—passive seated passenger or flight attendant in typical clothing (1.2 MET, 0.6 clo).
NOTES: Colored zones represent thermal comfort and stress ranges; + symbols indicate data points for observed inflight cabin conditions. Measurements from the top of descent—identified by the onset of increasing cabin pressure and, when available, data on changes in altitude—were used to represent in-flight conditions in the ACER and ASHRAE 1262 datasets. Conditions shift toward cool discomfort, while warm-side conditions remain well below heat stress levels. Shading indicates that the transitions from comfort to discomfort and from discomfort to stress are gradual and continuous, rather than abrupt, and it reflects the variation in individual-level tolerances. Importantly, the methods used to generate the boundaries may underestimate exposure at high and low humidity, and the boundaries should not be applied outside the scope of this study. Exposure duration is not depicted, but the effects are not instantaneous; the

potential for negative health effects and greater severity increases with longer durations of exposure.

Figure 5-9 presents boarding conditions mapped to thermal response zones for case scenario 1 (active flight attendant in typical clothing) using data from Nicholls and Vink—the only dataset with pre-departure measurements. Boarding conditions are broadly similar to in-flight conditions but show more points near the heat stress threshold, reflecting the absence of full environmental control and higher humidity levels during ground operations. However, no recorded conditions fell within the heat stress or cold stress zones.

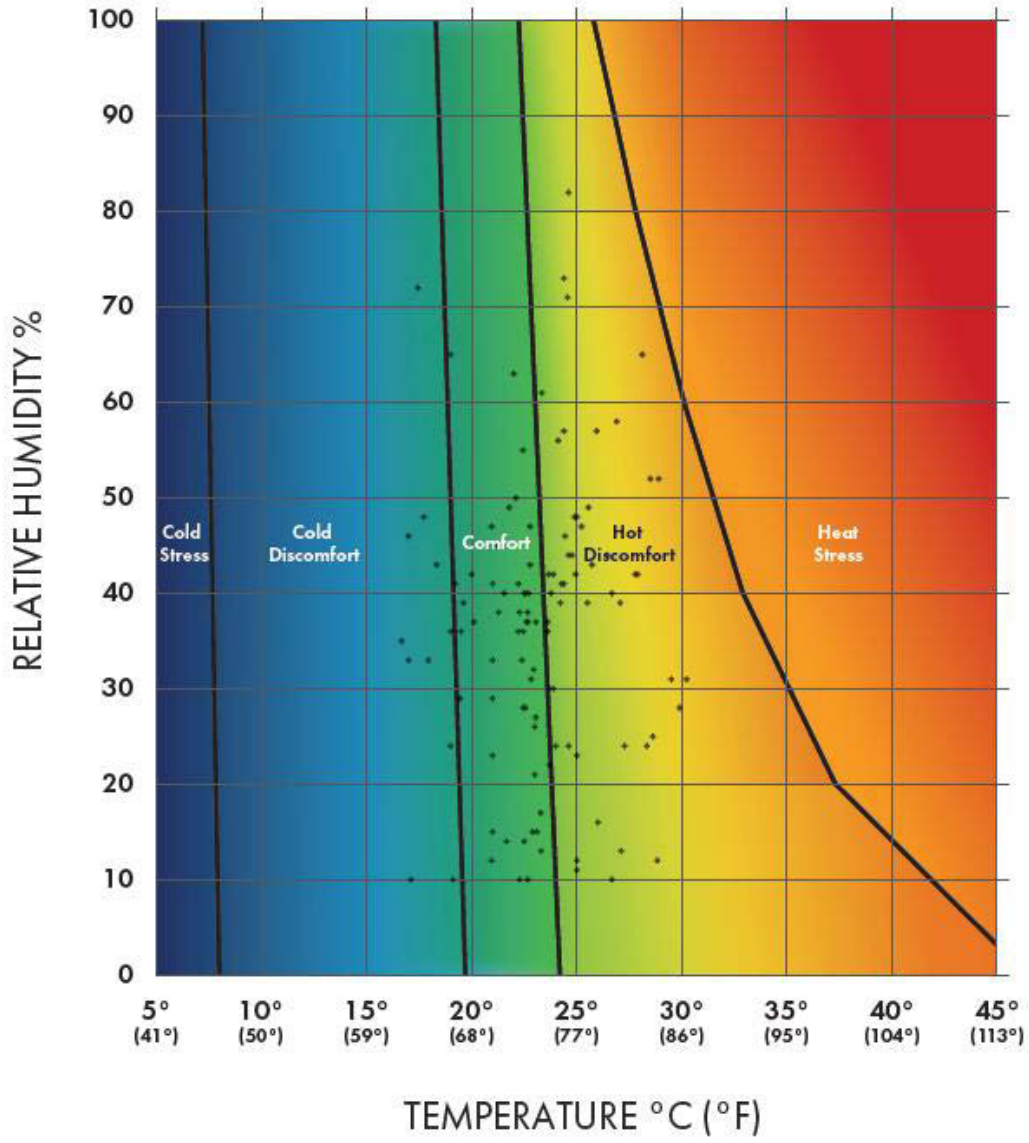

FIGURE 5-9 Boarding conditions from Nicholls and Vink data overlaid on thermal response zones for case scenario 1—active flight attendants in typical clothing (2.3 MET, 0.6 clo). NOTES: Colored zones represent thermal comfort and stress ranges; + symbols indicate data points for observed boarding cabin conditions. Conditions are similar to inflight patterns but include more points near the heat stress threshold, reflecting limited cooling and higher humidity during ground operations. Shading indicates that the transitions from comfort to discomfort and

from discomfort to stress are gradual and continuous, rather than abrupt, and it reflects the variation in individual-level tolerances. Importantly, the methods used to generate the boundaries may underestimate exposure at high and low humidity, and the boundaries should not be applied outside the scope of this study. Exposure duration is not depicted, but the effects are not instantaneous; the potential for negative health effects and greater severity increases with longer durations of exposure.

Case scenarios 1 and 2 depict two activity levels that generally represent the range of activities expected on aircraft. As seen in Figures 5-8 and 5-9, the fraction of the conditions that falls within each zone, not surprisingly, is much different for low activity than for high activity. In reality, activities will fall on a continuum with most activities not at either extreme, especially for flight attendants. Figure 5-10 examines how activity level across a broader range influences the fraction of cabin conditions falling within each thermal zone, based on combined inflight data from all three datasets. As activity level increases, the proportion of conditions classified as warm discomfort rises, while the proportion of cool discomfort decreases. This trend illustrates how metabolic rate interacts with cabin conditions to shape thermal experience. It is important to note that zone boundaries represent average responses; individual variability can be substantial. Even though the zones are represented as discrete boundaries in Figures 5-8 and 5-9, the transition from comfort to discomfort and to stress is gradual, and the level of discomfort is greater at conditions near a stress boundary than at conditions near a comfort boundary.

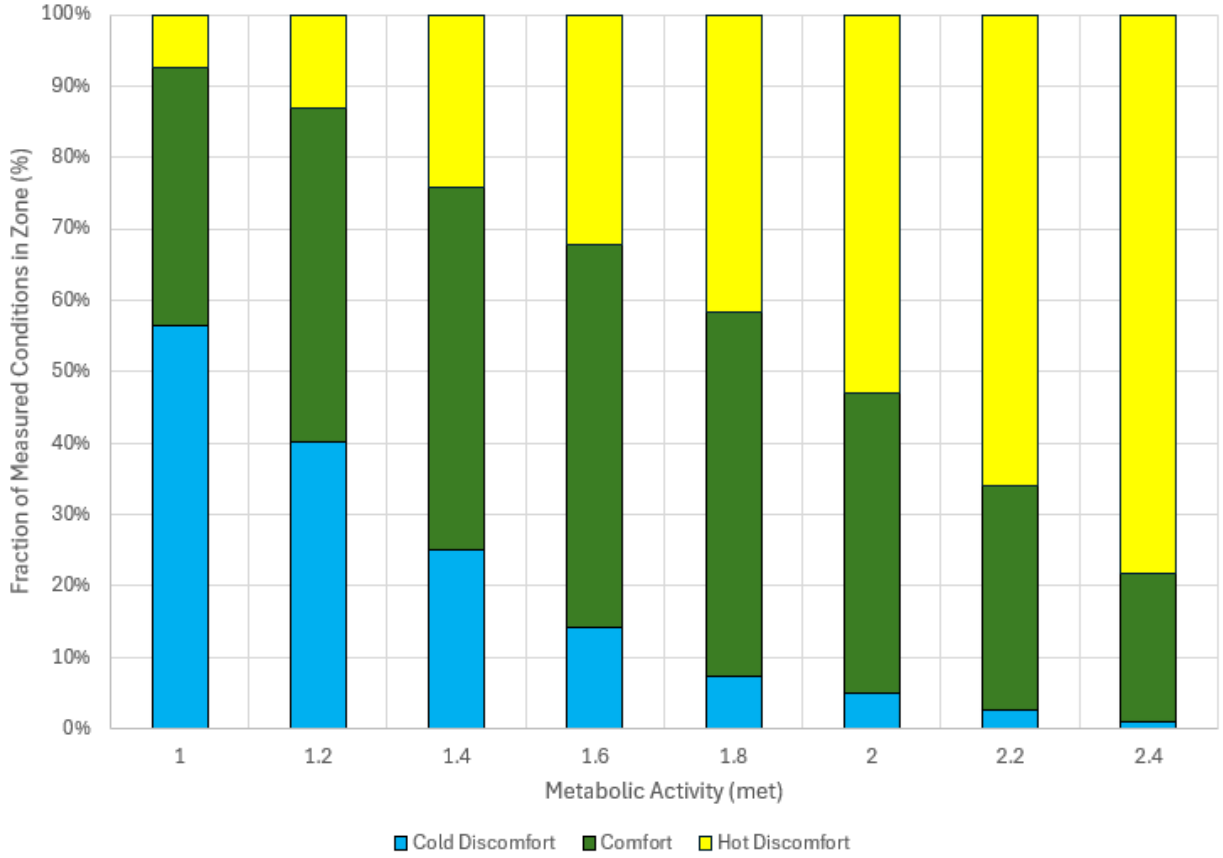

FIGURE 5-10 Effect of activity level on the fraction of cabin conditions falling within each thermal zone, based on combined data from ACER, ASHRAE 1262, and Nicholls and Vink.

NOTES: Hot discomfort increases with higher activity levels, while cold discomfort decreases, illustrating the interaction between metabolic rate and cabin environment. Fractions of measured conditions falling in each zone for the different metabolic activity levels were interpolated from boundaries based on the 1.2- and 2.3-MET conditions.

The mapped cabin conditions represent a single point in time for each flight representative of cruise (Figures 5-7 and 5-8) or boarding (Figure 5-9) conditions, but, as discussed throughout this report, duration has a significant influence on the health and safety impacts of temperature exposures. Longitudinal measurements available from the ASHRAE 1262 and ACER datasets suggest that the in-flight cabin conditions depicted in Figures 5-7 and 5-8 represent extended exposures and are not just the result of short fluctuations in cabin conditions (see Appendix B). Longitudinal data are not available for ground conditions depicted in Figure 5-9.

Lacking corresponding humidity measurements, the temperature data from aviation safety and complaint systems could not be similarly mapped onto thermal response zones. However, many of the reports describe incidents occurring during ground operations (see Appendix B for flight phase specific analyses), when humidity would generally be higher than inflight levels, particularly in warmer seasons. Temperatures exceeding 35°C (95°F) as reported in NASA ASRS submissions, at even moderate humidity levels (30 to 40 percent), begin to approach heat stress conditions for individuals functioning at higher metabolic activity levels (see Figure 4-1). Reports from safety and complaint reporting systems generally lack information regarding the duration of exposure, however, which is a key factor influencing whether temperature exposures change from uncomfortable to unsafe conditions.

Summary and Synthesis

As indicated at the start of this chapter, the committee was guided in its analysis of indirect evidence of cabin-temperature-related health and safety impacts by key questions addressing the characterization of (1) exposure of cabin occupants to cabin temperatures outside the expected thermal comfort range and (2) the health and safety impacts of such exposures.

With regard to exposures, multiple sources indicate that cabin temperatures sometimes reach levels at which health and safety impacts would be expected. Data from the 372 flights included in research studies, when mapped to thermal response zones, show that in-flight temperatures and humidity generally fall within comfort zones, though warm or cool discomfort is common, depending on activity level. There is little evidence that cold thermal stress is widespread, though localized cold discomfort may occur. Boarding conditions in warmer seasons when humidity levels are elevated due to ambient conditions approach the thresholds for heat stress more frequently, underscoring ground operations as a critical phase for thermal management. In contrast, the temperatures reported through aviation safety or complaint systems (e.g., 2Hot2Cold, NASA ASRS) reflect more severe conditions—often far exceeding typical ranges. The reported health and safety impacts of such exposures include a combination of physical, cognitive, and behavioral effects (see Table 5-2), consistent with the published literature on thermal discomfort and stress described in Chapter 3. While these events are infrequent, their severity and potential safety implications warrant targeted mitigation strategies (discussed in Chapter 6), particularly for ground delays and equipment failures.

Conclusion 5-1: The Federal Aviation Administration has jurisdiction over crewmember safety and health. Evidence provided in this report indicates crewmembers continue to experience cabin thermal conditions that result in adverse physiological, cognitive, or behavioral effects.

While the figures depicted in this chapter provide valuable insight into typical cabin conditions and the extremes documented in complaint and safety reporting systems, they do not reveal how often these severe events occur. Understanding the frequency of such conditions is essential for determining the scale of the problem. To assess the magnitude of cabin temperature issues across Part 121 operations, the following section further examines available data sources, including voluntary reporting systems and medical consultation records.

ASSESSING THE MAGNITUDE OF THE PROBLEM

Comparing research datasets and aviation industry reporting system data reveals that extreme cabin temperature conditions are observed on a very small fraction of flights. The key question, therefore, is how often these more concerning conditions occur. The committee identified a total of 154 relevant NASA ASRS reports from a 36-year period (1990–2025) (see Appendix A), while approximately 5,000 2Hot2Cold complaints were submitted over 8 years (2018–2025). For context, U.S. carriers operated approximately 193 million scheduled passenger flights between 2004 and 2024 (approximately 9 million per year) (DOT, 2025a). Although the timeframes do not align perfectly, the committee calculated that ASRS reports equate to roughly 0.5 reports per 1 million flights (approximately 4 reports per year on average from 2004 to 2024). It is important to note that this number is the frequency of reports, not the frequency of events. Almost certainly it is an undercount of actual events as not every serious hot or cold cabin event is likely to be reported, and relevant reports may have been missed in the keyword search of the database. Unfortunately, no means to estimate the undercount was identified. The frequency calculated is a lower limit. It is not known if it is an accurate estimate, a gross underestimate, or somewhere in between. Similarly, 2Hot2Cold reports are unlikely to represent all occurrences of uncomfortable conditions. Awareness of the reporting app among passengers is likely limited, as most submissions (89 percent) come from flight attendants (AFA, 2025). Even among flight attendants, awareness may vary from airline to airline. Based on available data, committee calculations indicate that 2Hot2Cold reports correspond to approximately 0.8 events per 10,000 flights (approximately 700 events per year). Again, this figure is the frequency of reports and not necessarily the frequency of events. No means to estimate the undercount was identified, and this rate may be an accurate estimate, a gross underestimate or somewhere in between. While complaint conditions appear to occur on a small percentage of flights, they are not negligible, given the scale of commercial air transport operations.[6] Also, extreme conditions as described in the ASRS reports and complaints as documented in the 2Hot2Cold data are not expected to occur randomly. They likely are concentrated at certain locations, on certain flight routes, on certain types of aircraft, and on certain types of airlines (e.g., regional versus major).

[6] Data have been collected using the 2Hot2Cold app since 2018, a shorter period than for the NASA ASRS. Additionally, reporting dropped precipitously in 2020, reflecting decreased air travel during the COVID-19 pandemic, making annual estimates from this dataset more uncertain. While characterized as complaint data, it is notable that 173 of the nearly 5,000 reports submitted over the 8-year period noted a need for medical attention, underscoring that reports in this data set are not limited to complaint conditions.

Even though excessively warm or cold conditions may occur on a small fraction of flights, some individuals—certain crew members in particular—may experience these conditions repeatedly and with much greater frequency than the overall statistics indicate.

While not linked to health and safety impacts, airline data on the frequency of hot and cold cabin reports also informed the estimations of the magnitude of the problem. Reported numbers of hot cabin events between 2021 and 2025 varied across responding airlines and ranged from 0 to 0.159 percent of total flights during that period (corresponding to a rate of 0 to 15.9 events per 10,000 flights) (A4A, 2026). Cold cabin reports during this same period were generally less frequent and ranged from 0 to 0.109 percent of total flights (corresponding to a rate of 0 to 10.9 events per 10,000 flights).

The airline and aviation safety and complaint system self-reporting data were supplemented by evidence the committee received from two aviation medical consultation organizations, which further suggested the rarity of medically serious health impacts from cabin temperature exposures. A review of two independent databases—MEDAire (2025) and STAT-MD (2025)—yielded very few relevant cases (see Appendix A for description of information requests).

- **MedAire**: Among 28,072 pre-flight medical consultations for 22 Part 121 carriers over approximately 1.5 years (January 1, 2023–August 31, 2025), only seven cases appeared to involve cabin temperature exposures. Four occurred on previous inbound flights after landing and three during departure prior to takeoff. Of 63,330 inflight consultations during the same period, none were related to cabin temperature.
- **STAT-MD**: Across 50,577 consultations over almost 9 years (November 1, 2016–September 17, 2025), only 12 cases were potentially temperature-related: seven linked to heat, two to cold, and three to dehydration (which may or may not have been temperature-related).

The limitations of the data need to be kept in mind when interpreting them in the context of estimating the frequency of cabin-temperature-related health and safety events. These limitations include:

- Reliance on keyword searches of case notes (e.g., for terms like “hot,” “heat,” “cold”) may have resulted in missed cases.
- Not all airlines contract with medical consultation organizations, and, for those that do, cases managed onboard without third-party involvement would not appear in these databases.
- Heat-related illnesses may have been treated by general medical services after deplaning, bypassing aviation-specific reporting systems.

Consumer complaint data tracked by DOT’s Office of Aviation Consumer Protection (OACP) also suggest that occurrences of cabin temperature issues severe enough to prompt reporting through DOT mechanisms available to passengers are infrequent. Between 2014 and 2023, less than 1 percent of the consumer complaints received by DOT (409 of approximately 200,000) related to cabin temperatures (DOT, 2025b). OACP investigations launched in response to these consumer complaints identified 44 violations of cabin temperature requirements (i.e., the requirement to maintain a “comfortable” cabin temperature during tarmac delays in accordance with 49 USC § 42301, as discussed in Chapter 1). Over the same period, OACP issued 13 warning letters and one enforcement order related to violations of cabin temperature

requirements (DOT, 2025b). Of note, passenger complaints to individual airlines would not be included in DOT OACP records.

In summary, while the committee cannot precisely quantify the frequency of extreme hot or cold cabin conditions, available evidence indicates that events that pose serious health and safety risks occur on a very small fraction of flights—less than 1 per million flights. By contrast, conditions causing substantial warm and cold discomfort, though not medically severe, occur more routinely—perhaps 1 in 10,000 flights, equating to, on average, roughly two incidents per day across the U.S. fleet.

Operational factors likely contribute to these exceedances. For example, NASA ASRS reports often cite equipment issues such as inoperative auxiliary power units (APUs) or air conditioning packs (see Chapter 2). While prohibiting flights under these conditions could prevent many extreme events, such policies might disrupt thousands of flights annually to avoid only a handful of severe incidents. Until more comprehensive data are available, broad policy changes should be approached cautiously in order to balance safety, effectiveness, and operational feasibility. Policy and other mitigation strategies are discussed in Chapter 6.

Conclusion 5-2: Conditions involving cabin temperatures that pose serious health and safety risks in the form of physiological effects are not routinely encountered in Part 121 operations. However, temperatures eliciting thermal discomfort are likely to occur more frequently and are capable of producing cognitive and behavioral effects. Although the frequency of health and safety incidents involving physiological, cognitive, or behavioral effects cannot be reliably estimated with currently available data, reports of cabin-temperature-related health and safety incidents suggest a need for improved monitoring, reporting, and assessment of hazards and risk mitigation options.

ADDRESSING CURRENT DATA LIMITATIONS

Limitations of Existing Data

A key takeaway from the analyses presented in this chapter is the limited availability of reliable data from which conclusions regarding the health and safety impacts of cabin temperatures can be drawn. Direct evidence linking health outcomes to aircraft cabin temperatures was confined to a single study that relied on subjective reporting. The committee's analyses of indirect evidence were based largely on studies involving small convenience samples of flights and variable measurement methods as well as voluntary reporting systems with self-reported data, none of which provided a comprehensive or representative picture. Despite these limitations, the available data provide useful insights for guiding mitigation strategies. For example, multiple sources indicate that hot cabin events are more frequent in summer and during ground operations (see Figures B-1 and B-5 in Appendix B), reinforcing the need for seasonal planning (discussed further in Chapter 6).

The committee explored additional sources of health and safety data that do not rely on subjective reporting, including OSHA injury data, emergency medical services (EMS) data, and records from organizations providing medical consultation services to the aviation industry (discussed earlier in this chapter). However, these sources proved largely uninformative for the following reasons:

- OSHA injury data: As airlines must meet OSHA recordkeeping requirements,[7] the committee commissioned an analysis to explore associations between outdoor ambient temperature—which has been found to correlate with boarding temperatures (Nicholls and Vink, 2025)—and reported flight attendant injuries occurring on aircraft. However, airlines are not required to list the actual injury location in OSHA logs, and the available data typically reflect the flight attendants' home base rather than the site of the incident, precluding meaningful linkage to ambient temperature.
- EMS and medical consultation data: National-level EMS data can identify encounters at airports or on airplanes but cannot distinguish whether incidents involved cabin occupants versus other scenarios (e.g., ground crew working outside on the ramp). While state-level data may offer greater detail, collecting and analyzing these data was not feasible within the committee's timeframe. Similarly, medical consultation databases yielded very few cases potentially related to cabin temperature, and keyword-based searches may have missed relevant events (e.g., cases of heat-related conditions that are not recognized heat illnesses).

Although these data were not useful for the committee's analyses, it is conceivable that changes to data collection and reporting methods for these sources could increase their utility in the future.

Conclusion 5-3: There are no systematically collected data with which to assess the health and safety impacts of aircraft cabin temperature on flight attendants and passengers. Available data on cabin temperature and humidity are fragmented, incomplete, and based on extremely small samples relative to the millions of commercial flights conducted annually. The lack of health and safety data—including cognitive and behavioral effects and data specific to vulnerable populations—impedes the assessment of associations between outcomes and temperature-related exposures.

Future Data Needs for Estimating Frequency of Cabin Temperature and Humidity Hazards

It follows from Conclusions 5-2 and 5-3 that additional data collection efforts are needed to improve assessment of cabin temperature and humidity hazards. Analyses of newly captured data could advance risk mitigation approaches, although such actions need not wait on data collection efforts (see Chapter 6). Data obtained from a research effort would ideally be made publicly available following completion of the research and publication of the findings, consistent with general practice for government-funded research.

Recommendation 5-1: The Federal Aviation Administration, in collaboration with airlines and aircraft manufacturers, should establish a research program to

[7] In 2023, OSHA implemented a final rule (88 FR 47254) requiring establishments with 100 or more employees to electronically submit detailed records of every work-related injury and illness through the agency's Injury Tracking Application. Publicly available records on flight attendant injuries can be found at https://www.osha.gov/Establishment-Specific-Injury-and-Illness-Data (accessed March 6, 2026).

systematically monitor, record, and assess temperature and humidity conditions in a representative sample of Part 121 passenger aircraft cabins.

The objectives of the recommended research program would be primarily to develop an initial evidence base for predicting the frequency and severity of cabin-temperature-related health and safety events in higher-risk settings. An appropriately robust estimate of the frequency and distribution of measurements falling across the categories represented in Figures 4-1 and 4-2 is essential for such predictions. A feasible research effort should be restricted to a sample of high-risk settings. To identify these settings and design temperature and humidity data collection instrument packages and procedures for the distribution and collection of appropriate data in such settings, a multi-step process is suggested. Below the committee offers, as one of several reasonable options, a possible approach to the recommended research.

Step 1:

a. Consult with Part 121 passenger-carrying airlines and aviation labor organizations (flight attendant unions in particular) to identify locations, aircraft, and other factors where hot or cold problems occur. The purpose would be to identify where and when conditions or situations posing health and safety risks are most likely to occur so they can be targeted.
b. Consult with Part 121 passenger-carrying airlines and aviation labor organizations to establish procedures for the installation and removal of portable sensors on aircraft, charging of batteries, and downloading the data they collect.
c. Based on the results in 1a, identify routes, airports, aircraft, and times to target where there is a relatively high probability of hot or cold cabin events occurring.

Step 2:

a. Develop the instrument package to be used for data collection, including sensors, data storage, and downloading capabilities.
b. In cooperation with Part 121 passenger-carrying airlines, deploy a modest number of the portable sensor packages on aircraft (on the order of 10) to pilot test their operational capabilities and to work out the details of the tracking, data downloading, and sensor maintenance, among other considerations. Airplane system configuration (e.g., pack and APU settings) and ground PCA operations should be recorded.

Step 3:

a. In cooperation with the impacted airlines, and based on the results of 2b, develop a detailed deployment plan for a substantial number of instrument packages, including a detailed plan for managing deployment and tracking, and for downloading, storing, managing, and assessing the data collected.
b. Based on experiences with the prototype instrument packages, modify as needed and construct the required number of instrument packages, perhaps on the order of 50. The aircraft chosen for deployment of sensor packages should include both regional and larger commercial aircraft.

Step 4:

a. Deploy and operate the fleet of instrument packages according to the plans developed in Step 3. Continue the operation for at least 1 year to allow a full range of potentially at-risk flights to be evaluated. Documentation of air conditioning pack, APU, and PCA operations for each flight should be recorded.

b. When (and if) thermal conditions posing health and safety risks are identified, conduct follow-up investigations as to why they occurred and what could have been done to prevent them.

Step 5:

a. Based on the results of this research, evaluate whether to have temperature and humidity sensors on all aircraft as standard equipment and, if so, develop a plan for data collection and management.

The committee identified a number of issues that would need to be considered either in the research effort or in the case of a conclusion that indicates more widespread ongoing collection of data is necessary.

While onboard monitoring systems offer the most reliable environmental data, older aircraft generally lack these capabilities and are unlikely to be retrofitted. Where suitable onboard sensors and data recording capabilities already exist, the program should take advantage of those systems immediately. For aircraft lacking these capabilities, portable instrument packages (sensors and data loggers) that measure, at a minimum, air temperature, humidity, and cabin pressure (to identify flight phase) and feature onboard recording and remote download capability would likely need to be developed. Such tools may be particularly important for capturing cabin humidity levels, as the committee heard that onboard systems do not currently monitor and record such data (A4A, 2026; AVA, 2026; RAA, 2026) and have been used in previous research on cabin environmental factors (Batelle, 2018).

Current technologies for low-power compact sensors, batteries, data storage, and communication make continuous measurement feasible over multiple days without recharging or downloading. The primary challenge lies in logistics—deploying, maintaining, tracking, and managing the sensors and the large volumes of data collected. Procedures will need to be developed to ensure consistent deployment, recharging, data retrieval, management, analysis, and interpretation. Because temperature and humidity are not uniform throughout the cabin, more than one sensor may be needed on some aircraft to assess spatial variation (e.g., between classes of service, near open doors while aircraft are on the ground, and measurements on solar side of aircraft).

Ideally, a sufficient number of sensor packages would be deployed to collect data across a representative cross-section of aircraft, flights, routes, and environmental conditions with enough flights monitored to capture infrequent events. Consultation with statisticians may help inform the number of sensor packages that would be sufficient to achieve a representative cross-section. Data on ambient thermal conditions would ideally also be collected when capturing cabin thermal data during ground phases to better understand high-risk conditions. Depending upon the types of infrequent events to be captured, the magnitude of the monitoring required can become infeasible with a random sampling approach. With dozens of different aircraft makes and models, dozens of different types of flights, dozens of different types of routes, and a variety of different types of environmental conditions, capturing infrequent events—for example, that occur on perhaps one in 10,000 flights—and parsed by each of these factors would require an astronomical number of flights to be monitored. Identifying and targeting high-risk conditions—such as routes that operate within hot or cold environments, airports where cabin temperature issues are identified more frequently, identified problem routes, or aircraft with deferred APU repairs—should increase the likelihood of capturing infrequent events of interest where health and safety are clearly at risk of being compromised. Such targeting is essential for a practical, limited scale research data collection effort.

At least two possible outcomes of the proposed FAA-funded research program can be envisioned:

1. There is sufficient evidence that incidents of temperature exceedances occur such that cabin-temperature-related health and safety incidents are predicted to occur with such frequency and wide distribution to warrant an ongoing monitoring program.
2. The evidence suggests that problem exceedances are sufficiently localized that targeted mitigation measures (targeting specific aircraft, routes, seasons) would sufficiently address cabin-temperature-related hazards without the need for an industry-wide monitoring program.

In the first scenario, there are both potential benefits and challenges to an ongoing monitoring program that would need to be considered. Such a program could benefit industry by supporting ongoing quality-assurance efforts, benchmarking, and predictive risk modeling. Similar approaches are already used by organizations such as the International Air Transport Association for other operational parameters (IATA, 2026). The resulting data from such a program would also enable the ongoing evaluation of circumstances and conditions that predispose critical medical emergencies and inform strategies to prevent them.

In contrast to a research program, however, reliance on temporary sensors and data loggers for routine monitoring of cabin environmental conditions is not feasible. A long-term monitoring program would therefore require onboard sensor systems for recording and downloading cabin temperature and humidity, the feasibility of which (e.g., technological, logistical) would need to be evaluated. Some data collection challenges may resolve over time as older aircraft models are replaced with newer ones that include temperature recording and download capabilities. However, as noted above, aircraft used in Part 121 operations do not currently include equipment for monitoring humidity. Achieving such capabilities would require manufacturers to offer retrofit kits to airlines and/or incorporate integrated fixed humidity sensors into the aircraft design for new production aircraft, which, the committee acknowledges, would be accompanied by nontrivial tradeoffs (e.g., added weight, data storage needs, power requirements, maintainability). Moreover, assurance of the reliability of the data (precision and accuracy) and calibration requirements need to be considered, given the difficulty with humidity measurement at the low ranges typical for in-flight conditions (between 10 and 20 percent) and elevated ranges during ground operations (i.e., greater than 50 percent).

Because collecting temperature and humidity data on all flights may be prohibitive, a systematic sampling of airlines and flights could be done annually to collect the necessary information to serve as the basis of tracking of thermal conditions, their burden, and their consequences, either industry-wide or within sub-groups, if indicated. A program that might serve as a model for such a tracking system is the U.S. Department of Labor's Bureau of Labor Statistics annual national sample of enterprises to report occupational injuries and illnesses, which makes it possible to provide national estimates of the distribution, frequency and burden of occupational injury and illnesses (BLS, 2024).

Environmental factors beyond temperature and humidity are recognized as important to the health and safety of cabin occupants. Therefore, such a program, if pursued, could be integrated with monitoring efforts for other cabin air quality parameters, achieving greater efficiency than independent monitoring programs. The FAA-funded Cabin Air Quality and Bleed Air Contamination Detection project (FAA, 2025) outlines such a program and may serve as a guide.

Separately, FAA should also explore (e.g., through a workshop) methods for systematic and direct collection of data on health outcomes from exposure to hot or cold cabin temperatures, particularly for vulnerable populations (e.g., infants and young children, individuals with chronic conditions, and others with increased susceptibility). Changes in passenger and cabin crew demographics, particularly the aging of the U.S. population, likely affect vulnerability to cabin environmental conditions and should be considered. Health-related data to supplement those from existing complaint and safety reporting systems are more challenging to collect at scale, but examples of potential methods include simple surveys to collect self-reported data on physiological, cognitive, and behavioral effects of cabin thermal conditions and digital health technologies (e.g., smartwatches), which provide objective physiologic measures to complement environmental monitoring and self-report data. Most airlines and airline associations periodically conduct passenger surveys to gain insights into passenger satisfaction, behaviors, and expectations. Stakeholders across diverse segments (e.g., air carriers, airports, manufacturers) can use the resulting data and insights to make informed decisions that guide research projects, enhance strategies for operations, or inform policy decisions with the goal of improving passenger experiences and aligning more closely with evolving passenger and crewmember needs. Surveys for health, safety, or cognitive/behavioral experiences that carry minimum burden for airlines and passengers could be modeled on these. By using a mix of closed- and open-ended questions, air carriers could gather both quantitative and qualitative data on experiences of thermal discomfort and any associated physical, cognitive, and mental health symptoms. Air carriers can distribute surveys through a variety of channels, such as email, mobile apps, in-flight entertainment systems, or social media platforms.

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6
Strategies for Managing Cabin Temperatures and Associated Health and Safety Risks

The committee was tasked with developing recommendations to guide strategies for monitoring, assessing, and managing cabin air temperature and its associated health and safety impacts. As reviewed in Chapter 5, the available evidence demonstrates that while data limitations hinder the precise monitoring and evaluation of health and safety impacts, cabin temperatures can reach levels that may impair passenger and flight attendant cognition and behavior and, less frequently, physiology. Although the frequency of such outcomes cannot be reliably estimated with existing data, the potential severity of these risks warrants prompt mitigation efforts rather than delay pending further data collection.

This chapter outlines actionable steps that airlines, airport authorities, and the Federal Aviation Administration (FAA) can take to address thermal conditions in aircraft cabins, even as improved data collection systems are developed. Strategies for managing cabin temperatures may include standards, policies, programs, operational practices, or combinations thereof. This chapter begins with the committee's assessment of the applicability and feasibility of existing standards for ensuring the health and safety of aircraft cabin occupants, as directed in the Statement of Task. The chapter then discusses policies, programs, and practices that can be implemented as part of a systems approach to managing cabin temperatures, emphasizing coordinated action across stakeholders.

STANDARDS

Standards play a critical role in ensuring consistency across entities (such as airlines) and provide a foundation for regulatory enforcement when oversight is deemed necessary to protect safety and health. As discussed in Chapter 1, there is currently no mandatory, enforceable standard for cabin temperature in commercial aviation. However, a voluntary consensus standard—Standard 161-2023 (*Air Quality within Commercial Aircraft*) of the American National Standards Institute (ANSI) and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)—includes recommended target and maximum temperature design limits for both inflight and ground operations (ANSI/ASHRAE, 2023a).

In response to ongoing challenges with cabin temperature exposures, the Association of Flight Attendants (AFA) petitioned the Secretary of the U.S. Department of Transportation (DOT) in July 2018 to initiate rulemaking to establish operational temperature standards for all passenger flights operated by U.S. commercial airlines and foreign airlines while operating in the United States (AFA, 2018). The petition argued that such standards are necessary to prevent incidents of extreme temperature conditions on commercial passenger aircraft. The committee heard similar concerns from AFA representatives and other flight attendant labor organizations

during a public information-gathering session focused on lived experiences and perspectives from flight attendant representatives (Heiple, 2025). To date, DOT has not issued a formal response granting or denying the AFA petition or published a notice of proposed rulemaking on cabin temperature standards.

A standard cannot prevent all incidences of cabin-temperature-related health and safety events. Equipment failures and unforeseen events (e.g., emergencies requiring diversions) are likely to continue to result in situations in which cabin temperatures pose health and safety risks even following promulgation of a regulatory standard. However, enforcement of a standard that has been adopted into regulation would be expected to reduce the number of incidents that are predictable and preventable, particularly during ground operations when there is more opportunity to apply administrative and engineering practices to mitigate risks from exposure to hot or cold cabin temperatures.

Conclusion 6-1: Past recommendations from the National Academies of Sciences, Engineering, and Medicine and others prompted FAA-supported data collection efforts on aircraft cabin environmental conditions. These efforts focused primarily on air quality and have not led to meaningful improvements in temperature exposures for cabin occupants. Air carriers have been aware of these issues for many years, but cabin-temperature-related health and safety incidents are still being reported. Without rulemaking, the committee is concerned about the adequacy of preventive actions to reduce or eliminate these incidents.

The committee was not tasked with recommending a specific standard for cabin temperature or humidity. Accordingly, this report does not address the question of whether ANSI/ASHRAE Standard 161-2023—or some other specific temperature standard—should be adopted into regulation. Instead, in accordance with its charge, the committee evaluated the applicability of existing temperature and humidity standards for indoor environments to ensuring the health and safety of cabin occupants and the feasibility of their implementation in an aircraft setting. Factors affecting the applicability and feasibility of existing standards are discussed in detail in the sections that follow and are summarized in Table 6-1.

TABLE 6-1 Summary of Factors Affecting Applicability and Feasibility of Existing Temperature and Humidity Standards

	ANSI/ASHRAE Standard 161-2023	**Thermal Comfort Standards (ISO 7730:2025, ANSI/ASHRAE Standard 55-2023)**	**Heat Stress Standards and Guidelines (ACGIH, ISO)**
Applicability Factors			
Comfort versus safety and health application	Focused on thermal comfort (references ANSI/ASHRAE Standard 55) with limited linkage to health and safety risks	Focused on thermal comfort	Focused on physiological aspects of safety and health
Applicability to aircraft environment	Developed specifically for aircraft but based in part on ANSI/ASHRAE Standard 55	Requires adaptation for aircraft environment	Environmental conditions/ temperature extremes addressed likely rare in aircraft settings
Humidity effects	Not considered	Considered	Considered
Duration of exposure	Not considered	Intended for steady-state application (no limits on duration)	Considered through time-weighted and work-rest cycles
Applicability to aircraft occupants (populations)	Developed for general commercial aircraft population. Does not account for vulnerable sub-populations	Developed for indoor environmental conditions for healthy adults. Does not account for vulnerable sub-populations	Developed for worker populations (on average healthier than general population), not general passenger population
Feasibility Factors			
Measurement constraints	No constraints	Requires multiple inputs (e.g., humidity, metabolic rate, clothing), limiting implementation in aircraft	Requires environmental and physiological variables (e.g., WBGT, workload), challenging to implement in aircraft settings
Variability in occupant needs	Does not distinguish thermal needs for flight attendants versus passengers	Narrow comfort range that differs based on activity level	Accounts for metabolic workload
Real-time monitoring capabilities and implementation	Absolute temperature limits are simpler to implement in real time	Aircraft currently cannot measure humidity, making real-time implementation challenging	Aircraft currently cannot measure humidity or globe temperature, making real-time implementation challenging

NOTE: ECS = environmental control system, WBGT = wet bulb globe temperature.

Applicability of ANSI/ASHRAE Standard 161-2023

As discussed in earlier chapters of this report, ANSI/ASHRAE Standard 161-2023 is specifically directed to airplane environmental systems design and recommends a target temperature range of 18.3°C to 23.9°C (65°F to 75°F) while an aircraft is in flight and during ground operations (ANSI/ASHRAE. 2023a). The maximum recommended temperature is 26.7°C (80°F) except when in-flight entertainment (IFE) systems are operating during ground operations, during which time the standard allows for a higher temperature maximum (29.4°C, or 85°F), although allowable durations of exposure to these higher temperatures are not addressed. While the standard indicates that temperature criteria are based on aircraft environmental control system (ECS) design experience and ANSI/ASHRAE Standard 55-2023 (*Thermal Environmental Conditions for Human Occupancy*), there is no evidence to suggest that thermal comfort limits would be altered by the operation of IFE, and the allowance for higher on-ground temperatures when IFE is operating appears to be driven by feasibility, given the heat-generating effects of IFE.

Figure 6-1 presents cabin temperature and humidity data collected during research studies and considered reasonably representative of more typical Part 121 flight operations (see Chapter 5). These data are compared against the recommended target ranges and maximum temperature limits from ANSI/ASHRAE Standard 161-2023. The majority of measured conditions fall outside the target temperature range, and many in-flight conditions (black symbols) exceed the recommended in-flight temperature maximum of 26.7°C (80°F). Only a small number of cases exceed the on-ground maximum temperature allowed when IFE is operating (29.4ºC or 85ºF). However, complaint and safety and health reporting data (see Figure 5-3 in Chapter 5) indicate that even this extended limit is occasionally surpassed.

Figure 6-1 shows that inflight thermal conditions are most frequently warmer than the target range of ANSI/ASHRAE Standard 161-2023. Once established in flight, the aircraft ECS typically has ample capacity to provide cooling to maintain desired temperatures (see Chapter 2). Thus, the thermal conditions on most flights during cruise are expected to be the result of choice, not ECS limitations. By the point in the flight where the inflight data were recorded, passengers would be expected to be well settled into a sedentary activity level, and even flight attendants would be expected to be settled into a more routine and less rushed activity as compared with the hustle often associated with boarding. Figures 6-2 and 6-3 support this observation. With the high activities in Figure 6-2, the comfort zone more or less aligns with the target range of ANSI/ASHRAE Standard 161-2023, while the comfort zone for sedentary activity in Figure 6-3 more or less aligns with the region above the target range consistent with much of the inflight data.

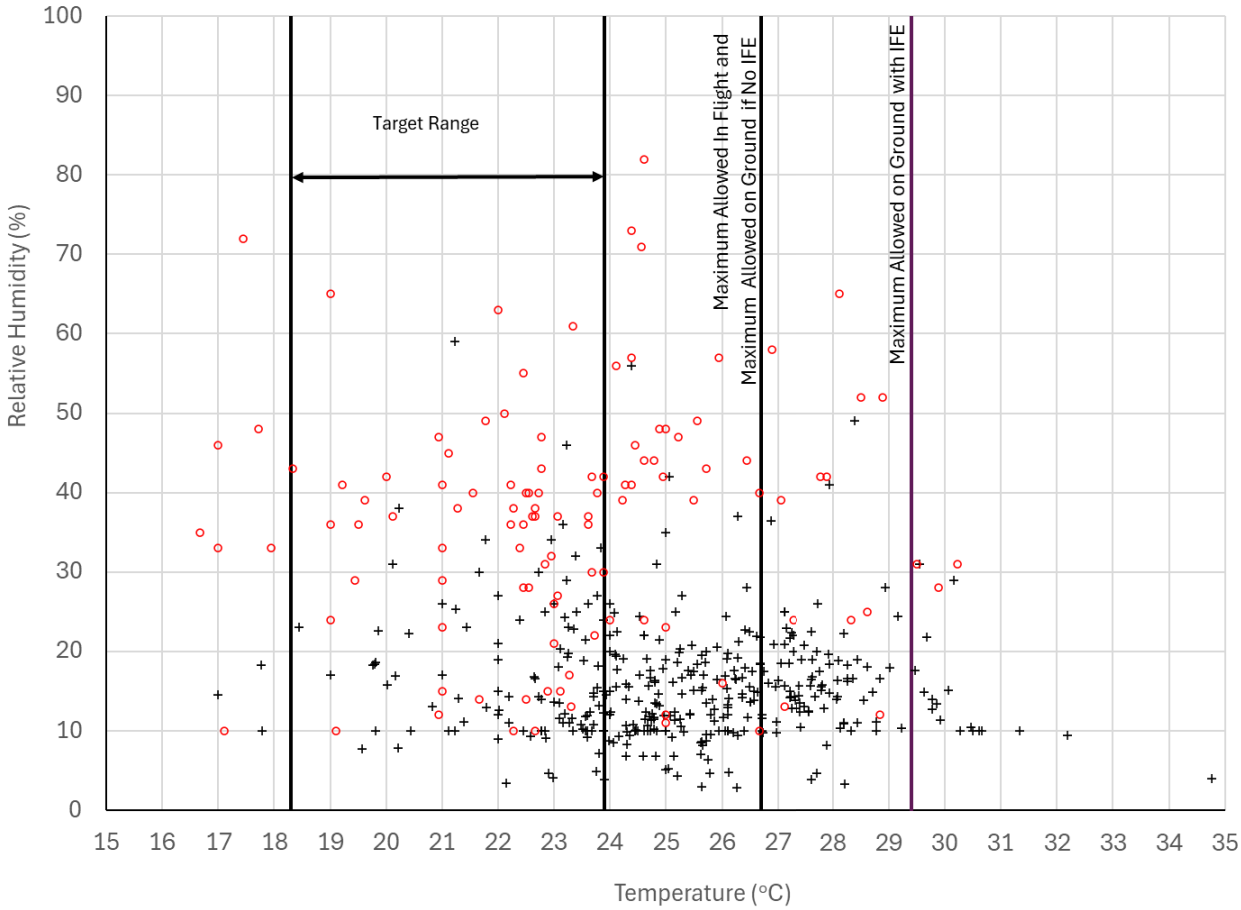

FIGURE 6-1 Comparison of measured aircraft cabin temperatures with ANSI/ASHRAE Standard 161-2023 limits.
NOTES: Black symbols represent combined in-flight data from three datasets (top of descent data from ACER and ASHRAE 1262, and 1-hour after takeoff data from Nicholls and Vink), which are described in Chapter 5; red symbols represent boarding data from the Nicholls and Vink dataset. The figure highlights instances where observed conditions exceed recommended thresholds defined in ASHRAE Standard 161-2023. The distribution and exceedances may represent choice (temperature selection during cruise) and/or may reflect the several different instruments and protocols used in the studies from which inflight data was taken. IFE = in-flight entertainment.
SOURCE: Created with data from ACER (2025), ASHRAE (2026), and Nicholls and Vink (2025).

Figures 6-2 and 6-3 illustrate how the recommended target and maximum temperature criteria from ANSI/ASHRAE Standard 161-2023 intersect with thermal comfort, discomfort, and stress zones derived from established thermal comfort and heat and cold stress standards and guidelines (see Chapter 4). These zones vary with humidity, which explains why the boundaries in the figures are sloped rather than vertical. The effects of humidity are greatest at higher temperatures and have a pronounced impact on the boundary between hot discomfort and heat stress. Notably, ANSI/ASHRAE Standard 161-2023 does not account for humidity, even though humidity significantly influences thermal comfort and heat stress risk.

Figure 6-2 represents the conditions for the higher activity levels typical of flight attendants during busy periods (i.e., an estimated metabolic activity rate of 2.3 MET, representing an average of routine service and movement activities) while wearing typical clothing (0.6 clo). Under these conditions, the ANSI/ASHRAE Standard 161-2023 target range aligns reasonably well with the thermal comfort zone. However, the standard's maximum temperature—particularly, the extended limit for ground operations with IFE operating—falls within the hot discomfort zone and, at high humidity (greater than 65 percent), approaches heat stress thresholds. It is not possible to set humidity levels in aircraft in the same manner that temperature can be adjusted, which has implications for temperature limits for comfort and thermal stress (Wang et al., 2024). While humidity during flight is typically very low (10–20 percent), ground operations in humid ambient environments can produce much higher cabin humidity levels (though not necessarily equivalent to those outside the aircraft), especially when ventilation systems are off (e.g., engines shut down and auxiliary cooling unavailable). As discussed in Chapter 3, even discomfort short of heat stress can impair cognitive and behavioral performance, posing safety risks.

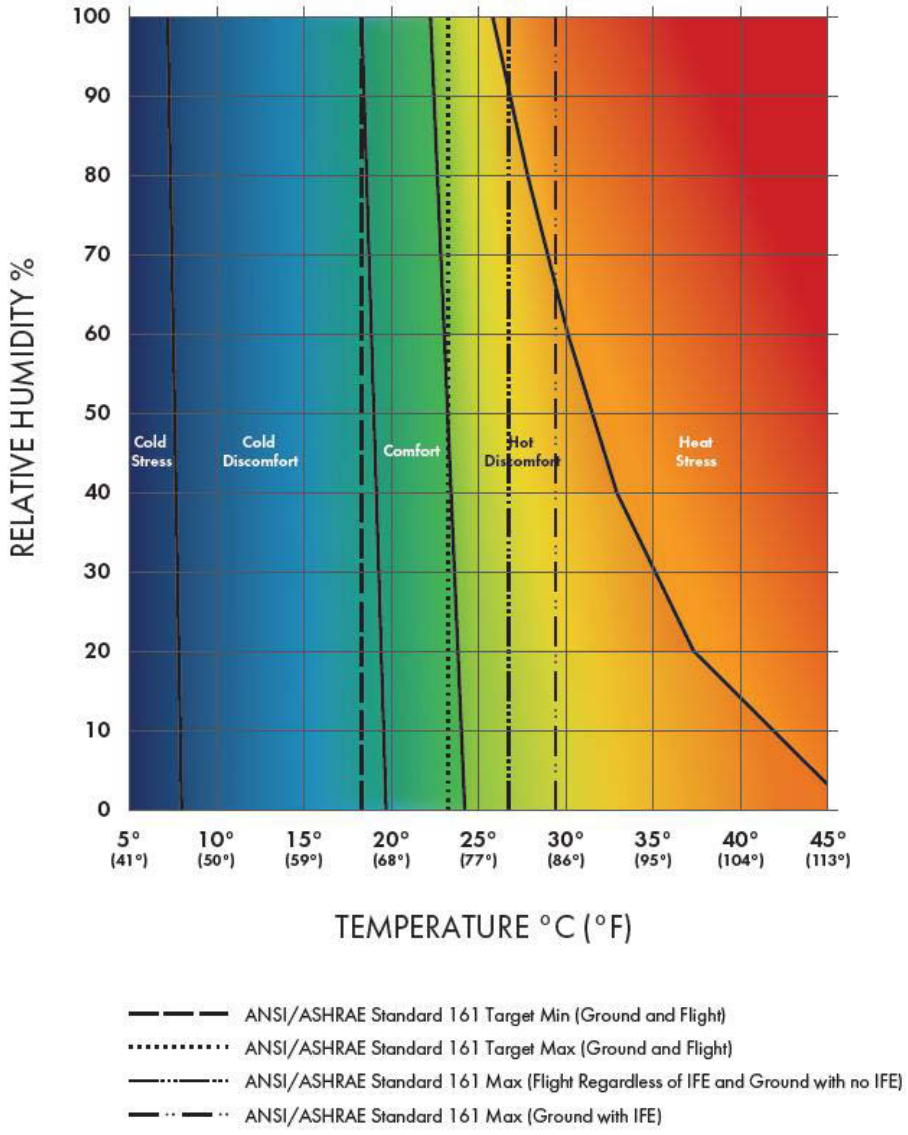

FIGURE 6-2 Thermal response zones from application of thermal comfort and heat and cold stress standards and guidelines for moderate activity levels typical of a busy flight attendant (2.3 MET) and typical clothing (0.6 clo).
NOTES: ANSI/ASHRAE Standard 161:2023 target and extended limits (ANSI/ASHRAE, 2023a) are overlaid for comparison, showing that protective capacity varies with humidity. A description of the approach to generating boundaries for colored thermal response zones can be found in Chapter 4. Shading indicates that the transitions from comfort to discomfort and from discomfort to stress are gradual and continuous, rather than abrupt, and it reflects the variation in individual-level tolerances. Importantly, the methods used to generate the boundaries may underestimate exposure at high and low humidity, and the boundaries should not be applied outside the scope of this study. Exposure duration is not depicted, but the effects are not instantaneous; the potential for negative health effects and greater severity increases with longer durations of exposure. IFE = in-flight entertainment.

These findings underscore a key limitation: fixed temperature limits alone cannot ensure protection of health and safety. Because the ANSI/ASHRAE Standard 161-2023 does not account for humidity effects or duration of exposure, its upper limits may allow conditions that are unsafe during ground operations, considering that the relative humidity can be much higher and that both flight attendants and passengers may be more active. Future standards considerations need to address temperature–humidity interactions (particularly at higher temperature levels) to better protect cabin occupants.

Conclusion 6-2: Relative humidity is a critical factor in determining heat-related discomfort and stress and should be included in regulatory or recommended temperature standards.

At lower activity levels (approximately 1.2 MET), typical of seated passengers and flight attendants during inactive periods, the risk of thermal stress is greatly reduced when cabin temperatures remain below the recommended maximum (see Figure 6-3). However, some occupants may experience cool discomfort at temperatures near the low end of the ANSI/ ASHRAE Standard 161-2023 target range.

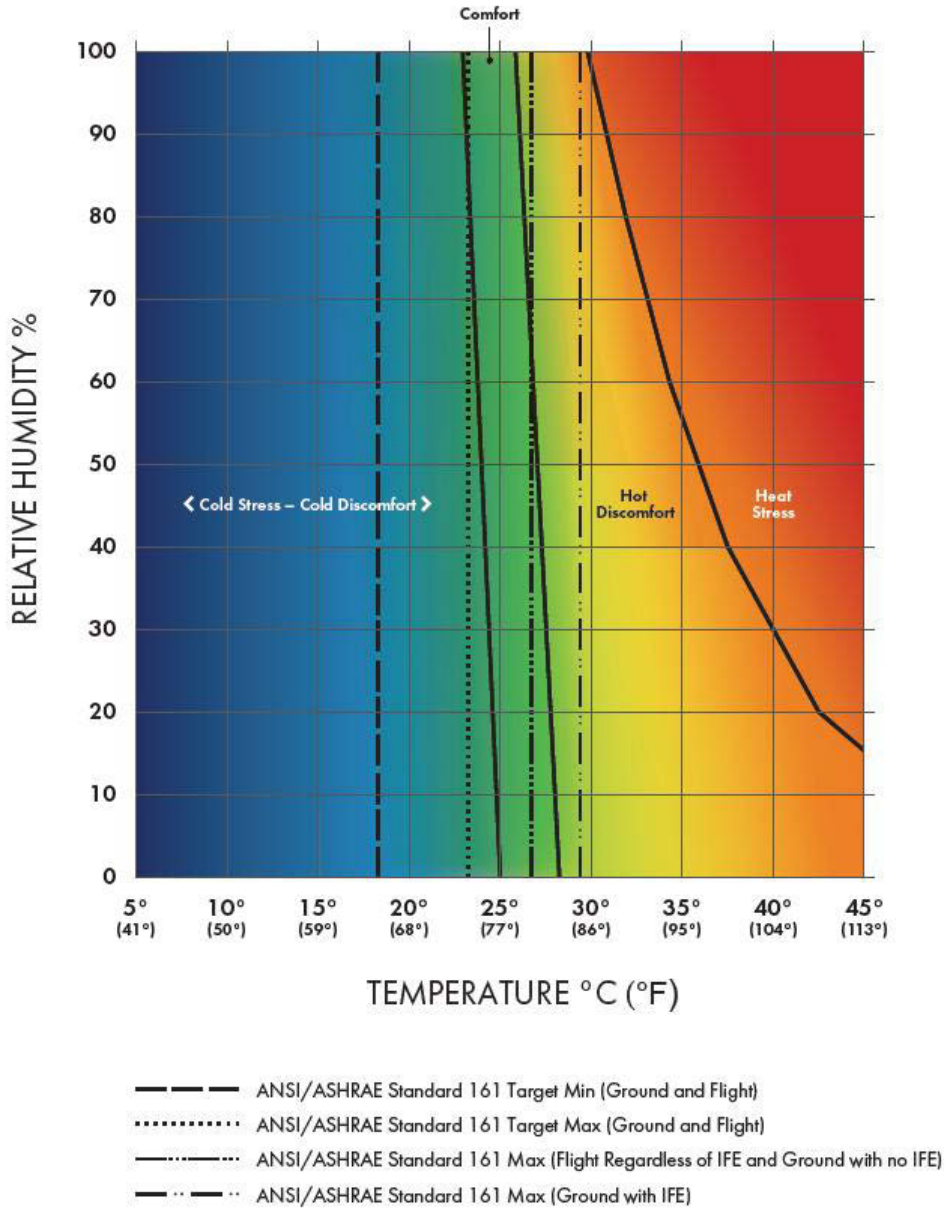

FIGURE 6-3 Thermal response zones from application of thermal comfort and heat and cold stress standards and guidelines for low activity levels typical of a seated passenger or flight attendant (1.2 MET) and typical clothing (0.6 clo).
NOTES: ANSI/ASHRAE Standard 161:2023 target and extended limits (ANSI/ASHRAE, 2023a) are overlaid for comparison, showing that protective capacity varies with humidity. A description of the approach to generating boundaries for colored thermal response zones can be found in Chapter 4. Shading indicates that the transitions from comfort to discomfort and from discomfort to stress are gradual and continuous, rather than abrupt, and it reflects the variation in individual-level tolerances. Importantly, the methods used to generate the boundaries may underestimate exposure at high and low humidity, and the boundaries should not be applied outside the scope of this study. Exposure duration is not depicted, but the effects are not instantaneous; the potential for negative health effects and greater severity increases with longer durations of exposure. IFE = in-flight entertainment.

This highlights a persistent challenge: maintaining thermal comfort for both active cabin crew and sedentary passengers. While higher temperatures may benefit passengers prone to cool discomfort, they can increase warm discomfort for active flight attendants, especially during ground operations in humid conditions.

It is important to note that the thermal response zones shown in Figures 6-2 and 6-3 are based on thermal comfort and heat/cold stress standards and guidelines designed for healthy adults. These zones do not account for increased sensitivities among vulnerable populations. Combined temperature and humidity levels that may cause only discomfort for a healthy adult could pose significant health risks—such as heat stress—for infants and young children, older adults, or individuals with certain medical conditions (see Chapter 3).

Conclusion 6-3: While ANSI/ASHRAE Standard 161-2023 establishes thermal requirements for aircraft cabins, its implementation may not fully protect occupant health and safety, particularly during ground operations when both cabin temperature and humidity can be elevated. The upper limits specified in ANSI/ASHRAE Standard 161-2023—up to 29.4°C (85°F) during ground operations with in-flight entertainment (IFE) operating and 26.6°C (80°F) without IFE—may still permit conditions that pose health and safety risks to passengers and cabin crew, especially given that ANSI/ASHRAE Standard 161-2023 does not account for humidity or duration of exposure, both of which can alter the potential for heat stress under certain conditions.

Applicability of Thermal Comfort Standards and Heat Stress Guidelines

Thermal Comfort Standards

While ANSI/ASHRAE Standard 161-2023 was developed specifically for aircraft, the committee also considered other temperature and humidity standards for indoor environments, such as ANSI/ASHRAE Standard 55-2023 (*Thermal Environmental Conditions for Human Occupancy*) (ANSI/ASHRAE, 2023b) and Standard 7730:2025 (*Ergonomics of the Thermal Environment*) of the International Organization for Standardization (ISO) (ISO, 2025).[1] Notably, these thermal comfort standards are not typically used for regulatory purposes but rather have been successfully used in building design. The cabin environment differs from typical indoor building spaces in a number of ways that have implications for the applicability of thermal comfort standards (Space et al., 2000). For example, air exchange rates are higher in aircraft—the entire volume of cabin air is exchanged with outside air every 2 to 3 minutes (Bezold, 2021)—and aircraft feature limited cabin volumes with high occupant density. These characteristics can alter thermal perception and responses to thermal exposure. Nevertheless, unlike ANSI/ASHRAE Standard 161-2023, thermal comfort standards account for humidity, which significantly influences thermal comfort and health and safety risk. Consequently, they may offer a more protective framework for health and safety than fixed temperature limits alone.

[1] As discussed in Chapter 4, both thermal comfort standards use the Fanger model as the primary basis for evaluating indoor environments for thermal comfort. ISO Standard 7730:2025 defines three classes of environments based on the predicted mean vote (PMV); Class B corresponds to the comfort range for ANSI/ASHRAE Standard 55-2023 ($-0.5 < PMV < +0.5$).

However, applying these standards in an aircraft setting presents challenges. Thermal comfort models assume relatively stable conditions and allow for adjustments in clothing or activity (ISO, 2025)—options that are often limited in aircraft cabins. Implementation would require assumptions about activity levels (e.g., a metabolic rate of 1.2 MET for seated passengers and 2.3 MET for active flight attendants) and clothing insulation. These assumptions are critical because thermal comfort zones shift with metabolic rate and clothing, as illustrated in Figures 6-2 and 6-3.

While these standards, if appropriately adapted, could improve protection compared with ANSI/ASHRAE Standard 161-2023, they still would not address duration of exposure or vulnerable populations (e.g., infants and young children, older adults, individuals with chronic conditions), which may remain at higher risk even within "comfort" zones.

Conclusion 6-4: Thermal comfort standards such as ANSI/ASHRAE Standard 55-2023 and ISO Standard 7730:2025 account for humidity and, therefore, offer a more comprehensive basis for protecting health and safety than fixed temperature limits alone. If applied to aircraft cabins, these standards could reduce the risks associated with thermal discomfort and heat stress, particularly during ground operations in humid environments. However, thermal comfort standards were developed based on healthy adult populations, which may or may not reflect the composition of aircraft occupants.

Heat Stress Guidelines

Several established occupational heat stress guidelines and criteria for recommended workplace standards were evaluated for potential applicability to the aircraft cabin environment. Notably, the American Conference of Governmental Industrial Hygienists (ACGIH, 2025) and the National Institute for Occupational Safety and Health (Jacklitsch et al., 2016) publish criteria that prescribe work-to-rest cycles based on metabolic rate, clothing insulation, and environmental heat exposure. Importantly, the environmental conditions addressed in these heat stress criteria are more severe than those considered in thermal comfort standards (e.g., see "heat stress" zones in Figures 6-2 and 6-3), and while it is possible that temperatures in an aircraft cabin may reach such levels (Figure 6-1), this is likely to occur in only a small fraction of flights and would only be relevant in extremely humid conditions, which cannot currently be measured using existing integrated monitoring systems on commercial aircraft (A4A, 2026). Moreover, the occupational heat stress guidelines do not account for occupations characterized by high cognitive loads, such as flight attendants, whose performance may degrade under less extreme but still thermally challenging conditions. For these reasons, this committee deemed thermal comfort standards more appropriate for informing recommendations on acceptable thermal environments in aircraft cabins.

Feasibility of and Considerations for Implementing Cabin Temperature Standards

In response to committee inquiries, aircraft manufacturers indicated that cabin thermal control design criteria and operational guidance are informed by existing industry standards and manufacturers' own experience (OEM, 2025). In these responses, the standards referenced by manufacturers varied but included the three noted above: ANSI/ASHRAE Standard 161-2023, ANSI/ASHRAE Standard 55-2023, and ISO Standard 7730:2025. Target temperature ranges provided by manufacturers generally aligned with ANSI/ASHRAE Standard 161-2023 (e.g., between 18 and 25°C [64.4–77°F]), and these ranges are incorporated into environment control

system (ECS) design. Therefore, maintaining cabin temperature within these ranges should be feasible in most circumstances when ECS and auxiliary power units (APUs) are fully operational.

Another consideration is operational feasibility. In a response to a committee request for information, airlines raised concerns about the feasibility of complying with the temperature limits specified in ANSI/ASHRAE Standard 161-2023. Among their concerns were problems with temperature sensor accuracy and placement in aircraft, the capacity of aging aircraft to maintain originally designed temperature performance, the age of airport ground support technology, and variations in air supply systems and the temperature of delivered air while on the ground (A4A, 2026). Moreover, using thermal comfort standards to guide decisions—such as delaying boarding or deplaning—would require real-time monitoring of temperature and humidity, integration with safety management systems, and clear thresholds for action. As indicated in Figures 5-7 and 5-8, even in more typical operating conditions it is difficult to maintain cabin thermal conditions within the narrow range established by thermal comfort standards, given the variable activity levels of passengers and cabin crew.

Establishing a mandatory cabin temperature standard would represent the most stringent approach to managing thermal conditions. In general, publishing desirable norms and incentivizing voluntary compliance would be preferable, as it would allow flexibility while promoting best practices. However, in the absence of sufficient motivation or financial incentives, voluntary measures may fail to adequately protect passenger and cabin crew health and safety. Under such circumstances, a regulatory standard could help address variability in airline policies, such as differences in boarding temperature limits, and define required actions when ECSs are not functioning as intended.

If a cabin temperature standard were adopted, it would need to incorporate operational flexibility to avoid unintended consequences. For example, a mandatory temperature threshold for boarding—or deplaning in the event of ground delays—could increase flight delays, with cascading impacts on schedules and passenger experience. While delays would be warranted when cabin conditions pose health and safety risks, the standards should consider the duration of exposure as a critical factor. As discussed in Chapter 3, the health and safety effects of temperature exposure are heavily influenced by duration of exposure. Brief exceedances of a temperature threshold—such as during initial cooling after APU activation—may not present the same risk as prolonged exposure. Therefore, rigid enforcement without accounting for exposure time could impose operational burdens without meaningful safety benefits.

Conclusion 6-5: It is technologically feasible for aircraft to maintain cabin temperatures within the thermal requirements outlined in ANSI/ASHRAE Standard 161-2023 in the vast majority of circumstances, provided that the ECS and APU are fully operational during both flight and ground operations. However, challenges arise when these systems are inoperative, under deferred maintenance, during periods of extreme ambient temperatures during ground operations, or when ground-sourced conditioned air is unavailable or inadequate. Such scenarios increase the likelihood of cabin temperatures exceeding recommended limits, particularly during boarding and extended ground delays.

Conclusion 6-6: Basing cabin temperature limits on thermal comfort thresholds from applying ANSI/ASHRAE Standard 55-2023 or ISO Standard 7730:2025 may be difficult due to the variable activity levels of flight attendants and passengers throughout a flight, especially given the lack of current monitoring of cabin humidity levels to inform

temperature limits. Additionally, these standards have narrow acceptable temperature ranges, which would need to be examined for operational practicability.

A SYSTEMS APPROACH TO RISK MITIGATION

Regardless of whether formal standards are adopted into regulation, there are effective strategies to mitigate risks from thermal exposures by integrating cabin temperature and humidity management into existing aviation safety frameworks. A systems approach will ensure that these efforts are coordinated, comprehensive, and sustainable. Key elements of such an approach include

- identifying hazards and managing risks
- establishing and implementing operational best practices; and
- training and education.

The following sections discuss each of these elements in detail, highlighting strategies that airlines and other stakeholders can adopt to protect the health and safety of passengers and crewmembers.

Identifying Hazards and Managing Risks

Leveraging Existing Safety Management Systems

The aviation industry has established processes for identifying and managing hazards that can be used to address health and safety risks associated with cabin temperatures. Title 14 of the Code of Federal Regulations (14 CFR) Part 5, *Safety Management System for Domestic Flag and Supplemental Operations Certificate Holders* final rule, requires aircraft operators to have an FAA-approved safety management system (SMS) (FAA, 2024a), and it provides detailed requirements for and elements of an SMS.[2]

> An SMS is an organization-wide, comprehensive, and preventive approach to ensuring system safety. An SMS includes a safety policy, promotion of a positive safety culture, formal methods for identifying hazards and mitigating risk, and assurance of the overall safety performance of aviation organizations. An SMS is intended to be designed and developed so the aviation organization's employees are able to manage risks as a part of the operations and business decision-making processes. An SMS assists an aviation organization's leadership, management teams, and employees in making effective and informed safety decisions (FAA, 2024b).

Incorporating cabin temperature and humidity hazards into an existing SMS offers a significant advantage: it embeds thermal risk management within a broader, established safety framework rather than creating a separate system. Safety management is never finished—it must be continually applied to identify and address emerging concerns in aviation safety. Furthermore, all aspects of safety analysis—the metrics and methods for identifying and addressing risks, the

[2] 14 CFR 5.

data gathered, the processes for analyzing data, and organizational structure and culture—must themselves be constantly reviewed and updated to address new challenges (NASEM, 2024).

FAA does not specify hazards that should be addressed through an airline's SMS but rather leaves it to each airline to assess risks through a safety risk assessment (SRA) process. However, FAA can inform and provide guidance to airlines regarding specific hazards that airlines may then consider addressing through their SMS. As stated previously, humidity significantly influences thermal comfort and heat stress risk. FAA could, for example, require operators to consider the risk of both cabin temperature and humidity levels when applying SMS principles to analyze safety data and assess the risks associated with emerging hazards. This would ensure that airlines are better prepared to proactively develop and implement mitigations that are appropriate to their specific environment and operations. Given that existing temperature standards (ANSI/ASHRAE Standard 161-2023 and thermal comfort standards) do not address duration of exposure, airlines would benefit from FAA guidance on acceptable limits for the duration of thermal exposure when cabin temperatures and humidity levels exceed comfort limits.

Existing FAA advisory documents could be the basis for conducting an SRA. For example, FAA issued Advisory Circular (AC) 121-35, *Management of Passengers during Ground Operations without Cabin Ventilation* (FAA, 2003), in 2003 in response to a recommendation in the National Research Council's 2002 report *The Airliner Cabin Environment and the Health of Passengers and Crew* (NRC, 2002). AC 121-35 provides guidance regarding air carrier procedures for the use of ventilation and ground-based air conditioning during ground operations as well as for the management of passengers during ground operations with no cabin ventilation. Updates to this guidance may be considered given that preventable cabin temperature events appear to be a greater issue during ground operations (see Chapter 5 and Appendix B).

Another mechanism FAA can use to draw attention to a potential hazard is by publishing a safety alert for operators (SAFO), which contains important safety information and may include recommended action (see, for example, FAA, 2025). Since a SAFO is a guidance document, conforming with any recommended actions is voluntary, and a SAFO is not used by FAA as a basis for affirmative enforcement action or administrative penalties.

According to information provided to the committee, some airlines already incorporate cabin-temperature-related health and safety information into their SMS for analysis (A4A, 2026). Delta Airlines, for example, reports use of its SMS as a framework for proactively managing heat-related risks and describes processes for regularly analyzing data from employee safety reports, Occupational Safety and Health Administration recordable injuries reporting, equipment reliability reports, and passenger experience reports (Delta Airlines, 2024). However, these efforts appear focused only on the most serious heat injuries and illnesses and may not address the full range of health and safety impacts (e.g., cognitive, behavioral) that may result from thermal exposures in aircraft cabins. Expanding such efforts across all airlines and to include a broader framing of thermal exposure risks as described in Chapter 3 of this report would support improved risk mitigation and allow airlines to determine the best way to manage risks while maintaining operational flexibility to ensure positive outcomes for passengers and cabin crew.

Recommendation 6-1: Airlines should integrate the management of cabin temperature and humidity hazards associated with health and safety risks into their safety management systems, as approved by the Federal Aviation Administration. This integration would ensure that temperature-related risks are addressed within an

established, organization-wide safety framework, using formal processes for hazard identification, risk assessment, and mitigation.

Recommendation 6-2: To inform airline efforts to integrate the management of cabin temperature and humidity hazards into their Federal Aviation Administration (FAA)–approved safety management systems (SMSs), FAA should

- **issue a safety alert for operators (SAFO) advising air carriers of the hazards and risks associated with cabin temperatures and humidity of varying durations as well as their potential impacts on crewmembers and passengers, including higher-risk subpopulations. The SAFO should emphasize that successful management of these risks should be evaluated through each carrier's FAA-approved SMS;**

- **update Advisory Circular 121-35, *Management of Passengers during Ground Operations without Cabin Ventilation,* to reflect technological advances, industry feedback, and recommended best practices; and**

- **establish guidance on the acceptable duration of thermal exposure where cabin temperatures and humidity levels may approach health and safety limits.**

In implementing this recommendation, FAA should consider opportunities to engage with and consult experts in human performance and accident prevention in aviation settings (e.g., the National Transportation Safety Board). Additionally, in developing the recommended guidance on the acceptable duration of exposure to thermal conditions approaching health and safety limits, FAA will need to coordinate with DOT to ensure consistency with requirements to maintain a comfortable cabin temperature during lengthy tarmac delays in accordance with carriers' tarmac delay contingency plans required by 49 USC § 42301. As discussed in Chapter 1, DOT issued the *Enhancing Airline Passenger Protections* final rule in response to concerns about excessive delays in ground operations. Also known as the Tarmac Delay Rule, it requires covered carriers to begin to "return to a suitable disembarkation point no later than 3 hours (for domestic flights) or 4 hours (for international flights) after the main aircraft door is closed in order to deplane passengers."[3] In setting these limits on providing opportunities for deplaning, the only consideration given to the temperature levels in the cabins of planes experiencing delayed departure was to provide comfortable cabin temperatures. However, DOT has provided no definition of "comfortable" in this context (DOT, 2014).

Improving Aviation Industry Utilization of Health and Safety Event Data to Identify Hazards

As discussed in Chapter 5, voluntary reports of symptoms or illness in passengers and cabin crewmembers can inform an understanding of temperature effects in the aircraft cabin environment. While individual events may be managed appropriately by airline crewmembers, and, as described earlier, air carriers may independently review cabin-temperature-related health and safety reports as part of safety management processes, the committee found no industry-wide

[3] 14 CFR § 259.4.

program for systematic temperature hazard identification and risk management that has been designed to take maximum advantage of these reports.

Narrative health and safety reports related to cabin temperatures are currently voluntarily reported in any of several systems (see Chapter 5), including independent airline in-house safety reporting systems, union-developed reporting systems, and systems maintained by federal agencies (e.g., FAA, NASA). The resulting data fragmentation impedes efforts to identify and quantify cabin temperature hazards. To make better use of these reports (complaints as well as health and safety incident data) for mitigation purposes within and across airlines, there should be a single common system designed to aggregate and organize the reports into a pre-determined set of categories of type and severity of outcome and, where possible, to link outcomes to aircraft thermal conditions. Presently the committee is not aware of any structure for organizing these incident data, especially as they are received from a variety of sources.

Recommendation 6-3: To link environmental factors to possible health and safety outcomes, the Federal Aviation Administration, in collaboration with airlines, should develop a standardized approach to systematically collect, report, and periodically analyze health and safety outcome data (including cognitive and behavioral effects) from complaint and health and safety reports.

Developing a structured, common format for organizing health, safety, and complaint data could enhance understanding of reports not otherwise easily understood from the report narrative and ultimately support mitigation of cabin-temperature-related risks by providing an enhanced understanding of higher-risk conditions and impacts on vulnerable populations. Airlines could use the output from the common system to examine their experience internally in whatever manner best suits their circumstances. But having a common structure for all airlines would enable the establishment of industry benchmarks that airlines could use for quality improvements as needed and to support learning from one another's efforts to mitigate any problems identified. Such benchmarking could be done with assistance (e.g., deidentification to ensure confidentiality) from airline trade associations or FAA. It is also likely that structured organization of reports could lead to ongoing (possibly automated) preparation of standardized reports of the different outcome categories, making it easier to regularly examine the categories of outcomes across temperature differences, aircraft classes, and across time. Such a structure will better position the airlines to recognize previously hidden problems that can be addressed. Information derived from this improved management of reports could also be used as an important input to airlines' SMSs (Recommendation 6-2).

Identifying Sentinel Events

By leveraging the standardized system to collect and organize health, safety, and complaint reports called for in Recommendation 6-3, a sentinel event program could be introduced with little additional effort to make better use of the organized data to help prevent future occurrences. Experience in other arenas suggests that a sentinel event program could help identify as soon as possible less common but higher-priority concerns. Such a scheme could help target system concerns and lead to better identification and management of temperature-related health and safety risks that need more immediate attention.

A sentinel event has been defined as "a preventable disease, disability, or untimely death whose occurrence serves as a warning signal that the quality of preventive and/or therapeutic medical care may need to be improved" (Rutstein et al., 1983, p. 1054). Sentinel health programs

have successfully served public health objectives in such diverse areas as maternal health (Theerman, 2022; Wallace et al., 1954), vaccine-preventable infectious disease (Birkhead and Maylahn, 2000), and occupational disease (Rutstein et al., 1983). When sentinel events are determined to be preventable, such programs seek to identify and address the underlying cause. The Joint Commission, which accredits hospitals in the United States, has established a number of adverse outcomes in the hospital setting as sentinel health events of health care quality (Joint Commission, 2026). When such events are identified, hospital authorities receive timely information, allowing action to follow quickly to prevent similar events in the future. It is important to note that sentinel event programs do not require mandatory or complete reporting. Rather they rely on the determination that the individual sentinel event is sufficiently indicative of a prevention failure to warrant preventive action going forward (Joint Commission, 2026).

How might this apply in the air cabin setting? A subset of health, safety, and complaint outcomes or groups of outcomes that have been organized into categories, as suggested in Recommendation 6-3, could be defined as sentinel events. The ongoing analysis of the structured aggregated data could include alerts when a sentinel event occurs, which would elevate the importance of timely action to address a health or safety risk in accordance with airlines' SMSs (see Recommendation 6-1). This requires first the establishment of a set of health conditions and/or symptoms (single or repeated) coupled with circumstances that would qualify as sentinel events (i.e., outcomes determined sufficiently likely to indicate preventable heat or cold illness). As warranted, some of these could be labeled as requiring specific immediate attention, while others could be monitored over time to seek trends that could inform airlines of the need for system improvements.

> **Recommendation 6-4: The Federal Aviation Administration should work with airlines to define sentinel events that would enhance the value of reported cabin-temperature-related health and safety events for identifying a hazard. This should include developing a preliminary list of conditions and symptoms reasonably predicted to be associated with adverse thermal exposures in aircraft cabins. The sentinel events would supplement analyses of health and safety reports for use in airline safety management systems.**

Identifying a recommended list of sentinel events indicative of actionable temperature-related incidents for use in a surveillance system would enhance airlines' ability to implement preventative actions in a timely manner, tailored to specific settings as appropriate. This list should include events reported in safety and complaint systems and in airline medical consultation records as well as those reported by health care personnel. In developing this list, the FAA could engage with experts in aerospace medicine and physiology from existing professional organizations, such as the Aerospace Medical Association and the American Physiological Society.

Establishing and Implementing Operational Best Practices

A review of comments included with some of the reports from aviation industry complaint or safety reporting systems (e.g., NASA's Aviation Safety Reporting System [ASRS], the Association of Flight Attendants' [AFA's] 2Hot2Cold app) indicates that poor decision making or poor logistics can cause or exacerbate cases of extreme temperatures in aircraft cabins. Examples include boarding an aircraft with compromised air conditioning that is already hot, dispatching an aircraft with an inoperative APU to an airport without suitable ground-

sourced air conditioning, and not having ground-sourced air conditioning ready for aircraft landing in hot environments. Airlines can mitigate cabin-temperature-related health and safety risks by adopting policies and procedures and providing employee training that prevents such situations.

Operational practices and policies that may be implemented by airlines and, in some cases, airports (and their contractors) to address challenges related to thermal control on aircraft are discussed in Chapter 2 and summarized in Box 6-1. Coordination across stakeholders is critical when the responsibility for equipment is shared, as may be the case for ground-based air conditioning units. Many of these practices are already being implemented by air carriers and other stakeholders but variably so. For example, some but not all airlines have policies on boarding temperature limits (A4A, 2026), and the limits established in these policies vary. For instance, the threshold for one air carrier is 32°C, or 90°F (Malis, 2025), whereas another sets the limit at 29.4°C, or 85°F (Pawlyk, 2023). It is prudent for airlines to develop and enforce established policies (best practices) that prevent the boarding of an aircraft that is likely to have unreasonably extreme temperature conditions for an extended period. At the same time, there are enormous challenges in operating tens of thousands of flights with millions of passengers every day in an environment with continually changing factors such as weather, cancelled or delayed flights, air traffic congestion, and system failures. Airlines organizing and sharing best practices with one another as they address the complex problems of maintaining healthy and safe cabin temperatures could address this complexity with shared ingenuity.

It is important to include flexibility along with best practice objectives to allow decisions that facilitate the smooth flow of aircraft operations while providing adequate protection of cabin occupants. For example, a best practice might consider boarding a hot aircraft that has fully functioning air conditioning and is cooling down to be acceptable while setting limits on boarding a hot aircraft that has compromised or non-functioning air conditioning where conditions will only worsen as occupancy increases. In the former case, temporary discomfort would be expected, while the latter case could lead to serious discomfort and safety concerns. Additionally, many passengers are likely to prefer a short period of discomfort over delayed boarding to allow an aircraft cabin to cool to a comfortable temperature if the result is a delayed flight. Airline temperature-limit guidelines for boarding are encouraged and should align with any FAA-developed guidance on acceptable duration of thermal exposure (see Recommendation 6-2). However, the focus should be on preventing prolonged exposure of passengers and crewmembers to temperature and humidity conditions that result in substantial discomfort or safety concerns and not just adherence to an arbitrary limit.

BOX 6-1
Engineering and Management Practices for Mitigating Extreme Cabin Temperatures and Associated Health and Safety Impacts

Over the course of its information-gathering process, the committee heard from manufacturers, airlines, and pilot and flight attendant union representatives regarding policies and practices that, if routinely implemented, would help prevent exposures to cabin temperatures that pose health and safety risks to occupants. Additional practices were sourced from the published literature. While empirical evidence regarding the effectiveness of the practices listed below is lacking, consistency in the suggested mitigation strategies across multiple stakeholders indicates their potential as operational best practices based on real-world experience. The responsibility for implementing such policies and practices falls largely to

airlines, though in some cases other stakeholders (e.g., airport authorities) may have shared responsibilities (as indicated below).

Engineering practices[a]

1. Conduct regular preventive maintenance on ECS components (including APU) and ground-based PCA units (stationary and mobile systems) according to manufacturer instructions, and expedite repairs during seasons in which aircraft will be operating in high or low ambient temperature environments.
2. Install personal air outlets in aircraft, including at each passenger seat, cabin crewmember workstation, jumpseat, and crew bunk consistent with ANSI/ASHRAE Standard 161-2023.
3. Ensure the proper sizing, airflow, and cooling capacity of ground-based PCA units (stationary and mobile systems), considering local climatic data and, when possible, using sensors to evaluate performance (e.g., adequacy of airflow and air temperature).
4. Use PCA unit hose management systems that minimize conditions resulting in air pressure loss (e.g., kinking, hose damage) and inspect hoses regularly for signs of wear and tear that may impact airflow.
5. Deploy monitoring systems that can provide real-time information to airline operators on the operational status of the gate equipment used for managing the cabin thermal environment.

Management/administrative practices and policies

1. Establish and enforce temperature limit guidelines for pre- and post-boarding decision making, giving consideration to the effects of humidity and ensuring adequate time and equipment for pre-boarding assessment of cabin temperatures and protection from punitive action.
2. In hot ambient conditions, precool aircraft and implement other procedures that can be used to manage cabin temperatures (e.g., turning off IFE, closing window shades, opening personal air outlets, limiting time with aircraft doors open).
3. Prohibit the dispatching of aircraft operating with a nonfunctional APU or air conditioning pack (i.e., under deferred maintenance in accordance with the operator's approved minimum equipment list) to locations with extreme ambient temperatures when functional ground-sourced air conditioning systems are not available.
4. Ensure that standard operating procedures address decision making regarding the use of alternative sources of conditioned air during ground operations (e.g., APU, gate-attached PCA units, ground carts) and take into account the capacity and availability of each air source and different potential operational scenarios (e.g., heat-soaked aircraft, short turnaround times).
5. Train ground crew personnel on the proper connection of ground-based PCA units and conduct visual checks during use to ensure proper use (e.g., no kinks in hosing).
6. Provide flexibility in flight attendant uniform clothing selection to allow adjustments for a variety of thermal conditions and individual preferences (discussed further in Chapter 4).
7. Ensure the availability of supplies in aircraft cabins to assess and manage potential incidents of thermal stress (e.g., thermometers, ice, electrolyte-containing beverages, blankets).

[a] Responsibility for implementing these practices may be shared among airlines, airport authorities, and contracted suppliers/operators of ground-based air conditioning systems.

SOURCES: A4A (2026)[4]; Anderson (2025)[5]; ANSI/ASHRAE (2023a); NASEM (2019); OEM (2025); RAA (2025)[6].

The committee is aware that an ASHRAE working group with representation from multiple aviation stakeholder groups (e.g., flight attendant unions, airlines, manufacturers) is already developing a consensus guideline, *Operational Best Practices for Air Quality within Commercial Aircraft*, which is intended as a companion to ANSI/ASHRAE Standard 161 and will address cabin temperature, among other things. The committee was unable to review the draft working group document, but the guideline, once published, may be a useful reference for airlines as a source of operational best practices that could be implemented to mitigate cabin-temperature-related health and safety impacts.

Aviation industry trade and professional organizations (e.g., Airlines for America, the International Air Transport Association, the International Civil Aviation Organization) represent additional potential sources of operational best practices and are well positioned to help facilitate dissemination to improve the consistency of implementation across airlines. Additionally, InfoShare is a semi-annual, industry-sponsored event facilitated by the FAA that brings together professionals from aviation operators, manufacturers, labor organizations, and government agencies to share information on safety issues, best practices, and mitigation strategies in a confidential, non-punitive environment (FAA, 2018). The forum fosters collaboration to improve safety by identifying trends and systemic risks and could be used as a mechanism for collecting and sharing operational best practices related to mitigating cabin temperature-related health and safety risks.

The safety assurance component of SMS requires airlines and other stakeholders to monitor and measure safety performance. This includes the continued effectiveness of implemented risk control strategies and the identification of new hazards. Safety assurance provides insight and analysis regarding the most effective methods and opportunities for improving safety and minimizing risk while ensuring the performance and effectiveness of safety risk controls. Continuous safety assurance functions support the identification of new hazards and ensure that an organization meets or exceeds its safety objectives through processes for collecting, analyzing, and assessing information (FAA, 2024b). Additionally, an airline required to have an SMS must establish and implement processes to correct identified safety performance deficiencies.

With ongoing evaluation of potential engineering and administrative mitigation strategies, and as technology continues to evolve, it will be important for airlines and other stakeholders to remain aware of industry best practices and to continuously consider whether updates are needed to their policies and procedures.

[4] Personal communication, A4A (Airlines for America), February 4, 2026. Included in the project public access file, available by request at https://www8.nationalacademies.org/pa/managerequest.aspx?key=HMD-HSP-24-18.

[5] Personal communication, Judith Anderson, Industrial Hygienist in the AFA-CWA Air Safety, Health and Security Department, Association of Flight attendants, October 10, 2025. Included in the project public access file, available by request at https://www8.nationalacademies.org/pa/managerequest.aspx?key=HMD-HSP-24-18.

[6] Personal communication, RAA (Regional Airline Association), February 6, 2026. Included in the project public access file, available by request at https://www8.nationalacademies.org/pa/managerequest.aspx?key=HMD-HSP-24-18.

Recommendation 6-5: The Federal Aviation Administration and airlines should leverage existing mechanisms and establish new ones where needed for collecting and sharing operational best practices—as well as barriers to the successful implementation of those best practices—to mitigate cabin-temperature-related health and safety impacts. This mechanism should support the continuous improvement and integration of best practices into existing safety management systems and operational procedures as applicable. The following operational practices that address issues commonly raised in complaint and safety reports should be prioritized by air carriers:

- **Working with airports to ensure that the ground-based air conditioning systems used to manage cabin thermal environments are reliable and adequate, taking into consideration capacity needs related to different aircraft types and historical data on ambient temperatures and humidity.**

- **Ensuring that ground personnel are trained on the proper connection and operation of ground-based air conditioning sources as well as visual checks of hoses.**

- **Prohibiting the dispatch of aircraft operating with an inoperative auxiliary power unit or air conditioning pack to locations experiencing extreme ambient temperatures when functional ground-based air conditioning sources are not available.**

The dispatch of aircraft with inoperable air conditioning packs or APUs was commonly noted in health and safety and complaint reports reviewed by the committee (see Chapter 2). Additional attention is needed to deferred maintenance allowances in accordance with the master minimum equipment list and airlines' minimum equipment lists for aircraft components used for thermal control in flight and during ground operations, particularly given the rising frequency of ambient temperature extremes.

Recommendation 6-6: The Federal Aviation Administration and airlines should periodically review master minimum equipment lists and minimum equipment lists to consider whether current allowances regarding deferred maintenance of environmental control system components, as well as auxiliary power units, allow adequate thermal control.

Empowering Flight Attendants to Better Protect Health and Safety

While all of the practices listed in Box 6-1 merit consideration, the committee wishes to draw particular attention to airline administrative policies that would empower flight attendants to better protect their own safety and that of passengers when cabin-temperature-related issues arise.

First, flight attendants need to have the authority to address unsafe thermal conditions on the aircraft without the risk of disciplinary action. During a public information-gathering meeting, the committee heard from flight attendant unions for airlines operating under a Part 121 certificate that few airlines recognize flight attendants' participation in decision making about flight operations when cabin temperatures are considered unsafe in their estimation, especially at

boarding (Heiple, 2025; Malis, 2025). Data from the AFA's 2Hot2Cold app, discussed in Chapter 5, indicates that the majority of temperature complaints occur during boarding, when pilots, who are responsible for controlling the ECS, may not be present. Further, while some airlines include cabin temperature thresholds for safe boarding (albeit different thresholds), specific criteria for the duration of the temperature exposure are missing. Some union representatives reported that flight attendant concerns are sometimes dismissed by pilots and that they feel threatened with disciplinary actions should they raise a concern about cabin thermal conditions that may affect the health and safety of cabin occupants (Click, 2025; McDaniel, 2025).

Second, flight attendants need greater agency over their own safety and thermal comfort in terms of uniform accommodations. As discussed earlier in this report, the ability to individually adapt clothing to account for ambient thermal conditions, activity level, and thermal preference is a powerful means to improve thermal comfort. Figure 4-4 in Chapter 4 shows how clothing choices can offset the effects of activity levels. Airline clothing policies that offer flexibility can thus help flight attendants maintain acceptable thermal conditions over a wide range of activity levels while maintaining standards of professionalism. For example, air carriers could provide an option for cabin crew to wear knee-high boots with socks during cold conditions, make pantyhose or tights optional, offer seasonal variations of uniform pieces (short-sleeved shirts or wool sweaters) (Eton College, 2024), and not require crew to wear their suiting jacket during boarding and deplaning.

It should be emphasized, however, that clothing policies should be part of a more comprehensive approach to mitigating temperature-related health and safety impacts and should not be seen as an alternative to implementing other practices such as those described in Box 6-1.

Recommendation 6-7: Airlines should ensure that input from flight attendants is included in real-time operational decisions related to cabin thermal conditions that may affect the health and safety of cabin occupants.

Recommendation 6-8: Airlines should provide flight attendants maximum feasible flexibility in uniform options and outfit selection to allow adjustments for varying thermal conditions and individual preferences.

Training and Education

Preventing incidents of thermal stress from exposure to cabin temperatures requires an awareness of the conditions that contribute to hot and cold cabin temperatures as well as a means of preventing negative health and safety outcomes. This section discusses opportunities to better raise awareness through training for crewmembers and public education efforts.

Certain populations are more susceptible to the adverse effects of thermal stress (e.g., infants and young children, older adults, people with certain medical conditions), as discussed in Chapter 3. Both training and education efforts should therefore include a specific focus on these groups and underscore the potential for hot or cold cabin conditions to cause physiological strain or discomfort in select subpopulations or individuals.

Training for Crewmembers

Crewmembers have critical roles in implementing preventive strategies like those discussed earlier in this chapter and also in managing incidents of extreme cabin temperatures to

mitigate associated health and safety impacts. Doing so effectively requires that the crewmembers have adequate training. During a public information-gathering session, the committee heard from representatives from pilot and flight attendant unions that airlines provide general training for crewmembers on issues related to cabin temperatures but that there are opportunities for improvement, both in terms of the content and the format of training.

Pilots and flight attendants have different responsibilities related to ensuring the safety and well-being of aircraft occupants, and the content of training materials for these two crewmember groups should reflect their different responsibilities while remaining harmonized. For example, flight attendants have more direct contact with passengers and are therefore better positioned to recognize signs and symptoms of thermal stress if trained on what to look for (Scorsone, 2025). The committee heard that flight attendant training on the signs and symptoms of heat stress does not currently address potential differences across population groups (e.g., unique symptoms in infants and children), which represents a notable area for improvement. This is because children and infants are often the first passengers on an aircraft to become affected by thermal stress. It was also mentioned that infants and children with compromised health often travel to medical appointments on airplanes, and thus, because of their vulnerable states, they can be affected more quickly by high and low temperatures in the aircraft cabin (Heiple, 2025).

Another potential focus for flight attendant training is reinforcing the importance of the use of mitigation strategies to reduce thermal stress risk. The committee was told that not every flight attendant training module provides specific actions that could reduce the possibility of cabin temperature increases and thus minimize the chance of thermal stress issues on a future flight. These specific actions include such things as requiring a flight attendant to make an announcement for passengers to lower their window shades and open personal air outlets (A4A, 2026).

Pilots on the other hand may be responsible for communicating signs and symptoms to aviation medical consultation organizations when incidents occur on a flight (Schwantner, 2025). Pilots also have more control over cabin temperature than do flight attendants, and pilot training could emphasize temperature management strategies such as APU use and common pitfalls with ground equipment that lead to inadequate temperature regulation. Explicitly highlighting the importance of open communication between flight attendants (who may perceive symptoms in passengers) and pilots (who have more direct control over the cabin environment) may reduce any issues arising from the disparate experiences of flight attendants and pilots while on board.

Training format is another factor that needs to be carefully considered. Flight attendant union representatives indicated that cabin crew training on cabin temperature issues is often web-based and delivered in the form of a slide deck or video (Rhinehart, 2025). It was also mentioned that training is a “one and done” event and often is not provided on a regular basis. Training on cabin temperature issues should be delivered in multiple formats and integrated into line-oriented scenario-based training for better long-term recall of the information and skills. Training modalities that simulate the more serious scenarios that may be encountered and provide opportunities for crewmembers to practice mitigation procedures may be more effective, especially given the need for close coordination among flight attendants and pilots in emergency and other unusual situations (FAA, 2020). Further, operators should assess both learning and learning transfer to evaluate training effectiveness. This includes assessing how successfully crewmembers met the training's learning objectives and how successfully they can apply what they learned when they return to the workplace. Finally, building knowledge or skill assessment

into the training with such things as knowledge checks, quizzes, or observations can provide evaluation data and reinforce learning at the same time (CDC, 2024).

Recommendation 6-9: Airlines should require initial and recurrent training for flight attendants and pilots on the contributors to cabin temperature issues, signs and symptoms of temperature-related illness (including variability across age and health groups), and preventive and responsive mitigation measures. This training should meet established effectiveness guidelines and be continuously evaluated and updated as needed.

Flight attendant training covering variability across age and health groups should include a focus on the most vulnerable populations (i.e., risk for and signs and symptoms of thermal stress in infants and young children, older adults, and people with health conditions or disabilities that can impair behavioral or autonomic thermoregulation). Training on responsive mitigation measures should include airline-specific mechanisms for obtaining real-time information and guidance in the event of a concern as appropriate. For example, some airlines contract with MedAire or STAT-MD for access to aviation-trained emergency physicians who can provide instructions on the management of in-flight medical emergencies and inform diversion decisions.

Public Education

Information provided to the public on cabin temperature issues and their potential health and safety impacts can serve two key purposes—to raise awareness regarding the signs and symptoms of thermal stress and to inform passengers on actions they can take prior to and after boarding a plane to improve their thermal comfort.

In many cases, individuals may become aware of clinical symptoms (in themselves or their traveling companions) related to thermal exposure before signs may be apparent to cabin crewmembers. Early action upon recognition of thermal stress symptoms can prevent the situation from becoming more serious, underscoring the importance of public education efforts. While media reports are helping to draw additional attention to health issues that can arise from exposure to hot cabin temperatures (Cook, 2017; Fingert, 2025; Grant and Sweeney, 2023), airlines can help raise public awareness by sharing information on the signs and symptoms of thermal stress and on the populations that may be especially vulnerable, drawing on information provided in FAA advisory documents (see Recommendation 6-2). Informational materials could also provide information on how clothing choices can impact thermal comfort while flying. Such information can help to empower members of the public to attend to their own comfort, which is important given the person-to-person variation in thermal tolerances.

The FAA and many airlines already provide information to passengers in the form of travel tips (see, for example, FAA, n.d.; Southwest Airlines, 2024; United Airlines, 2026), which can be expanded upon to include considerations related to cabin temperatures. Airlines are encouraged to make use of existing communication materials and platforms when possible to share information related to cabin temperatures that may help improve public awareness on this issue. This can be effectively achieved by taking advantage of the vast array of existing public-facing resources developed by health care and other professional organizations that outline health risks associated with extreme temperature exposures and the associated signs and symptoms and offer actionable steps for risk reduction (AAP, 2024; EPA, 2025; Health in Aging Foundation, 2019; NIA, 2022). Using resources from specific organizations may provide an advantage by

specifically addressing the needs of vulnerable groups, including pediatric and geriatric populations. This approach ensures that the guidelines are inclusive and relevant to individuals who may be more susceptible to the effects of extreme temperatures.

Recommendation 6-10: Airlines should provide passengers with access to information about the hazards of varying cabin temperatures and actions they can take to prepare for and respond to hot and cold conditions. These efforts should include

- **identifying higher-risk groups;**
- **describing mitigation measures, such as adjustable clothing, hydration strategies, and the use of personal air outlets, to improve comfort and ensure safety while aboard the aircraft; and**
- **urging passengers to alert flight attendants if an issue related to thermal stress arises.**

CONCLUDING REMARKS

In closing, the committee emphasizes that managing cabin temperatures and the associated health and safety risks is not simply a technical or regulatory issue, but also a systems challenge that spans aircraft design, airline operations, airport infrastructure, and oversight frameworks. The evidence reviewed in this report indicates that while extreme temperature events that pose serious health risks are relatively rare, the conditions that produce substantial discomfort of the sort that may have cognitive or behavioral effects occur more frequently and can impact the ability of flight attendants to perform safety-critical duties. These risks are heightened during ground operations, when elevated temperature and humidity, equipment constraints, and operational pressures can converge. Addressing these challenges requires coordinated action that recognizes the dynamic nature of the aircraft cabin environment and the shared responsibilities among stakeholders.

The committee's recommendations, summarized and categorized according to stakeholder in Box 6-2, are intended to provide a practical path forward. Collectively, they emphasize improved monitoring and data collection, the integration of temperature and humidity hazards into existing safety management systems, the adoption of operational best practices, and enhanced training and communication for both cabin crew and passengers. Taken together, these actions can reduce the likelihood and severity of adverse thermal exposures while accommodating the operational realities of Part 121 operations. Implementing these recommendations would also establish a stronger empirical foundation for future decision making, enabling regulators and operators to better assess risks, evaluate mitigation strategies, and adapt to evolving conditions in air travel.

BOX 6-2
Recommendations Aligned with Stakeholders[a]

FAA

• Establish a program to systematically monitor, record, and assess temperature and humidity conditions in passenger aircraft cabins. (Recommendation 5-1)

• Update Advisory Circular 121-35, issue a SAFO advising air carriers of the hazards and risks associated with cabin temperatures and humidity, and establish guidance on the acceptable duration of thermal exposure where cabin temperatures and humidity levels may approach health and safety limits. (Recommendation 6-2)
• Collaborate with airlines to develop a standardized approach to systematically collect, report, and periodically analyze health and safety outcome data. (Recommendation 6-3)
• Define sentinel events to enhance the value of temperature-related health and safety reports for hazard identification. (Recommendation 6-4)
• Leverage existing mechanisms and establish new ones where needed for collecting and sharing operational best practices as well as information on barriers to successful implementation. (Recommendation 6-5)
• Periodically review master MELs and MELs to consider whether current allowances for deferred maintenance of ECS components and APUs allow adequate thermal control (Recommendation 6-6)

Airlines
• Integrate the management of cabin temperature and humidity hazards associated with health and safety risks into FAA-approved SMSs. (Recommendation 6-1)
• Leverage existing mechanisms and establish new ones where needed for collecting and sharing operational best practices as well as information on barriers to successful implementation. (Recommendation 6-5)
• Periodically review master MELs and MELs to consider whether current allowances for deferred maintenance of ECS components and APUs allow adequate thermal control. (Recommendation 6-6)
• Ensure that input from flight attendants is included in real-time operational decisions related to cabin thermal conditions. (Recommendation 6-7)
• Provide flight attendants maximum feasible flexibility in uniform options and outfit selection. (Recommendation 6-8)
• Require initial and recurrent training for flight attendants and pilots on contributors to cabin temperature issues, signs and symptoms of temperature-related illness, and preventive and responsive mitigation measures. (Recommendation 6-9)
• Provide passengers with access to information about the hazards of varying cabin temperatures and actions they can take to prepare for and respond to hot and cold conditions. (Recommendation 6-10)

Airports
• Work with airlines to ensure that the ground-based air conditioning systems used to manage cabin thermal environments are reliable and adequate (Recommendation 6-5)

[a] *Recommendations in this box have been abbreviated. See main chapter text for complete recommendation language.*

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Appendix A
Study Approach and Methods

In response to a request by the Federal Aviation Administration (FAA), the National Academies of Sciences, Engineering, and Medicine (National Academies) convened the Committee on Health and Safety Impacts of Aircraft Cabin Temperatures. This committee was charged with reviewing the evidence on potential health and safety impacts of cabin temperatures and assessing the applicability and feasibility of applying existing standards on air temperatures and humidity levels to ensure the health and safety of cabin occupants. This appendix describes the approach and methods used by the committee in conducting its assessment.

STAKEHOLDER ENGAGEMENT AND INFORMATION GATHERING STRATEGY

The Statement of Task for this study specifies that the committee should seek input from Part 121 operators (i.e., U.S. airlines operating under a Part 121 certificate of the FAA), aviation labor organizations, and other interested parties on the health and safety impacts of cabin temperatures. To inform its deliberations, the committee used several mechanisms to engage with stakeholders and gather information, including public meeting sessions, written information requests, and reviews of the published literature and publicly available data. These approaches are discussed further in the sections that follow.

Public Information-Gathering Sessions

The committee deliberated from July 2025 to March 2026, during which time it held six meetings, two of which included public sessions for the purposes of stakeholder engagement and information gathering. The committee's first public meeting, in July 2025, provided an opportunity to engage with the FAA's Civil Aerospace Medical Institute and the Department of Transportation's (DOT's) Office of Aviation Consumer Protection on questions of study scope and potential data sources. The second public session was held in conjunction with the committee's August 21, 2025, meeting and included discussions with labor organizations for flight attendants and pilots to help the committee better understand major contributors to extreme cabin temperatures, challenges experienced by flight attendants and pilots, and mechanisms for mitigating cabin temperature issues. Both public sessions afforded opportunities for public comment. The agendas for these public sessions follow.

First Committee Meeting
July 10, 2025

1:00 PM ET **Welcome and Introductions**

David Wegman, *Committee Chair*

Presentation of the Charge to the Committee
Anthony Tvaryanas, *Civil Aerospace Medical Institute, FAA*

Clarifying Questions on the Statement of Task

2:00 PM ET **Opportunity for Public Comment and Questions**

2:30 PM ET **Adjourn Public Session**

Second Committee Meeting
August 21, 2025

1:00 PM ET **Welcome and Introductions**
David Wegman, *Committee Chair*

Perspectives from Flight Attendant Labor Organizations
Seth Heiple, *Association of Flight Attendants–CWA*
Allie Malis, *Association of Professional Flight Attendants*
Chris Click, *Transportation Workers Union of America*

Discussants:
Andrew Rhinehard, *Association of Professional Flight Attendants*
Thom McDaniel, *Transport Workers Union of America*

Committee Discussion

2:00 PM ET **Perspectives from Pilot Labor Organizations**
Rondeau Flynn, *Allied Pilots Association and Coalition of Airline Pilots Associations*
Anna-Maria Scorsone, *Air Line Pilots Association, International*
Ken Schwantner, *Southwest Pilots Association*

Discussants:
Jody Reven, *Southwest Pilots Association*

Committee Discussion

3:15 PM ET **Adjourn Public Session**

Review of Published Literature, Standards, and Guidelines

Literature searches were conducted to identify articles published in English between 1990 and 2025 that addressed (1) aircraft cabin environmental conditions, including temperature and humidity, and (2) health and safety effects related to thermal exposure. Separate searches were carried out in PubMed, Scopus, Medline, and Embase. Records were extracted to Endnote.

Additional searches of the gray literature were conducted to capture reports published outside of peer-reviewed journals by academic, professional, government, and private-sector organizations. The specific sources of such reports included websites for the following organizations:

- DOT/FAA
- European Union Aviation Safety Agency (EASA)
- Airliner Cabin Environment Research (ACER) Program
- American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)

As the committee was asked to assess the applicability of existing standards on air temperatures and humidity levels to ensuring the health and safety of cabin occupants, a search for relevant standards and guidelines was conducted by searching websites of the following standards development organizations and professional and governmental organizations that publish guidelines related to thermal exposures:

- ASHRAE
- American National Standards Institute (ANSI)
- SAE International
- International Organization for Standardization (ISO)
- American Conference of Governmental Industrial Hygienists (ACGIH)
- Occupational Safety and Health Administration
- National Institute for Occupational Safety and Health
- European Committee for Standardization (CEN)

Relevant standards and guidelines from these organizations are further described in Chapter 4.

Information Requests

The committee sent written information requests to several aviation industry stakeholders to collect information that was not otherwise publicly available (described below and summarized in Table A-1). Copies of these requests and their complete responses can be requested from the committee's public access file.[1]

TABLE A-1 Overview of Committee Information Requests to Aviation Industry Stakeholders

Stakeholder Group/Organization	Information Request Description
Federal Aviation Administration	Quantitative information on cabin-temperature-related health or safety incidents.
Department of Transportation Office of Aviation Consumer Protection	Passenger complaint data regarding comfortable cabin temperatures and information regarding DOT investigations into those complaints.
Aircraft manufacturers	Technical information regarding the design, operation, testing, and performance of environmental control systems (ECSs) for aircraft operated by Part 121 air carriers under normal and extreme ambient temperature conditions.

[1] In some cases, responses from different organizations within a stakeholder group (e.g., manufacturers, airlines) were aggregated and de-identified prior to sharing with the committee. In those cases, only the aggregated, de-identified responses are available through the public access file.

Part 121 airlines	Cabin temperature and humidity data; quantitative information on cabin-temperature-related health or safety incidents; equipment issues that contribute to challenges with thermal control on aircraft; airline policies and practices related to cabin temperatures; and operational considerations for implementing existing temperature standards.
Aviation medical consultation organizations	Quantitative information regarding temperature-related health/medical incidents experienced by cabin occupants as captured in proprietary databases.

FAA

As the primary federal agency with authority over aviation safety, FAA was a major source of the quantitative information that the committee gathered on cabin-temperature-related health or safety incidents. Specific information requested included

- distributions of cabin-temperature-related health and safety incidents over time and by season, U.S. geographic region, aircraft model, and operational phase (i.e., on ground versus in flight);
- cabin temperatures captured in reports of cabin-temperature-related health and safety incidents;
- major incident types (e.g., passenger illness or distress, crewmember illness or distress, unruly passenger incidents, problem with crewmember performance of safety-critical duties); and
- major underlying causes that result in reports of cabin-temperature-related health and safety incidents (e.g., equipment issues, extreme ambient conditions, operational practices).

In response to the committee's request, FAA staff analyzed data collected from FAA's Accident and Incident Data System (AIDS) and Service Difficulty Reporting System (SDRS), as well as from the National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS), all of which are encompassed by the Aviation Safety Information Analysis and Sharing (ASIAS) system. These databases are described later in this appendix. FAA analyses informed the committee's assessment of cabin-temperature-related health and safety impacts (Chapter 5 and Appendix B).

DOT Office of Aviation Consumer Protection

DOT's Office of Aviation Consumer Protection (OACP) shares responsibility with FAA for the protection of airline passengers, as described in Chapter 1. OACP investigates passenger complaints related to tarmac delays and may bring cases against airlines in cases of noncompliance with DOT regulations. The committee requested summary data from OACP on consumer complaints related to cabin temperatures—including trends over time and by season, U.S. geographic region, aircraft model, and phase of flight—and the office's investigations into temperature-related consumer complaints. Also requested was information on OACP's mechanisms for monitoring airlines' compliance with regulations pertaining to emergency contingency plans for tarmac delays and how DOT defines "comfortable cabin temperature." The response from DOT was used in the report's description of the regulatory context for this study (Chapter 1) and in the committee's assessment of the health and safety impacts of aircraft cabin temperatures (Chapter 5 and Appendix B).

Aircraft Manufacturers

The committee was asked to gather input from aircraft manufacturers on the feasibility of applying identified temperature and humidity standards to aircraft cabin environments. For additional context, the committee also requested information on aircraft system (e.g., environmental control system) capabilities and design considerations, manufacturers' data from testing system performance, post-market modifications in response to operator feedback, and standards and best practices used or recommended by manufacturers.

Information requests were sent to and responses were received from all major manufacturers of aircraft used in Part 121 operations, including Boeing, Airbus, Embraer, and Mitsubishi Heavy Industries (which acquired aircraft fleets previously manufactured by Bombardier).[2] The responses from the manufacturers were aggregated and anonymized prior to sharing with the committee. Only the aggregate, de-identified compilation is available in the project's public access file. Some information requested by the committee was deemed to be proprietary and could not be provided to the committee. Manufacturer responses informed the committee's overview of aircraft cabin thermal control mechanisms (Chapter 2) and strategies for mitigating risks from hot and cold cabin temperatures (Chapter 6).

Part 121 Airlines

The Statement of Task for this study specified that the committee should identify and review available data from Part 121 operators on cabin air temperatures and available evidence on potential health and safety impacts on passengers and cabin crewmembers. Accordingly, the committee requested the following from Part 121 airlines (excluding cargo operators):

- temperature and humidity monitoring and recording capabilities of the current aircraft in their fleets;
- stored data files containing cabin temperature and humidity data or past analyses of such data;
- summary data on reports of hot or cold cabins by flight deck or cabin crewmembers;
- summary data on equipment issues (aircraft or ground-based air conditioning equipment) that contribute to hot or cold cabin temperatures;
- processes and systems used to capture health and safety incidents related to cabin-temperature exposures and summary data on such incidents for the last 3 years;
- summary data on flight attendant fatigue reports related to cabin temperature exposures;
- airline policies and procedures related to monitoring and managing cabin temperatures; and
- input on operational constraints that would affect the feasibility of implementing a cabin temperature standard.

Given the large number of Part 121 airlines, the committee worked with three U.S.-based airline trade associations—Airlines for America, Regional Airlines Association, and the Association of Value Airlines—to distribute information requests to individual airlines. The responses of member airlines were provided to the respective trade associations, which aggregated and anonymized the responses prior to submitting the compilation to the committee.

[2] Information requests were not sent to manufacturers of turboprop aircraft as these aircraft are generally no longer used in Part 121 operations.

Six of seven Airlines for America member airlines and one of five Association of Value Airlines member airlines contributed individual responses. No individual responses were received from members of the Regional Airlines Association, but a letter from the vice president for safety, operations, and regulatory affairs summarized input from regional airlines. Airlines were unable to provide the committee with cabin air temperature and humidity data, noting that no historical datasets were available to be retrieved or shared (A4A, 2026; AVA, 2026; RAA, 2026). Nor were data provided from reports of cabin-temperature-related health and safety incidents or fatigue reports citing cabin temperature as a contributor. Limited data were shared on frequencies of hot and cold cabin reports. Airline responses regarding other requested information informed the committee's overview of aircraft cabin thermal control mechanisms (Chapter 2), its assessment of the health and safety impacts of cabin temperatures (Chapter 5), and strategies for mitigating risks from hot and cold cabin temperatures (Chapter 6).

Aviation Medical Consultation Organizations

MedAire and STAT-MD are the major contracted providers of medical consultation services to Part 121 airlines. Their services include fitness-to-fly assessments and medical support when health/medical incidents occur inflight. Cases are documented in searchable proprietary data systems. The committee requested summary data from these two service providers on health/medical incidents captured in the MedAire/STAT-MD proprietary databases for which hot or cold cabin temperature was the primary or a contributing factor, including trends in incidents (e.g., over time, by season or geographic area), types of temperature-related medical conditions described, and demographic information about the affected individual(s). Relevant cases were identified by screening of records captured in key word database searches and were summarized prior to submission to the committee. This information informed the committee's assessment of cabin-temperature-related health and safety impacts (Chapter 5 and Appendix B). Prior to the distribution to the committee, responses were reviewed to ensure no personally identifiable or protected health information was included, and patient information was redacted as needed.

Collection of Data from Public and Nonpublic Databases

The committee's assessment of the health and safety impacts of aircraft cabin temperatures was informed by analyses of data available in a combination of public and nonpublic databases housing reports from aviation industry safety and complaint reporting systems. These databases are summarized in Table A-2 and discussed in additional detail below. Most of these databases rely on voluntarily reporting and therefore may be subject to underreporting and reporting bias.

TABLE A-2 Overview of Aviation Databases Containing Data Used by the Committee

Database Name	Database Access	Years of Available Data	Description of Database
NASA ASRS	Public	1988–2026	NASA-managed database of voluntary, confidential safety information submitted by aviation personnel (e.g., pilots, flight attendants) (NASA, n.d.) to help identify and correct system deficiencies and to decrease the

			likelihood of aviation accidents. ASRS is also used to inform policy and strengthen human factors research (FAA, n.d.a).
2Hot2Cold	Provided by AFA	2018–2026	App launched by AFA to collect data on extreme cabin temperatures on commercial flights to support union efforts to advocate for a cabin temperature standard (AFA, n.d.).
APFA Hot Cabin Reporting System	Provided by APFA	2019–2026	Dashboard capturing reported cabin temperatures and associated passenger and crewmember symptoms. The hot cabin reporting system supports union efforts to advocate for acceptable minimum and maximum cabin temperatures (APFA, 2025a).
FAA AIDS	Public	1978–2026	FAA-maintained database for reporting civil aviation incidents that do not meet the aircraft damage or personal injury thresholds contained in the National Transportation Safety Board definition of an accident (FAA, n.d.a).
FAA SDRS	Public	1988–2026	FAA database containing records of mechanical malfunctions, defects, and failures on civil aviation aircraft submitted by members of the aviation community when an aircraft system, component, or part fails to function in a usual manner (FAA, n.d.b). The system enables FAA to identify trends and proactively mitigate safety risks (FAA, 2023).

NOTES: Data from databases that are not publicly available can be requested from the committee's public access file. AFA = Association of Flight Attendants; AIDS = Accident and Incident System; APFA = Association of Professional Flight Attendants; ASRS = Aviation Safety Reporting Systems; FAA = Federal Aviation Administration; NASA = National Aeronautics and Space Administration; SDRS = Service Difficulty Reporting System.

NASA Aviation Safety Reporting System (ASRS)

Searches of NASA ASRS were conducted independently by FAA staff and the committee to inform the assessment of cabin-temperature-related health and safety impacts. Filters were used to limit search results to Part 121 operations, and keyword searches—conducted iteratively with screening and de-duplication of results—further narrowed the retrieved results to reports of cabin temperature issues.

The FAA search was restricted to reports submitted between 2000 and 2024. Keywords included: "cabin temp"; "extreme"; "cabin AND temp"; "excessive heat"; "hot AND cabin"; "increas AND temp"; "high AND temp"; "heat"; "excessive"; "cold"; "cool"; "freez"; "froz"; "low AND temp"; "cold AND cabin"; "low AND cabin"; "decreas AND temp." Screening of all retrieved records resulted in 92 reports of cabin temperature issues, representing approximately 1.8 percent of all Part 121-specific reports during the search period.

The committee's search strategy and selection of keywords were guided by NASA ASRS technical assistance personnel. Keywords included: "extreme AND temperature"; "cabin AND (temp% or high or extreme or cold or hot or warm or excessive)"; "inoperative APU"; "cabin AND inoperative APU". Keyword searches resulted in 151 unique relevant reports. Three additional relevant reports were identified in a NASA ASRS-posted set of flight attendant reports (NASA, 2024), yielding a total of 154 relevant ASRS reports. The data extracted from each

report for use in subsequent analyses included ACN number (unique identifier), report date (month and year), reported cabin temperature (when provided), phase of flight operation impacted by cabin temperature issues, contributing mechanical issue(s), reported health and safety impacts.

ASRS report data were used to generate frequency distributions (e.g., reports over time, across seasons, by flight phase); to catalog commonly reported physical, cognitive, and behavioral effects of temperature exposures; and to identify commonly reported contributing equipment issues. The results of these analyses can be found in Chapter 2 (for analyses of equipment issues contributing to hot or cold cabin temperatures) and Chapter 5 and Appendix B. Although the absolute numbers of the reports and the calculated percentages differed between committee and FAA analyses, observed trends (e.g., variation in reports by season and flight phase, relative frequencies of contributing equipment issues) were generally consistent.

2Hot2Cold

The Association of Flight Attendants (AFA) provided the committee with a redacted copy of the data from 4,961 reports captured in the 2Hot2Cold app over the period of April 2018 to July 2025. Reports for which "Airline Category" was described as "charter" were excluded from the committee's analysis, as were reports for which "Location of Measurement on Airplane" was "flight deck" (to limit analyses to Part 121 operations involving cabin temperature issues). After these exclusion, 4,679 reports were included in the committee's analysis of the 2Hot2Cold data. The committee analyzed the data using the statistical computing software environment R to generate frequency distributions (e.g., reports over time, across seasons, by flight phase, by airline category) and links to other parameters such as flight delays (see Chapter 5 and Appendix B). The "Additional Information" field was mined to identify commonly reported equipment issues contributing to hot or cold cabin temperatures. The results of these analyses can be found in Chapter 2.

Association of Professional Flight Attendants (APFA) Hot Cabin Reporting System

APFA provided the committee with access to a downloadable dashboard containing data from 352 hot cabin reports submitted by APFA members from June 2019 to September 2025, of which 261 contained reported cabin temperatures (APFA, 2025b). Other data elements included dates, flight numbers, and symptoms. The data were used to generate frequency distributions (e.g., reports over time, across seasons), which can be found in Chapter 5 and Appendix B.

FAA Accident and Incident Data System (AIDS)

In response to the committee's information request for information on cabin-temperature-related health and safety impacts, an FAA analyst conducted a keyword search of AIDS for incidents from Part 121 operations involving cabin temperature issues for the period of January 2000 to August 2025. Keywords used in the search included: "cabin" AND " temp"; "excessive heat"; "hot" AND "cabin"; "increas" AND "temp"; "extreme" AND "temp"; "excessive" AND "temp"; "cold"; "cool"; "freez"; "froz"; "low" AND "temp"; "decreas" AND "temp"; and "cold" AND "cabin." The search returned five relevant records submitted between 2000 and 2017 involving high cabin temperatures that necessitated flight diversions. These five incidents represent 0.11 percent of all incidents for Part 121 operations (N = 4,672) and 0.0067 percent of all incident reports (N = 74,207) submitted to AIDS over the search period (Tvaryanas, 2025). Reliance on keyword searching means the results may not be exhaustive. The small number of

relevant reports limited analyses that could be conducted using these data, but the reports provided context regarding the types of equipment problems that can contribute to cabin temperature events inflight (described in Chapter 2).

FAA Service Difficulty Reporting System (SDRS)

To address the committee's request for information on the major underlying causes of cabin-temperature-related health and safety incidents, an FAA analyst conducted a search of SDRS for reports from Part 121 operations coded as air conditioning service difficulty reports (SDRs). Joint Aircraft System/Component (JASC) codes used in the search included: 2100 Air Conditioning System, 2110 Cabin Compressor System, 2120 Air Distribution System, 2121 Air Distribution Fan, 2130 Cabin Pressure Control System, 2131 Cabin Pressure Controller, 2132 Cabin Pressure Indicator, 2133 Pressure Regul/Outflow Valve, 2134 Cabin Pressure Sensor, 2140 Heating System, 2150 Cabin Cooling System, 2160 Cabin Temperature Control System, 2161 Cabin Temperature Controller, 2162 Cabin Temperature Indicator, 2163 Cabin Temperature Sensor, 2170 Humidity Control System, and 2197 Air Conditioning System Wiring. A total of 33,586 reports were identified. Keywords and filters[3] were used to further narrow the results to reports citing cabin temperature issues, resulting in a final total of 1,374 relevant reports (approximately 4 percent of the Part 121 air conditioning–specific reports) (Tvaryanas, 2026). Reliance on filters and keyword searching means the results may not be exhaustive. The analysis of SDRS reports, in conjunction with data from other aviation industry reporting systems (e.g., ASRS, 2Hot2Cold), provided information on common equipment issues that may contribute to challenges with the control of cabin temperatures (discussed in Chapter 2).

Other Databases

Three other databases were examined for relevant data early in the study process but did not yield data that could be used in the committee's analyses. These were:

- National Transportation Safety Board's database, which contains records of civil aviation accidents and incidents that have occurred within the United States and in international waters since 1962 (NTSB, n.d.). A search of this database by FAA analysts in response to the committee's information request revealed no Part 121 aviation accidents linked to cabin temperature issues (Tvaryanas, 2025).
- National Emergency Medical Services Information System (NEMSIS), which provides access to emergency medical services (EMS) data collected from U.S. states and territories (NEMSIS, n.d.). Searches of national-level EMS data by NEMSIS technical support staff identified temperature-related incidents at airports, but the available data fields could not distinguish whether incidents involved cabin occupants.
- Occupational Safety and Health Administration (OSHA) Injury Tracking Application, which collects work-related injury and illness data that establishments meeting specifications related to industry type and employment size are required to submit (OSHA, n.d.). The committee was unable to link flight attendant injury data to cabin temperature exposures.

[3] Specific filters and keywords are available in the documentation submitted by FAA to the committee, which can be requested from the project's public access file.

While airlines maintain their own proprietary databases for capturing health and safety-related incidents occurring during airline operations as well as other relevant data such as flight attendant fatigue reports, the committee did not have access to those data.

DATA ANALYSIS METHODS

Many of the data analyses presented in this report represent simple summary statistics and graphical representations of frequencies/distributions generated in Excel or R. The committee's application of thermal comfort/thermal stress standards and guidelines involved more complex analytic methods which are described in the sections that follow. All calculations were independently checked for mathematical errors by a second individual (a National Academies staff member or committee member with statistics expertise).

Estimating Representative Metabolic Rates for Aircraft Cabin Occupants

To support analyses of thermal comfort and potential cold and heat-related risk in aircraft cabins, the committee identified representative metabolic rate assumptions for passengers and flight attendants. Metabolic rate, expressed as metabolic equivalents (METs), is a primary determinant of thermal comfort and physiological heat strain. Because direct measurement of metabolic rate during routine commercial flight operations is not feasible, the committee employed a task-based estimation approach using established reference sources. The objective was to identify plausible and defensible bounding assumptions that reflect routine cabin conditions during normal operations rather than to characterize peak exertion or individual variability.

Metabolic rate estimates were derived from the 2024 Adult Compendium of Physical Activities (Herrmann et al., 2024), which provides standardized MET values for a wide range of human activities based on empirical measurements and expert consensus. The Adult Compendium is widely used in occupational health, ergonomics, and thermal comfort research and provides a consistent framework for comparing activities across settings. Alternative methods for estimating metabolic rates are available, including ISO Standard 8996, which provides approaches for classifying and estimating metabolic activity across occupational tasks (ISO, 2021). The committee's approach, based on the Adult Compendium of Physical Activities, was selected to provide representative values aligned with observed aircraft cabin activities.

For passengers, activity levels were assumed to be predominantly sedentary, consisting primarily of seated rest with limited movement. Based on these assumptions and consistent with values reported in the Adult Compendium, a metabolic rate of 1.2 METs was selected to represent seated passengers during typical flight conditions. This value is widely used in thermal comfort analyses and reflects the activity profile of most passengers for the majority of flight time (Haghighat et al., 1999).

To characterize flight attendant activities, the committee relied on publicly available descriptions of flight attendant duties and task sequences from FAA materials (FAA, n.d.c). This source was used to identify common in-cabin tasks, including standing, walking in aisles, pushing service carts, lifting or handling items, bending, reaching, and assisting passengers. Flight attendant activity levels were recognized to vary across flight phases (see Table A-3) and to include periods of sustained movement and light to moderate heavy material handling. Rather than assigning a single task-specific metabolic rate, the committee mapped commonly performed

flight attendant tasks to comparable activities in the Adult Compendium and identified a representative value intended to capture sustained periods of routine in-cabin activity, such as during boarding, service, and cabin preparation.

Based on this task-based comparison, a metabolic rate of 2.3 METs was selected as a reasonable upper-bound estimate for active flight attendants. This value reflects moderate occupational activity and is intended to represent conditions typical of shorter-duration flights (e.g., 1 hour) or concentrated service periods, when required tasks are performed over a shorter timeframe and activity levels are expected to be higher.[4] While brief tasks may exceed this level, sustained activity at substantially higher metabolic rates is not typical for most flight attendants under normal operating conditions.

TABLE A-3 Flight Attendant Duties and Metabolic Equivalents Across Flight Phases

Flight Attendant Duties	Similar Work Description[a]	Metabolic Equivalent
Preflight		
Attend pre-flight briefing	Sitting tasks, general office work	1.5
Stock the galley	Light to moderate walking/standing while carrying/light lifting	3.0
Check all emergency and other equipment	Light to moderate walking/standing while carrying/light lifting	2.5
Monitor passenger access and seating	Standing, light activity	2.0
Assist with stowage of luggage	Carrying, loading, or unloading moderate loads (15–24 lbs/~7–11 kg)	4.0
Arm doors	Light to moderate walking/standing while carrying/light lifting	2.5
Fill out and provide paperwork	Sitting tasks, general office work	1.5
During Flight		
Attend to passenger safety and comfort	Standing, light activity	2.0
Provide safety instructions	Standing tasks, light effort	2.0
Enforce safety rules	Standing, light activity	2.0
Prepare and serve food/drinks	Walking/standing with light load	3.0
Distribute pillows, blankets, magazines	Walking/standing with light load	2.5
Operate audio/video equipment	Standing tasks, light effort	2.0
Collect trays, glasses, newspapers	Walking/standing with light load	2.5
Answer passenger questions	Standing, light activity	2.0
Communicate with flight crew	Standing tasks, light effort	2.0
Post-Flight		
Disarm doors	Walking/standing with light load	2.5
Deplane passengers	Walking/standing with light load	2.0
Check/tidy cabin	Walking/standing with light load	2.5
Report discrepancies	Walking/standing with light load	2.0

[4] In developing MET estimates for flight attendants, the committee examined 1-, 3-, and 12-hour flight durations. Longer flight durations provide more time for flight attendants to work at lower activity levels. To be conservative, the committee used MET estimates for short-duration flights.

[a]From 2024 Adult Compendium of Physical Activities (Herrmann et al., 2024).

Thermal Response Zone Boundary Calculations

This section provides a detailed description of the methods used to determine the thermal response zone boundaries (see Chapter 4) for readers who may wish to reproduce or verify the calculations.[5] The committee made these calculations to provide a clear basis for establishing boundaries between the various thermal response zones. In reality, there is no sharp distinction between the zones, and responses transition smoothly as conditions get warmer or cooler. Additionally, there is considerable variability between individuals with regard to physiological and perceptual responses to thermal conditions.

Chapter 4 provides an overview of the American Conference of Governmental Industrial Hygienists (ACGIH) heat stress and strain guideline and the ISO thermal comfort (ISO Standard 7730:2025) and cold stress (ISO Standard 11079:2007) standards (ISO, 2007; 2025) used to define the boundaries between thermal response zones along with the rationale for this approach. The ACGIH guideline was used to arrive at the heat stress lower boundary. ISO Standard 7730:2025 was used to arrive at the discomfort boundaries both for hot and cold discomfort, and ISO Standard 11079:2007 was used to arrive at the cold stress upper boundary. Below, the committee describes the methods that were used to define the thermal zone boundaries. Note that to illustrate the effects of different metabolic activity and clothing insulation levels on thermal response, this appendix uses the different case scenarios defined in Chapter 4 (see Table 4-3). Box A-1 provides definitions of terms used in this appendix.

BOX A-1
Definitions of Terms Used in Thermal Boundary Calculations

AL = action limits (are intended to be “protective of unacclimatized workers” and will vary with clothing and metabolic heat production) (ACGIH, 2019)

M = metabolic heat production (in watts). Metabolic heat production is provided in the ACGIH guideline table “Metabolic Rate Categories and the Representative Metabolic Rates with Example Activities.”

METs = metabolic equivalents (level of energy use, measured by the intensity of physical tasks relative to resting, where 1 MET is sitting still, and higher values mean more energy is being used.

PMV = predicted mean vote – (value for symptomatic comfort in a general population—see further explanation in Chapter 4)

PPD = predicted percent dissatisfied as a function of PMV (see further explanation in Chapter 4).

WBGT = wet bulb globe temperature (heat stress index for humans, combining air temperature, humidity, wind speed, radiant heat).

The following three subsections discuss how three types of boundaries were calculated across different ranges of temperature, humidity, and physical activity: the heat stress boundary (the point at which discomfort from heat generally might be considered great enough to impose physical stress on

[5] Calculations were initially conducted by a member of the committee and checked for mathematical errors by a member of the National Academies staff.

healthy people), the comfort zone (the range of temperatures in which healthy people will generally feel comfortable), and the cold stress boundary (the point at which the temperature generally starts imposing physical stress for healthy people wearing standard light clothing).

Calculation Instructions for ACGIH Action Limit Air Temperature (Heat Stress/Strain Boundary)

The ACGIH Heat Stress and Strain guideline provides the approach for calculating the action limits (AL) for the exposure of healthy unacclimatized workers to hot environments (ACGIH, 2022). The approach here is to first calculate the AL at which temperatures would reach heat stress levels for a given level of activity and then to calculate the combinations of temperature and humidity would result in reaching that AL.

The AL for heat stress is defined as a wet bulb globe temperature (WBGT) and depends upon the metabolic heat production according to the following empirical relationship:

(Equation 1) $$AL = 60.0 - 14.1 \log_{10}(M)$$

where M is the metabolic heat production in watts and AL is the WBGT action limit in ^{o}C.
The AL value can be adjusted for clothing insulation by referring to a table on WBGT clothing adjustment values in the ACGIH guideline (2022). However, throughout this report, all of the graphs of AL are for basic work clothing, which requires no adjustment. Two ALs were calculated based on two levels of activity: activity at rest and activity for flight attendants during boarding and service.

The Perry Weather WBGT calculator[6] was then used to determine the combinations of relative humidity (RH) and air temperature that correspond to a given WBGT. The calculator includes a measure of air speed that was set to 0.2 m/s to represent typical aircraft cabin conditions without gaspers operating. There is also an option to include solar radiation, which was set to 0 since the calculation is for an interior space (although a moderate level of solar radiation would appear for those sitting in window seats in the sun.)

The steps listed below are followed to determine combinations of relative humidity and air temperature that result in a WBGT matching the AL. It should be noted that WBGT-based approaches have limitations at environmental extremes, including very low and very high humidity conditions (ACGIH, 2022). As a result, the calculated temperature–humidity combinations used to define thermal response zone boundaries may understate the level in these regions.

Step A – Calculating the AL for a given activity and clothing level

1. For a given metabolic heat production level (M), find the value of M in watts according to M = 115 watts when sitting.[7]
2. Determine the value of AL from Equation 1 above.
   To select different values of M for Equation 1, the committee used MET values of 1.2 times the value of M at rest (i.e., M = 138 watts) to illustrate largely sedentary activity

[6] https://perryweather.com/resources/what-is-wbgt-and-how-do-you-calculate-it/ (accessed March 26, 2026).

[7] Conversion of METs to watts depends on body surface area, which varies across individuals. For this analysis, a representative value (115 watts per MET) was used, consistent with standard practice for population-level assessments. This approach is intended to provide reasonable average estimates rather than individual-specific values.

(seated passengers or flight attendants) and metabolic activity of 2.3 times the value of M at rest (M = 264.5) for activity for flight attendants during boarding and service.

- Activity while sitting: AL = 60.0 – 14.1 $\log_{10}$(1.2*115) = 29.83
- Activity during boarding and service: AL = 60.0 – 14.1 $\log_{10}$(2.3*115) = 25.84

3. Adjust the value of AL as needed for clothing (no adjustment needed).

Step B – Choosing different relative humidity levels to provide the boundary line

4. Set the relative humidity to the desired value (%), windspeed to 0.2, and solar irradiance to 0.

5. Convert AL to Fahrenheit (°F) according to

$T_F = 1.8\ T_C + 32$, where T_F is the temperature in Fahrenheit and T_C is the temperature in Celsius.

- Activity while sitting: AL = 85.69
- Activity during boarding and service: AL = 78.52

Step C – Determining the air temperature for action levels at the different levels of RH using an iterative process

6. Guess a value of air temperature (T_{air}) in Fahrenheit (°F) that will yield the action limit and enter it into the Perry Weather calculator.

7. Compare the WBGT temperature from the Perry Weather calculator to the target AL. If the result is lower than the AL, then increase the T_{air} value and return to step 6. If the result is higher than the AL, decrease the T_{air} value and return to step 6. If the result is within 0.1 °F of the AL, accept that T_{air} value and continue.

8. Convert the final T_{air} value to Celsius according to $T_C = (T_F – 32)/1.8$

Result: The air temperature in step 8 and the relative humidity set in step 4 are now the coordinates for one point on the heat stress threshold curve.

This process was conducted for relative humidity values of 0%, 20%, 40%, 60%, 80%, and 100% for each metabolic activity value of interest (1.2 and 2.3 MET). These points are connected by straight line segments to generate the curves in the graphs shown in Figures 4-1 and 4-2 in Chapter 4.

Example Calculation: Below is an example calculation for the following conditions: metabolic rate of 2.3, 60% relative humidity, and no clothing adjustment following the same eight steps

1. M = 115 watts x 2.3 = 264.5 watts
2. AL = 60.0 – 14.1 $\log_{10}$(264.5) = 25.84°C (WBGT)
3. AL = 25.84°C + 0 = 25.84°C (WBGT)
4. RH=60% entered into Perry Weather calculator .
5. AL= 25.84 x 1.8 +32 =78.52°F (conversion to Fahrenheit)
6. Initial guess for T_{air} = 85°F, which is entered into Perry Weather calculator along with RH=60%. Resulting WBGT = 77.5°F. Result is low (below 78.52°F, as determined in step 5) so increase T_{air} value.
7. Update value for T_{air} = 86°F and enter into Perry Weather calculator. Resulting WBGT = 78.4°F. Result is still too low by a very small amount. Slightly increase T_{air} value. Update value for T_{air} = 86.1°F and enter into Perry Weather calculator. Resulting WBGT =78.5°F. Result is sufficiently equivalent to the AL temperature limit of 78.52°F (see step 5).

8. Convert T_{air} to Celsius as follows: $T_{air} = (86.1 – 32)/1.8 = 30.1^{o}C$
   30.1°C and 60% RH are the coordinates for one point on the heat stress threshold (ACGIH AL) curve for 2.3-MET activity and 0.6-clo clothing insulation.

The resulting T_{air} values used for the graphs presented in Figures 4-1 and 4-2 (see Chapter 4) for given levels of RH are presented in Tables A-4 and A-5. The resulting boundary line is repeated in similar figures in Chapters 4, 5, and 6.

TABLE A-4 Air Temperature (T_{air}) and Relative Humidity (RH) Values for Case Scenario 1 Representing a Busy Flight Attendant in Typical Clothing (2.3 MET, 0.6 clo, 0.2 m/s)

Relative Humidity (%)	Air Temperature (°C)
0	46.4
20	37.3
40	32.9
60	30.1
80	27.8
100	25.8

TABLE A-5 Air Temperature (T_{air}) and Relative Humidity (RH) Values for Case Scenario 2 Representing a Largely Sedentary Seated Flight Attendant or Passenger in Typical Clothing (1.2 MET, 0.6 clo, 0.2 m/s)

Relative Humidity (%)	Air Temperature (°C)
0	53.1
20	42.5
40	37.5
60	34.3
80	31.9
100	29.8

Calculation Instructions for ISO Standard 7730:2025 Thermal Comfort Zone

There are two widely used standards for the determination of thermal comfort in the general population—Standard 55-2023, *Thermal Environmental Conditions for Human Occupancy* (ANSI/ASHRAE, 2023), and ISO Standard 7730:2025, *Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria* (ISO, 2025). The committee used ISO Standard 7730:2025 for the determination of thermal comfort zones for given levels of metabolic activity and clothing insulation, as discussed in Chapter 4.

Calculations were conducted using the University of California, Berkeley, Center for the Built Environment (CBE) Thermal Comfort Tool.[8] The Thermal Comfort Tool lists options

[8] The CBE Thermal Comfort Tool is available at https://comfort.cbe.berkeley.edu/EN (accessed January 20, 2026).

for ASHRAE Standard 55-2023 and EN-16798. The latter is based on ISO Standard 7730 and is used for the calculations in this report.

The comfort zone is defined as the region where PMV does not exceed +/- 0.5 PMV, which corresponds to Class B in ISO Standard 7730:2025. The CBE thermal comfort tool requires the following inputs

- Air temperature, T_{air} (°C)
- Mean radiant temperature, T_{mrt} (°C)
- Air speed (m/s)
- Relative humidity (%)
- Metabolic rate (MET)
- Dynamic clothing insulation (clo)

For all calculations, the mean radiant temperature is set to the same value as the air temperature. The other parameters are straightforward except for dynamic clothing insulation. Body motion reduces clothing insulation due to several factors, and this parameter is an adjusted clothing insulation to reflect this effect. The CBE thermal comfort tool does not provide this calculation for the user and instead refers the user to ISO Standard 7730:2025. Unfortunately, the calculation in ISO Standard 7730:2025 is complex, involving seven highly nonlinear simultaneous equations that cannot be solved explicitly for the dynamic clothing insulation. A trial-and-error calculation is required. Additionally, the only activity addressed explicitly is walking. Other activities require the use of an equivalent walking speed to reflect the effect of elevated activity on clothing insulation.

On the other hand, ANSI/ASHRAE Standard 55-2023 uses a very simple relationship to address the effect of activity on clothing:

(Equation 2) $$I_{cl,d} = I_{cl}\,(0.6 + 0.4/M)$$

where I_{cl} is the clothing insulation (clo), M is the metabolic rate (MET), and $I_{cl,d}$ is the dynamic clothing insulation.

For simplicity, the above relationship was used rather than the complex relationship in ISO Standard 7730:2025. Not only did this simplification make the calculations more straightforward, but it also makes it practical for third parties to verify the calculations. Separately, a comparison was made of the above relationship from ASHRAE Standard 55-2023 and the values obtained using the relationships in ISO Standard 7730:2025. Over the range of clothing insulation and activities used to generate the plots in this report, the difference between the two methods was typically in the range of 0–0.04 clo and never more than 0.07 clo. This difference is well within the limits with which clothing insulation can be determined and is less than the effect of such factors as posture and clothing fit.

The curves of constant PMV on a humidity-versus-temperature graph are essentially straight lines. Thus, only four humidity-temperature points need to be determined to define the comfort zone for a given combination of activity and clothing insulation, for 0% and 100% relative humidity and PMV=0.5 and PMV=-0.5.

The step-by-step procedure is as follows.

1. Select the EN-16798 option on the CBE thermal comfort tool (top menu) and PMV method as the method.
2. Enter the desired values of air speed and metabolic activity
3. Calculate the dynamic clothing insulation using Equation 2 and enter it.

4. Enter the desired relative humidity (100 percent for the initial calculation).
5. Make an initial guess for the air temperature value that will result in PMV= 0.5 and enter it for both air temperature and mean radiant temperature.
6. If the resulting PMV is less than 0.5, go to step 5 and enter higher temperatures. If the resulting PMV is greater them 0.5, got to step 5 and enter lower temperatures. If the resulting PMV is equal to 0.5, continue to step 7.
7. The specified humidity and the air temperature found to result in PMV = 0.5 are the coordinates for one point on the thermal comfort zone threshold line.
8. Repeat steps 5 through 7 for PMV = -0.5.
9. Repeat steps 1 through 8 for relative humidity = 0%

Example Calculation: Below is an example calculation for the following conditions: Case Scenario 1: 2.3 MET, 0.6 clo, 0.2 m/s.

1. Select EN-16798 option on the CBE thermal comfort tool, and PMV method.
2. Enter 2.3 MET for metabolic activity and 0.2 m/s for air speed
3. $I_{cl,d}$ = 0.6 clo (0.6 + 0.4/2.3) = 0.46 clo
4. Enter 100 percent for RH
5. Enter initial guess for T_{air} and T_{mrt} = 22 °C.
6. PMV = 0.44. Increase T_{air} value.
7. Update value for T_{air} and T_{mrt} = 23 °C and reenter.
8. PMV = 0.69. decrease T_{air} value.
9. Update value for T_{air} and T_{mrt} = 22.24 °C and reenter.
10. PMV = 0.5
11. The upper right coordinate for the thermal comfort zone is T_{air} = 22.24°C and 100 percent RH.
12. Repeat with PMV = -0.5
13. Enter initial guess for T_{air} and T_{mrt} = 18°C
14. PMV = -0.54. Increase T_{air} value.
15. Update value for T_{air} and T_{mrt} = 18.16°C and enter.
16. PMV = -0.5
17. The upper left coordinate for the comfort zone is T_{air} = 18.16°C and 100 percent RH.
18. Repeat steps 4 through for 0 percent RH.

Results: The resulting upper and lower T_{air} limits used to define thermal comfort zones in the graphs presented in Figures 4-1 and 4-2 for given levels of RH are presented in Tables A-6 through A-11.

TABLE A-6 Case Scenario 1**:** Upper and Lower Air Temperature (T_{air}) Limits for Given Relative Humidity (RH) Values for Case Scenario 1 Representing a Busy Flight Attendant in Typical Clothing (2.3 MET, 0.6 clo, 0.2 m/s)

Relative Humidity (%)	Lower Air Temperature Limit	Upper Air Temperature Limit
0	19.70°C	24.20°C
100	18.16°C	22.24°C

TABLE A-7 Case Scenario 2**:** Upper and Lower Air Temperature (T_{air}) Limits for Given Relative Humidity (RH) Values for Case Scenario 2 Representing a Seated Flight Attendant or Passenger in Typical Clothing (1.2 MET, 0.6 clo, 0.2 m/s)

Relative Humidity (%)	Lower Air Temperature Limit	Upper Air Temperature Limit
0	24.97°C	28.25°C
100	22.94°C	25.84°C

TABLE A-8 Case Scenario 3: Upper and Lower Air Temperature (T_{air}) Limits for Given Relative Humidity (RH) Values for Case Scenario 3 Representing a Busy Flight Attendant in Warm Clothing (2.3 MET, 1.0 clo, 0.2 m/s)

Relative Humidity (%)	Lower Air Temperature Limit	Upper Air Temperature Limit
0	15.70°C	21.71°C
100	14.15°C	19.52°C

TABLE A-9 Case Scenario 4**:** Upper and Lower Air Temperature (T_{air}) Limits for Given Relative Humidity (RH) Values for Case Scenario 4 Representing a Seated Flight Attendant or Passenger in Warm Clothing (1.2 MET, 1.0 clo, 0.2 m/s)

Relative Humidity (%)	Lower Air Temperature Limit	Upper Air Temperature Limit
0	22.23°C	26.54°C
100	19.97°C	23.72°C

TABLE A-10 Case Scenario 5**:** Upper and Lower Air Temperature (T_{air}) Limits for Given Relative Humidity (RH) Values for Case Scenario 5 Representing a Busy Flight Attendant in Cool Clothing (2.3 MET, 0.4 clo, 0.2 m/s)

Relative Humidity (%)	Lower Air Temperature Limit	Upper Air Temperature Limit
0	21.55°C	25.37°C
100	20.10°C	23.60°C

TABLE A-11 Case Scenario 6**:** Upper and Lower Air Temperature (T_{air}) Limits for Given Relative Humidity (RH) Values for Case Scenario 6 Representing a Seated Flight Attendant or Passenger in Cool Clothing (1.2

MET, 0.4 clo, 0.2 m/s)

Relative Humidity (%)	Lower Air Temperature Limit	Upper Air Temperature Limit
0	26.35°C	29.10°C
100	24.45°C	26.92°C

Calculation Instructions for ISO 11079:2007 Minimum Required Clothing Insulation (Cold Stress/Strain Boundary)

As discussed in Chapter 4, the committee applied ISO Standard 11079:2007, *Ergonomics of the Thermal Environment — Determination and Interpretation of Cold Stress when Using Required Clothing Insulation (IREQ) and Local Cooling Effects*, to calculate cold stress thresholds for a given level of metabolic activity. ISO Standard 11079:2007 provides a method for assessing the required clothing insulation, I_{req}, as a function of environmental conditions. For the committee's purposes, it was used to determine the point at which the air temperature is cold enough to cause physical stress, depending on the humidity, specified clothing insulation, and activity level.

Since the online tool cited in ISO 11079:2007 was no longer available, the online tool provided by Lund University[9] was used for the calculations. The Lund tool requires the input of nine parameters, which are determined as follows:

- Metabolic energy production (W/m^2): The metabolic rates for the different cases are defined in terms of MET units. Standard 11079 specifies the metabolic rate for "resting, sitting" as 65 W/m^2. Resting and sitting is normally associated with a MET value of 1.0. Thus, for calculations with this standard, the MET-to-W/m^2 conversion is 1 MET = 65 W/m^2. Note that this ratio is different from, but close to, that which is specified in ISO Standard 7730:2025 (1 MET = 58 W/m^2).
- Rate of mechanical work (W/m^2): Generally, the work is small or zero, so it is set to zero. Activities such as pushing a beverage cart by a flight attendant may have a slight non-zero rate of mechanical work, but any errors associated with setting it to zero are small.
- Ambient air temperature (°C): This value was not set a priori, as the standard was used in an iterative approach to determine the air temperature associated with a given clothing insulation.
- Mean radiant temperature (°C): Set equal to air temperature.
- Air permeability (L/m^2s): ISO Standard 11079:2007 is normally used for outdoor applications where air permeation can be a major factor given the elevated wind speeds that can occur. For this indoor application, the wind speed is near zero compared with outdoor applications, and air permeation is not a significant factor. Air permeability is therefore set to the lowest value allowed, 5 L/m^2s.
- Work-created air movement (m/s): If zero is input, the tool automatically

[9] The Lund University online tool is available at https://www.design.lth.se/english/the-department/research-laboratories/aerosol-climate-laboratory/climate/tools/calculations-for-ireq-and-wct/ (accessed January 20, 2026).

calculates a value based on the metabolic activity.

- Relative air velocity (m/s): For other calculations, a value of 0.2 m/s is used, typical of aircraft cabins. The tool does not allow a value less than 0.4 m/s. Thus, this value is used. The inability to go lower is an additional justification for using the lowest air permeability.
- Relative humidity (%): Set to the desired value.
- Available clothing insulation (clo): Does not impact the I_{req} calculation as long as it is set at a value above the specified insulation (0.6 clo). Available clothing insulation was set to 4 clo.

Given these inputs, the tool calculates a required basic clothing insulation range. Note, the tool calculates two slightly different clothing insulation values: (1) Insulation Required, IREQ and (2) Required basic clothing insulation (ISO 9920), The latter value is used for these calculations. The lower value of the range is the minimum required clothing insulation for the specified environmental conditions and activity level.

The calculation approach is to guess air temperatures until the required basic clothing insulation calculated by the tool matches the specified clothing insulation (0.6 clo for the case scenarios used). There is some coarseness to the tool's calculations in that the clothing insulation is expressed only to the nearest 0.1 clo. As a result, there is a range of temperatures that will yield a 0.6 clo result. Since the objective is to find the lower limit temperature, the solution is carried out iteratively so as to find the lowest temperature that will result in the desired clothing insulation value and not just any temperature that yields the desired value.

The step-by-step procedure follows.

1. Set tool parameters that do not change: rate of mechanical work = 0, air permeability = 5, work created air movement = 0, relative air velocity = 0.4, available clothing insulation = 4
2. Set metabolic activity and relative humidity to desired values
3. Make an initial guess for the value of air temperature and set radiant temperature to air temperature.
4. Is the resulting lower value of required basic clothing insulation greater than the specified clothing insulation (0.6 clo)? If yes, continue to step 5 and increase the air temperature value slightly; if no, return to step 3 and decrease air temperature value.
5. Update the value of air temperature and set radiant temperature to air temperature.
6. Is the lower value of required basic clothing insulation equal to the specified clothing insulation (0.6 clo)? If yes, continue to step 7. If less than specified value, adjust the value of air temperature slightly lower and return to step 5. If greater than the specified value, adjust the value of air temperature slightly higher and return to step 5.
7. The last value for air temperature is the lower air temperature limit associated with the specified clothing insulation at the specified humidity.

Example Calculation: An example calculation for 100% RH, 2.3 MET and 0.6 clo follows.

1. Set the following parameters as indicated: rate of mechanical work = 0, air permeability = 5, work created air movement = 0, relative air velocity = 0.4,

available clothing insulation = 4

2. Metabolic activity = 2.3 x 65 = 149.5, relative humidity = 100%
3. Make initial guess for air temperature = 8.0°C. mean radiant temperature = 8°C.
4. Required basic clothing insulation = 0.6 clo. Decrease air temperature value to check for lower possible value requiring the same level of clothing insulation.
5. Updated value for air temperature = 7.0°C. Mean radiant temperature = 7.0°C.
6. Required basic clothing insulation = 0.7 clo. Lowering the temperature requires increasing the clothing insulation. Increase temperature value slightly to 7.1°C.
7. Updated value for air temperature = 7.1°C. Mean radiant temperature = 7.1°C.
8. Required basic clothing insulation = 0.7 clo. Increase temperature value slightly to 7.2°C.
9. Updated value for air temperature = 7.2°C. Mean radiant temperature = 7.2°C.
10. Required basic clothing Insulation = 0.6 clo.
11. For 100% RH and 0.6 clo, the threshold air temperature for cold stress is 7.2°C.

ISO Standard 11079:2007 recommends that it not be used for temperatures above 10°C but does not prohibit such use. The Lund University tool does not allow temperatures greater than 10°C. For clothing–activity combinations that result in a cold stress boundary greater than 10°C, no boundary was established.

Results: The calculated temperatures used for graphs in Figures 4-1 and 4-2 for given levels of RH are presented in Table A-12.

TABLE A-12 Air Temperature Values Calculated Using ISO Standard 11079 for Different Levels of Metabolic Activity and Relative Humidity

Relative Humidity (%)	Case Scenario 1 (2.3 MET, 0.6 clo, 0.2 m/s)
0	8.0℃
100	7.2℃

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Appendix B
Supplemental Data and Analyses

This appendix serves as an accompanying resource to the data and analyses presented in the body of the report, particularly Chapter 5, which presents the evidence on the health and safety impacts of cabin temperatures. It summarizes data from published research studies that include cabin temperature and humidity data and details the results of analyses that provide further support and context for the committee's conclusions and recommendations (see Chapters 5 and 6). Appendix A provides an accounting of the committee's data collection and analysis methods.

CABIN TEMPERATURE AND HUMIDITY DATA FROM PUBLISHED STUDIES

To characterize the range of cabin thermal conditions that would be reasonably representative of typical flights operated by Part 121 airlines, the committee reviewed the published literature (peer-reviewed articles and gray literature) for cabin temperature and humidity measurements captured in research studies. Table B-1 expands on Table 5-3 in Chapter 5 to also include the temperature and humidity ranges reported in the primary studies included in the review article by Wang and colleagues (2024). As discussed in Chapter 5, comparisons across studies should be interpreted cautiously, given the lack of standardized study protocols, common reliance on convenience sampling for flights, and variation in data collection instrumentation. Only the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) RP-1262 study evaluated a link between cabin conditions and health outcomes (Battelle, 2018), but several studies evaluated potential impacts on cabin occupant comfort by survey or comparison with expected thermal comfort ranges (Cui et al., 2017; Gameiro da Silva et al., 2023; Nicholls and Vink, 2025).

TABLE B-1 Summary of Cabin Temperature and Humidity Data from Published Studies

Data Source	**Number of Flights (N)**	**Reported Cabin Temperature** (°C)	**Reported Relative Humidity (%)**	**Flight Stage of Data Collection**
Spicer et al. (2004) (ASHRAE Research Project 1262-RP Part 1, 2026)	4	Stationary Measurements Min = 19.4°C Max = 26.4°C Mobile Measurements Min = 18°C Max = 27°C	Min = 7.1% Max = 57.6%	Monitored with 1-second time resolution from boarding phase through deplaning of passengers
Battelle (2018), Spengler et al. (2012) (ASHRAE Research Project 1262-RP Part 2, 2026)	80	Mean = 24.38°C Standard error of mean = 0.20 Min = 19.22°C 10th percentile = 22.36°C 25th percentile = 23.67°C Median = 24.47°C 75th percentile = 25.16°C 90th percentile = 26.20°C Max = 31.29°C	Mean = 10.74% Standard error of mean = 0.62 Min = 1.70% 10th percentile = 5.20% 25th percentile = 7.30% Median = 10.05% 75th percentile = 13.03% 90th percentile = 16.48% Max = 41.15%	Continuous measurements (1-minute averages) made in-flight from 10,000 feet ascent to 10,000 feet descent
RITE (2010)	6 for humidity and 11 for temperature (data only reported for a subset of nearly 200 measured flights)	Min = 22°C Max = 29°C	Beginning of Flight 35–50% Mid-flight 10–25%	Monitored continuously during cruise (from 10,000 feet ascent to 10,000 feet descent). In some cases, the system was operating from gate to gate), some sampling from gate to gate.

EASA (2017)	N = 12 for main study (aircraft with bleed air systems) and N = 8 for Boeing 787 study (aircraft with electronic compression system)	Main Study Results Min = 21°C Max = 28°C Mean = 24°C Median = 24°C 95th Percentile = 27°C B787 study Min = 18°C Max = 24°C Mean = 21°C Median = 22°C 95th percentile = 24°C	Main Study Results Min = 5% Max = 28% Mean = 13% Median = 13% 95th percentile = 20% B787 study Min = 10% Max = 43% Mean = 18% Median = 18% 95th percentile=24%	In-cruise
Nicholls and Vink (2025)	143	Boarding Data Min = 16.7°C Max = 30.2°C Mean = 23.5°C (SD 5.57) In-flight Data Min = 17.8°C Max = 31.3°C Mean = 24.4°C (SD 4.77)	Boarding Data Min = 10% Max = 82% Mean = 36.4% (SD 15) In-flight Data Min = 9% Max = 59% Mean = 20% (SD 10.6)	Measurements taken directly after boarding and 1 hour after takeoff.
Cui et al. (2017)	10	Min= 23.0°C Max= 26.6°C	Min = 15.4% Max = 20.8%	Automatically recorded every 30 seconds
Gameiro da Silva et al. (2023)	25	Data for “Cooling Season” (summer and spring months) Min = 22.7°C Max = 29.3°C	Data for “Cooling Season” (summer and spring months) Min = 23.3% Max = 37.6%	Recordings taken while flights were in cruising altitude

		Data for "Heating Season" (fall and winter months) Min = 23.6°C Max = 28.8°C	Data for "Heating Season" (fall and winter months) Min = 23.8% Max = 29.2%	
Primary Articles Included in Review by Wang and Colleagues (2024) *				
Yu et al. (2021)	2	Flight 1 Min = 26.2°C Max = 28.1°C Mean = 27.5 ± 0.4°C Flight 2 Min = 21.0°C Max = 28.1°C Mean = 27.2 ± 1.2°C	Flight 1 Min = 14.0 Max = 66.4 Mean = 29.7 ± 15.3 Flight 2 Min = 13.8 Max = 67.0 Mean = 33.6 ± 17.5	Recordings were taken at 1-second intervals throughout flight
Cui et al. (2014a)	14	Min = 24°C Max = 29°C		Recorded automatically every 30 seconds
Cui et al. (2014b)	10	Average for front seats = 24.6°C Average for middle seats = 26.2°C Average for back seats = 25.6°C	Average for Front Seats = 16.9% Average for Middle seats = 17.7% Average for back seats = 17.8%	Recorded automatically every 30 seconds from take off until landing
MacGregor et al. (2008)	4	Flight 1 mean = 24.5°C Flight 2 mean = 24.9°C Flight 3 mean = 24.8°C Flight 4 mean = 24.6°C	Flight 1 mean = 11.4% Flight 2 mean = 8.8% Flight 3 mean = 12.7% Flight 4 mean = 10.6%	Measurements taken during cruise
Ross et al. (2003)	7 (Aircraft 146) and 6 (Aircraft 747)	Aircraft 146 Min = 21.7°C Max = 26.6°C Mean = 23.7°C	Aircraft 146 Min = 13.2% Max = 32.2% Mean = 20.9%	Measurements began at boarding and were recorded at 1-minute intervals. The monitoring was stopped

		Aircraft 747 Min = 21.9°C Max = 23.9°C Mean = 23°C	Aircraft 747 Min = 22.4% Max = 29.4% Mean = 25.7%	towards the end of passenger disembarkation
Lindgren and Norback (2002)	26	Min = 17.4°C Max = 26.8°C Mean = 22.2°C	Min = 1% Max = 27% Mean = 6%	Most measurements were restricted to the cruising period, at a flight altitude of 11,000–12,000 During eight of the flights, continuous measurements were performed from gate to gate.
Waters et al. (2002)	36	Min = 19°C Max = 29.5°C	Min = 10.1% Max = 45.6% Mean = 19.8% SD = 6.7%	Sampling was performed continuously from (at minimum) gate departure to gate arrival or "gate to gate".
Dumyahn et al. (2000)	16 (1994 study) and 6 (1996 study)	1994 Survey Results Boarding: Min = 19°C Max = 25°C Mean = 23°C Cruise: Min = 23°C Max = 26°C Mean = 24°C 1996 Survey Results Boarding: Min = 23°C Max = 28°C Mean = 23.9°C Cruise: Min = 22°C	1994 Survey Results Boarding Min = 22% Max = 55% Mean = 33% Cruise Min = 10% Max = 24% Mean = 15% 1996 Survey Results Boarding Min = 25% Max = 40% Mean = 35% Cruise Min = 13%	Samples were continuously measured

		Max = 26°C Mean = 25°C	Max = 23% Mean = 18%	
Wieslander et al. (2000)	4	<u>Aft Galley</u> Min = 20.6°C Max = 25.4°C Mean = 22.2°C SD = 0.9 <u>Forward Galley</u> Min = 22.3°C Max = 23.3°C Mean = 23°C SD = 0.2	<u>Aft Galley</u> Min = 2.2% Max = 18.9% Mean = 6.4% SD = 3.5 <u>Forward Galley</u> Min = 1.8% Max = 8.7% Mean = 3.8% SD = 1.8	1-minute average values were sampled in flight
Lee et al. (1999)	16	Min = 17.8°C Max = 29.8°C Mean = 21.9°C	Min = 4.9% Max = 76.8%	Measurements were taken every 5 minutes each flight
Haghighat et al. (1999)	43	Min = 19 °C Max = 27 °C	Min = 2% Mean = 7%	Measurements taken every 5 minutes from time of boarding to landing
Pierce et al. (1999)	8	Min = 17.8°C Max = 26.1°C Mean (Domestic flights) = 22.8°C Mean (International flights) = 23.1°C	Min = 8.8% Max = 27.8% Mean (domestic flights) = 16.5% Mean (international flights) = 12.9%	Measurements taken with 5-minute averaging during boarding, ascent; and descent; while the aircraft was aloft; and during deplaning
Nagda et al. (1992)	92	Min= 21 °C Max = 27 °C Mean = approx. 24 °C	Min = 5% Max = 38%	Temperature and humidity were monitored continuously
O'Donnell et al. (1991)	45	Min = 13.2°C Max = 35.1°C Mean = 23.4°C SD = 1.6	Min = 4.6% Max = 48.5 Mean = 18.5% SD = 3.8	Data were recorded every 4 minutes for duration of flights
Malmfors et al. (1989)	48	Min = 20.1 °C Max = 28.3 °C	Mean = 25%	All samplers were turned on when the aircraft left the gate and turned off when the

				aircraft stopped at the gate upon arrival.

NOTE: Min = minimum; max = maximum; RH = relative humidity; SD = standard deviation.

* The primary article by Gladyszewska-Fiedoruk (2012) included in the review by Wang and colleagures (2024) only included data from a single flight and therefore did not report summary statistics. Data from that study are therefore not included in this table.

UNDERSTANDING CONDITIONS THAT CONTRIBUTE TO HOT AND COLD CABIN TEMPERATURES

Identifying when and why cabin temperatures exceed comfortable ranges is critical for developing effective mitigation strategies. While extreme heat or cold events are rare, patterns in complaint and safety reporting data (see Chapter 5) suggest that certain operational and environmental factors increase the likelihood of these conditions. Understanding these drivers provides insight into the magnitude of the problem (e.g., expected temporal and geographic variability) and can inform potential policies or procedures to reduce risk (discussed further in Chapter 6). For example, if problems primarily occur while aircraft are on the ground, mitigation efforts can be focused on that phase of operation.

This section examines the key contributors to cabin temperatures—including seasonal variation, flight phase, and aircraft type—that are crucial to better understanding the circumstances under which these temperatures become problematic. By exploring these factors, the committee aims to highlight opportunities for targeted interventions that can reduce risks from thermal exposures without imposing unnecessary operational burdens. Datasets from published research studies (e.g., Nicholls and Vink [2025], the Airliner Cabin Environment Research [ACER] program), and aviation industry safety and complaint reporting systems referenced in the discussions that follow (e.g., National Aeronautics and Space Administration [NASA] Aviation Safety Reporting System [ASRS], 2Hot2Cold app data) are described in Chapter 5 (see Tables 5-1 and 5-4).

Seasonal Variation and Relationship to Ambient Temperatures

Data from aviation industry reporting systems reveal a strong seasonal effect, with cabin temperature issues most frequently reported during the summer months (June through August), as shown in Figure B-1. Passenger complaints submitted to the Department of Transportation (DOT) Office of Aviation Consumer Protection also peak sharply during summer. Increased U.S. air travel in summer relative to other months (as shown in Figure B-2) does not fully explain the magnitude of seasonal differences observed in temperature-related reporting.

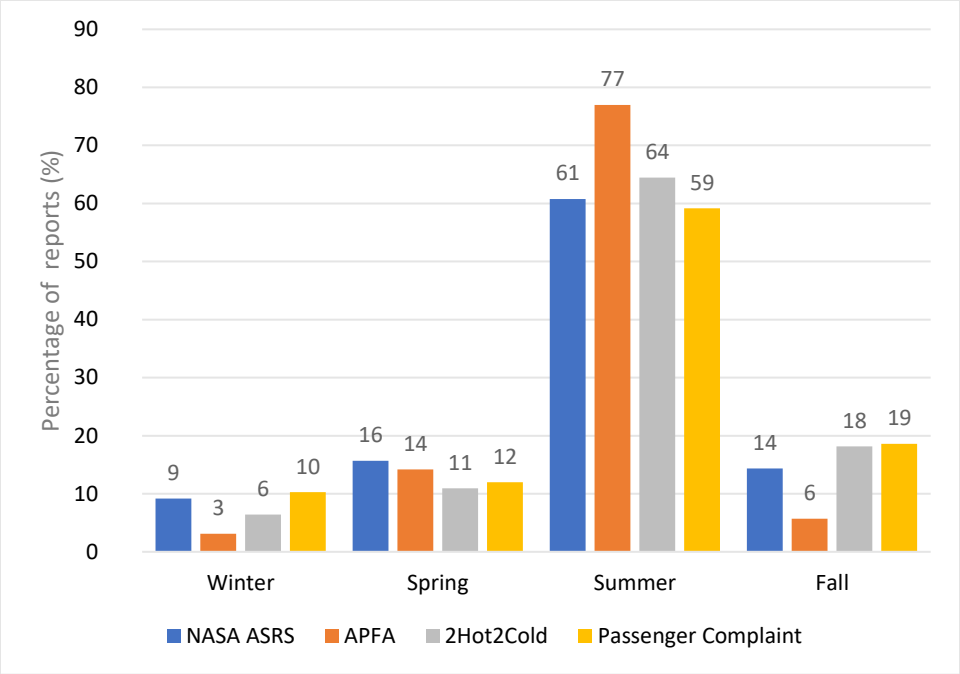

FIGURE B-1 Percentages of safety incident reports and complaints, by season.
SOURCE: Created using data from AFA (2025), APFA (2025), NASA (2025), and DOT (2025b).

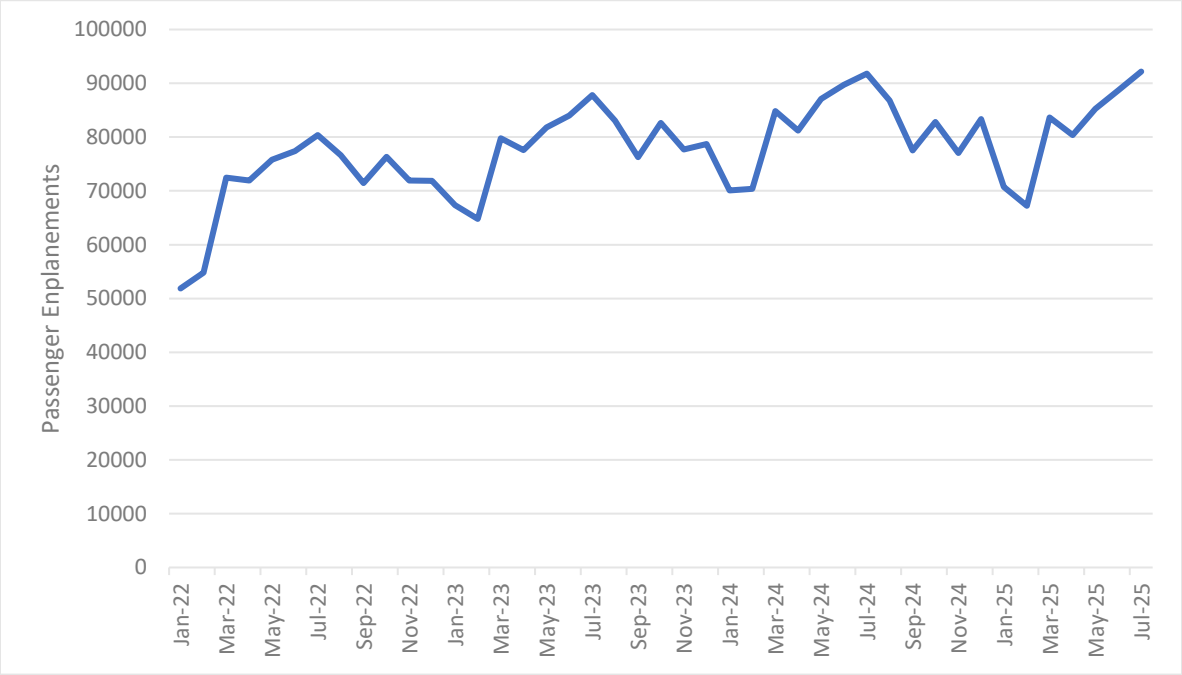

FIGURE B-2 Monthly scheduled passenger enplanements (domestic and international) from January 2022–July 2025 showing increased levels during summer months.
SOURCE: DOT (2025a).

Research data support this pattern. An analysis of an unpublished dataset from the Airliner Cabin Environment Research (ACER) program shows that boarding temperatures follow

expected seasonal trends—coolest in winter and warmest in summer (see Figure B-3). Inflight and post-landing conditions differ. Notably, fall flights recorded the highest inflight and post-landing temperatures despite cooler boarding conditions; one possible explanation is that flight crews may overcompensate for cooler outdoor temperatures by heating the cabin beyond comfortable ranges. These findings underscore the influence of ambient conditions and operational decisions on cabin temperature, particularly during ground phases.

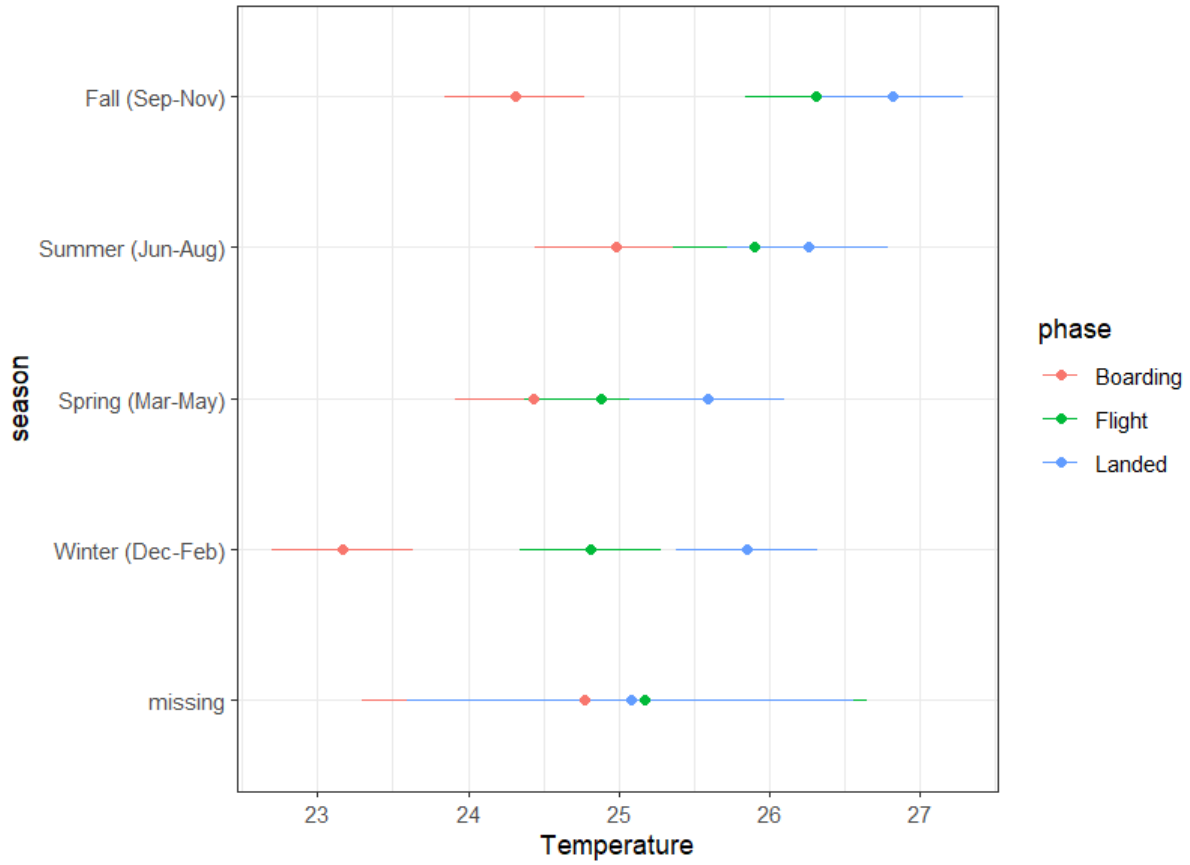

FIGURE B-3 Modeled marginal means and 95 percent confidence intervals by season (winter, spring, summer, fall) and flight-phase (boarding, inflight, after landing).
NOTES: Flight phases were identified using changes in altitude and air pressure; when altitude data were unavailable, pressure alone was used. Signal-processing algorithms were applied to detect sustained trends indicating ascent and descent, with boundaries reviewed and adjusted as needed. Because phase transitions were inferred from altitude and/or pressure data streams—without indicators of flight segment—some variability across algorithms is expected. The values shown here reflect results from one algorithm, and overall patterns were consistent across multiple approaches. "Missing" label indicates no date for the flight was captured, precluding seasonal categorization.
SOURCE: Created from unpublished ACER data (ACER, 2025).

Variation by Flight Phase

Limited data from research studies suggest that cabin temperatures are generally similar while on the ground and in flight (see Figure B-4). However, these data likely reflect typical operational conditions and do not adequately capture events involving very hot or cold cabins.

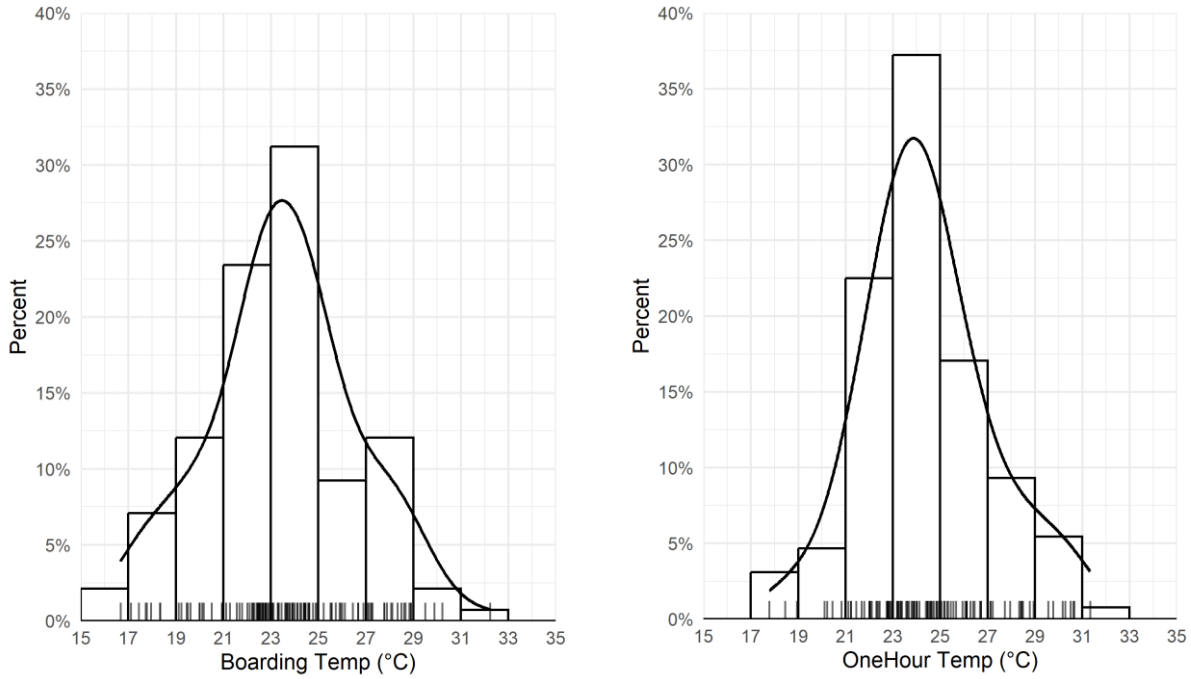

FIGURE B-4 Distribution of cabin temperatures during boarding and 1 hour after flight. SOURCE: Created with data from Nicholls and Vink (2025).

In contrast, data from aviation industry reporting systems suggest that cabin temperature issues occur more frequently during ground operations, which was also emphasized during the committee's public session discussion with flight attendant labor representatives. Only 15 percent of 2Hot2Cold reports referenced cabin temperature issues that occurred in flight; the majority occurred during boarding at the departure airport (see Figure B-5). As shown in Figure B-6, the highest cabin temperatures from the 2Hot2Cold dataset (greater than 30°C, or 86°F) are less commonly reported during flight. This pattern likely reflects the ability of the environmental control system to cool the aircraft once engines are running. However, approximately 20 percent of NASA ASRS reports describe temperature problems persisting both on the ground and in flight. For the most extreme temperature ranges observed (greater than 40°C, or 104°F), the number of cases involving both phases exceeded those occurring solely in flight (see Figure B-7). Multiple equipment issues—such as deferred pack repairs combined with auxiliary power unit (APU) or preconditioned air (PCA) unit failures—may explain these cases. Notably, of the NASA ASRS reports included in the committee's analysis that noted one or more specific

contributing equipment issues, 25.8 percent cited multiple equipment issues (NASA, 2025).

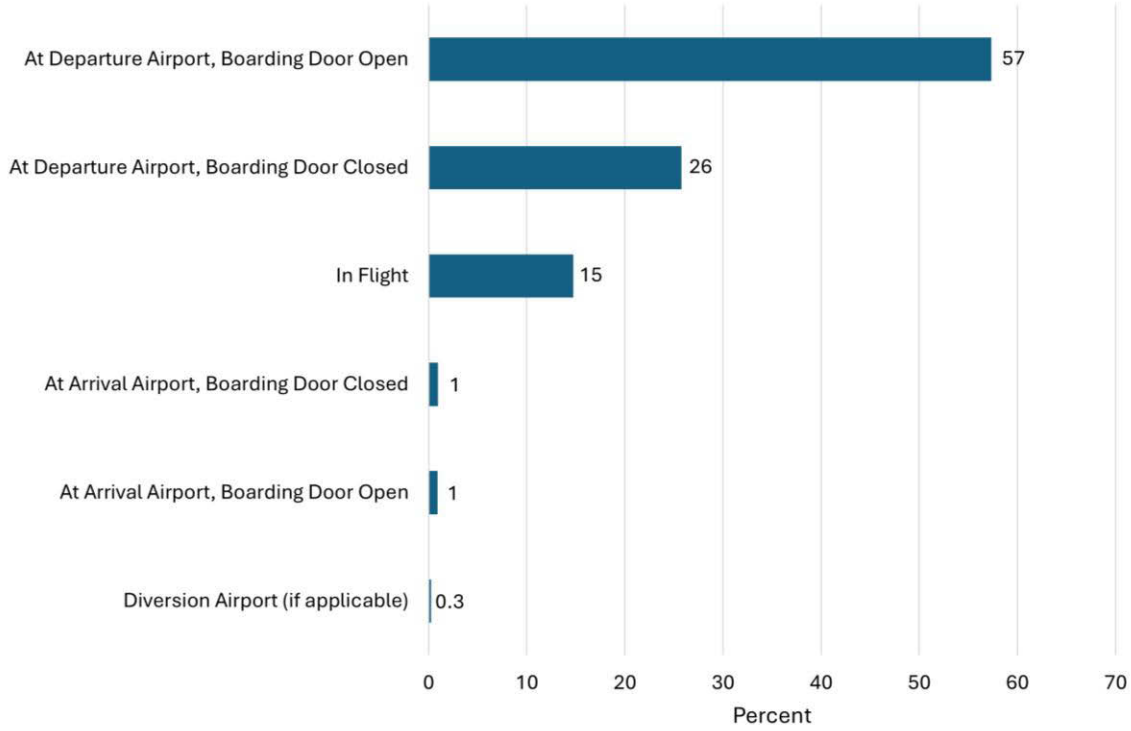

FIGURE B-5 Distribution of 2Hot2Cold reports across different operational phases.
NOTES: Details do not add to 100 because of rounding. N = 4,679.
SOURCE: Created with data from AFA (2025).

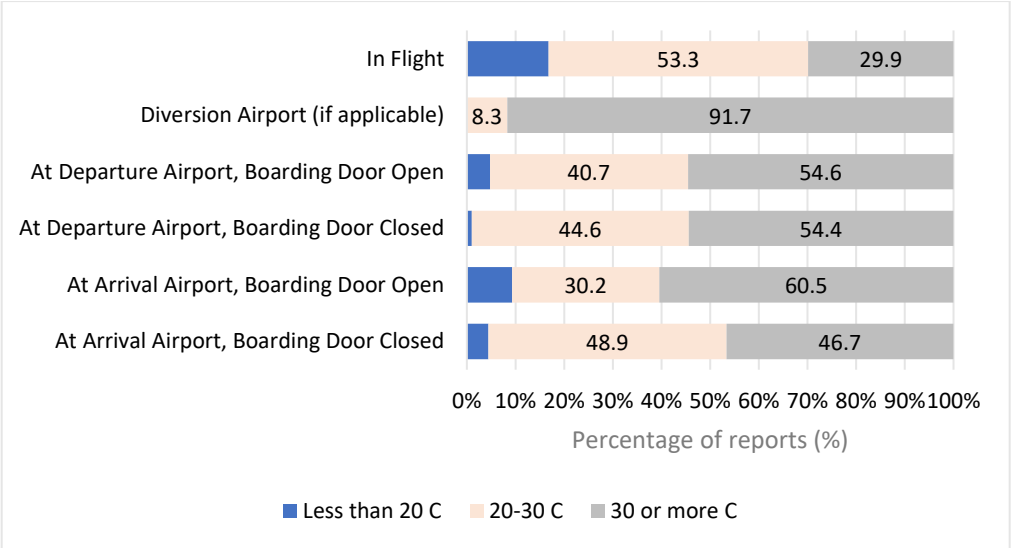

FIGURE B-6 Temperature range by phase of flight for 2Hot2Cold reports.
NOTES: Numbers in bars represent the percentage of reports for each temperature range stratified by phase of flight. N = 4,679.
SOURCE: Created with 2Hot2Cold data from AFA (2025).

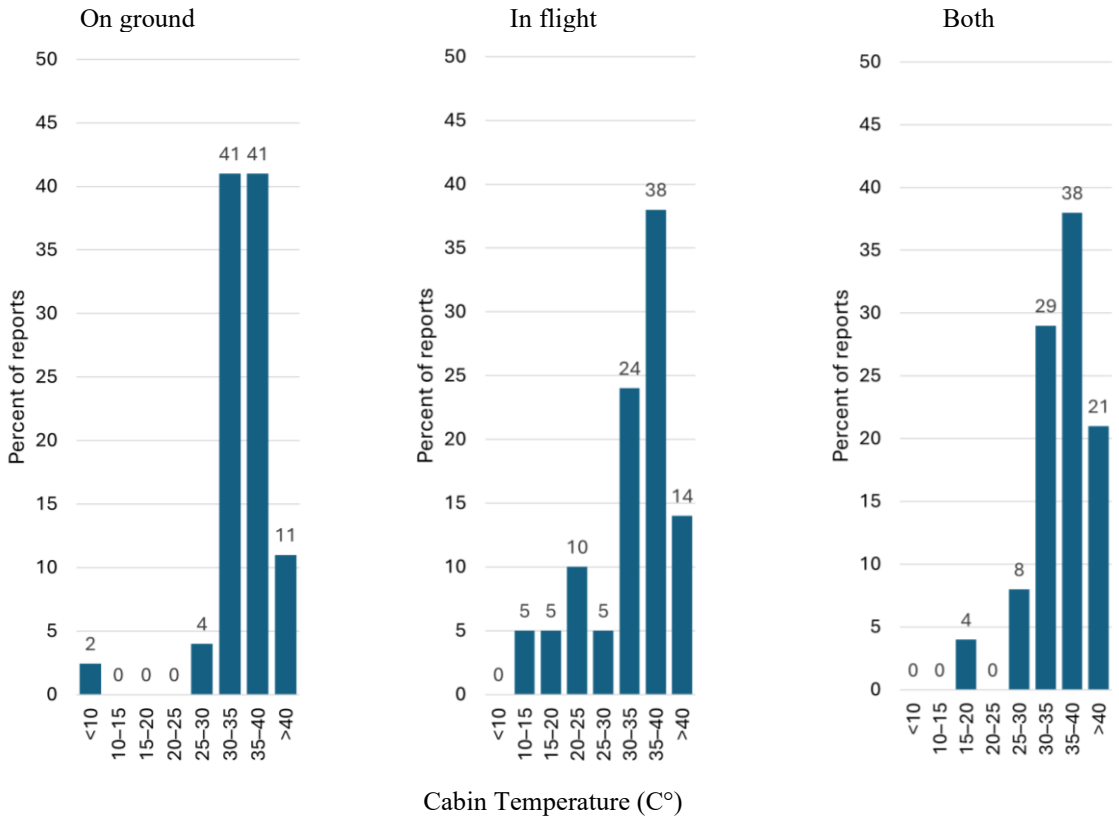

FIGURE B-7 NASA ASRS reports by flight phase, stratified by temperature categories.
NOTE: N = 46 on ground, 21 in flight, and 24 both. Percentages may not add to 100 due to rounding.
SOURCE: Created with data from NASA (2025).

Flight delays may further contribute to cabin temperature issues by extending ground time, during which temperature control is more challenging, especially under extreme ambient conditions. As shown in Figure B-8, reports of the highest temperatures (greater than 32.2°C, or 90°F) were more common in 2Hot2Cold records involving delays of 30 minutes or more.

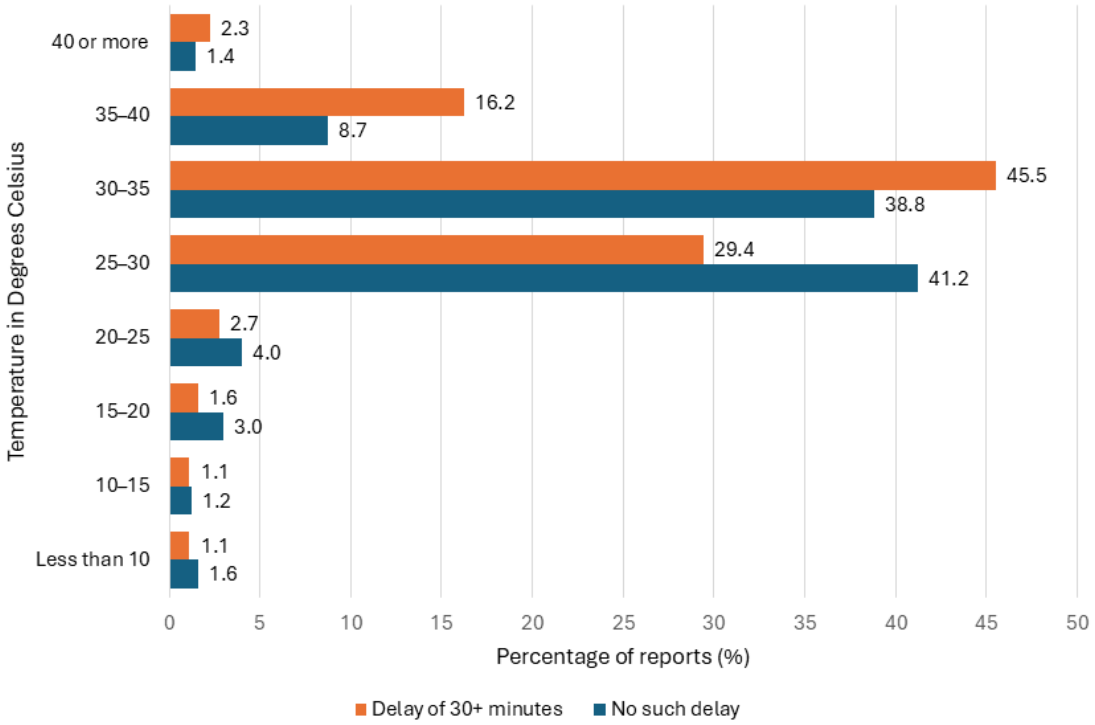

FIGURE B-8 Effect of delays on aircraft cabin temperatures.
SOURCE: Created with 2Hot2Cold data from AFA (2025).

Variation by Aircraft Manufacturer or Model

There is little indication that cabin temperature issues are specific to any one aircraft manufacturer or model. Data from research studies and aviation industry reporting systems indicate that these issues arise in aircraft from all major manufacturers (i.e., Airbus, Boeing, Embraer, and Mitsubishi [formerly Bombardier]) of commercial aircraft operated under a Part 121 certificate (see for example, Figure B-9).

While not tied to a specific manufacturer or model, an analysis of cabin temperature data from AFA's 2Hot2Cold app shows that the most extreme temperatures—above 35°C (95°F) and below 10°C (50°C)—are reported more frequently on regional airline flights than on legacy and value carriers (see Figure B-10). These findings may reflect design differences between regional and mainline jets, operational factors such as shorter turnaround times and higher flight frequencies, or a combination of both, as discussed in Chapter 2. For example, ground crews may lack sufficient time to connect pre-conditioned air (PCA) units during quick turnarounds, necessitating reliance on the aircraft's APU for cooling (NASEM, 2019).

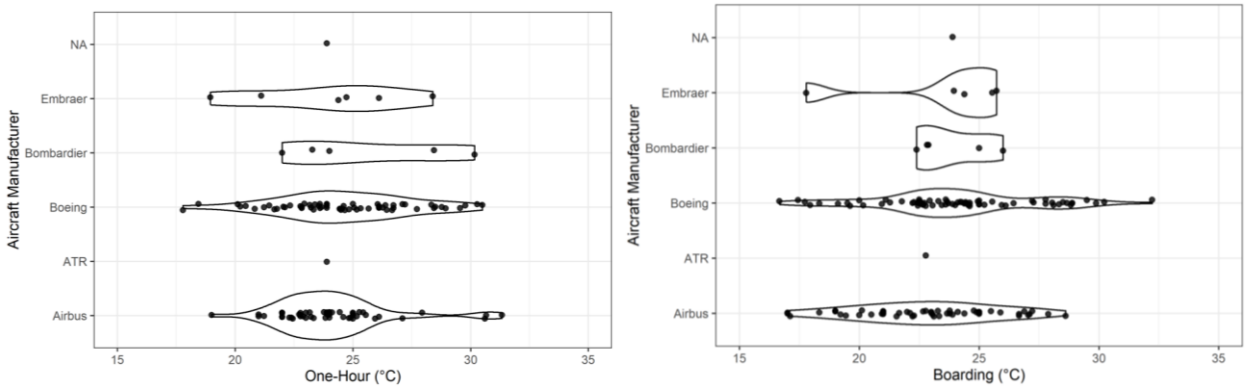

FIGURE B-9 Plots of cabin temperature by aircraft manufacturer during boarding and flight. SOURCE: Created with data from Nicholls and Vink (2025).

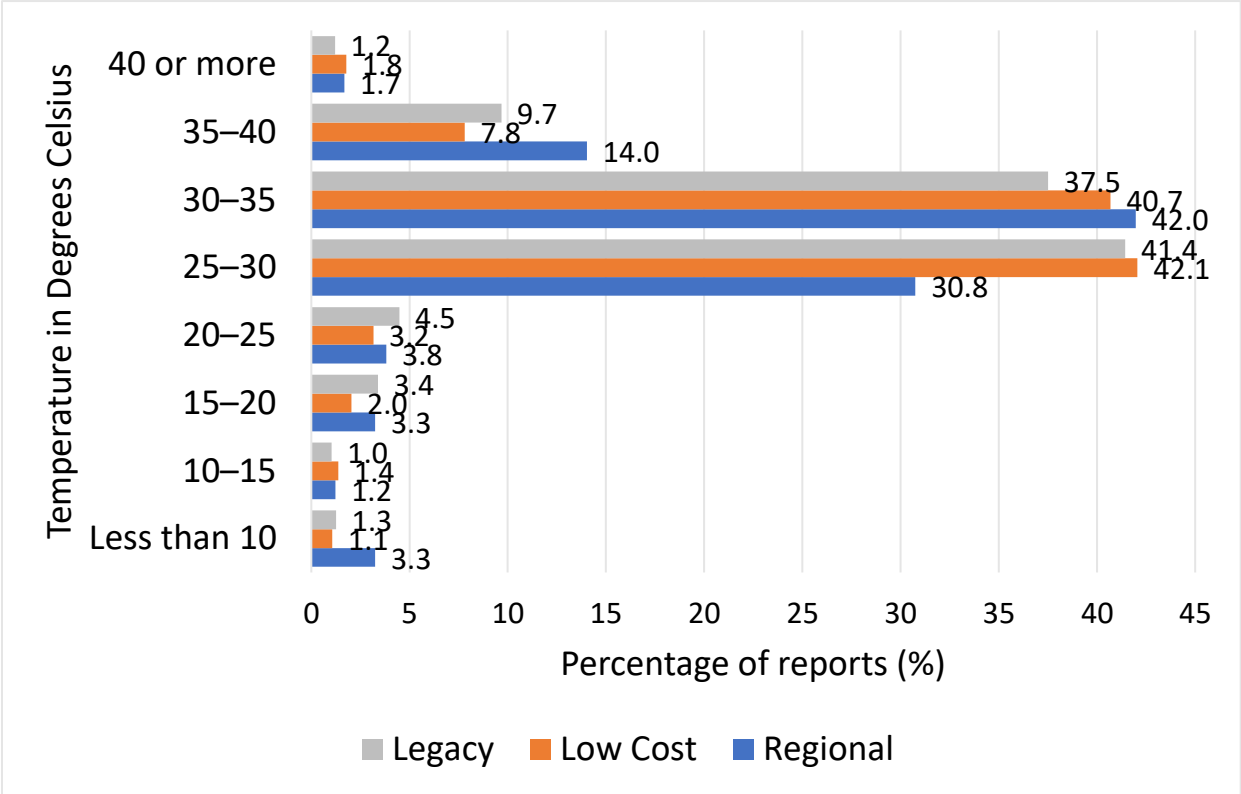

FIGURE B-10 Cabin temperature ranges from 2Hot2Cold dataset by airline category. SOURCE: Created with 2Hot2Cold data from AFA (2025).

Summary and Implications for Mitigation Strategies

Seasonal and flight phase variation in reports of cabin temperature issues point to summer ground operations as a critical risk period for heat-related discomfort and safety concerns. Elevated boarding temperatures during hot months, combined with operational factors such as delayed cooling or equipment limitations, increase the likelihood of conditions approaching heat stress thresholds. Conversely, cooler outdoor conditions in the fall may lead to overcompensation by heating systems, creating warm discomfort in flight. During winter,

however, increased heating is necessary to maintain comfort and prevent excessively cold conditions, underscoring the need for balanced temperature management across all seasons. These patterns suggest the value of mitigation strategies aimed at proactive temperature management during summer ground operations and crewmember training to avoid unnecessary overheating during milder ambient conditions in the fall, while ensuring adequate heating during the winter to maintain thermal comfort.

While environmental control systems typically stabilize conditions after takeoff, prolonged ground time combined with equipment limitations or failures can lead to extreme heat or cold exposures. These findings suggest that mitigation strategies focused on ensuring reliable cooling and heating during ground operations, prioritizing the rapid connection of ground-based air conditioning systems, and implementing contingency plans for delays could significantly reduce the risk of temperature-related discomfort and safety concerns.

Extreme cabin temperature events occur across all major aircraft types, but regional operations appear more vulnerable, potentially due to shorter ground times and limited access to PCA. These operational constraints, rather than inherent design flaws, likely drive the observed differences. Among the mitigation strategies that could improve ground cooling practices for regional flights are timely PCA connection and addressing APU reliability to ensure adequate cooling during quick turnarounds. These strategies are addressed further in Chapter 6, which outlines targeted interventions for ground operations and equipment management.

EXAMINING DURATION OF EXPOSURE

Chapter 5 presented in-flight temperature and humidity data from each of three datasets for which individual measurements were available (see Table 5-4). While longitudinal measurements were available for two of the datasets (ACER and ASHRAE-1262), the data presented from all three in Chapters 5 and 6 were at a single point in time—60 minutes into the flight for the Nicholls and Vink dataset, and at the top of descent for the ASHRAE 1262 (2026) and the ACER datasets. By picking a particular point in time it was hoped that unbiased data would result, as opposed to selecting data at arbitrary, inconsistent times. Additionally, the points in time used were far enough into the flights to provide a temperature that was representative of cruise conditions.

This procedure raises the question, however, of the duration of exposure associated with a given datum. This question is particularly import for hot conditions. A several-hour exposure is far different than exposure for just a few minutes. The ASHRAE 1262 (2026) and the ACER datasets include time-based recordings of temperature and humidity. Thus, these datasets include information about duration of exposures in addition to exposure at a given point in time. In order to assess exposure duration, flights for which the temperature was 27°C (80°F) or higher at top of descent—eight in total—were plotted and examined. This temperature is above the allowed range in ANSI/ASHRAE Standard 161-2023. Graphs of cabin temperature, cabin humidity, and cabin pressure are presented in Figures B-11 through B-18 for these flights.

A fairly consistent pattern is seen, with lower temperatures early in the flight that rise and then remain more or less stable, sometimes increasing slightly, during the remainder of the flight. This pattern likely reflects the higher activity levels and the preference for cooler conditions during boarding. There is also, consistently, a decrease in relative humidity as the flight progresses, which may also have some influence on the desired temperatures. There is no reason to expect the cooling capacity of the aircraft environmental control system (ECS) to decrease

during cruise. So, every indication is that this increase in temperature is intentional and not due to cooling system inadequacy, as discussed in Chapter 6. Such scenarios are distinct from situations involving elevated cabin temperatures during ground operations when inadequate cooling capacity may be a factor. What is not known is who was providing inputs and making decisions about temperature setpoints during cruise—flight crew, cabin crew, and/or passengers.

There is one exception to this pattern, flight F005 in Figure B-13, where there is about a 10°C (18°F) abrupt increase in temperature during cruise. There is no information in the dataset concerning the reason for this large change and whether there was an ECS malfunction. It has all the appearance of an inadvertent control setting error (e.g., accidentally set to maximum) since the temperature appeared to be returning to previous values as the recording ended. This particular flight generated the highest cabin temperature in the ASHRAE 1262 (2026) dataset.

With respect to the question of exposure duration, these graphs indicate that the temperatures used in the assessments are typically representative of an extended exposure and are not the result of short fluctuations in cabin conditions. Even with the one anomalous flight, the exposure at the elevated temperature was on the order of 20 minutes.

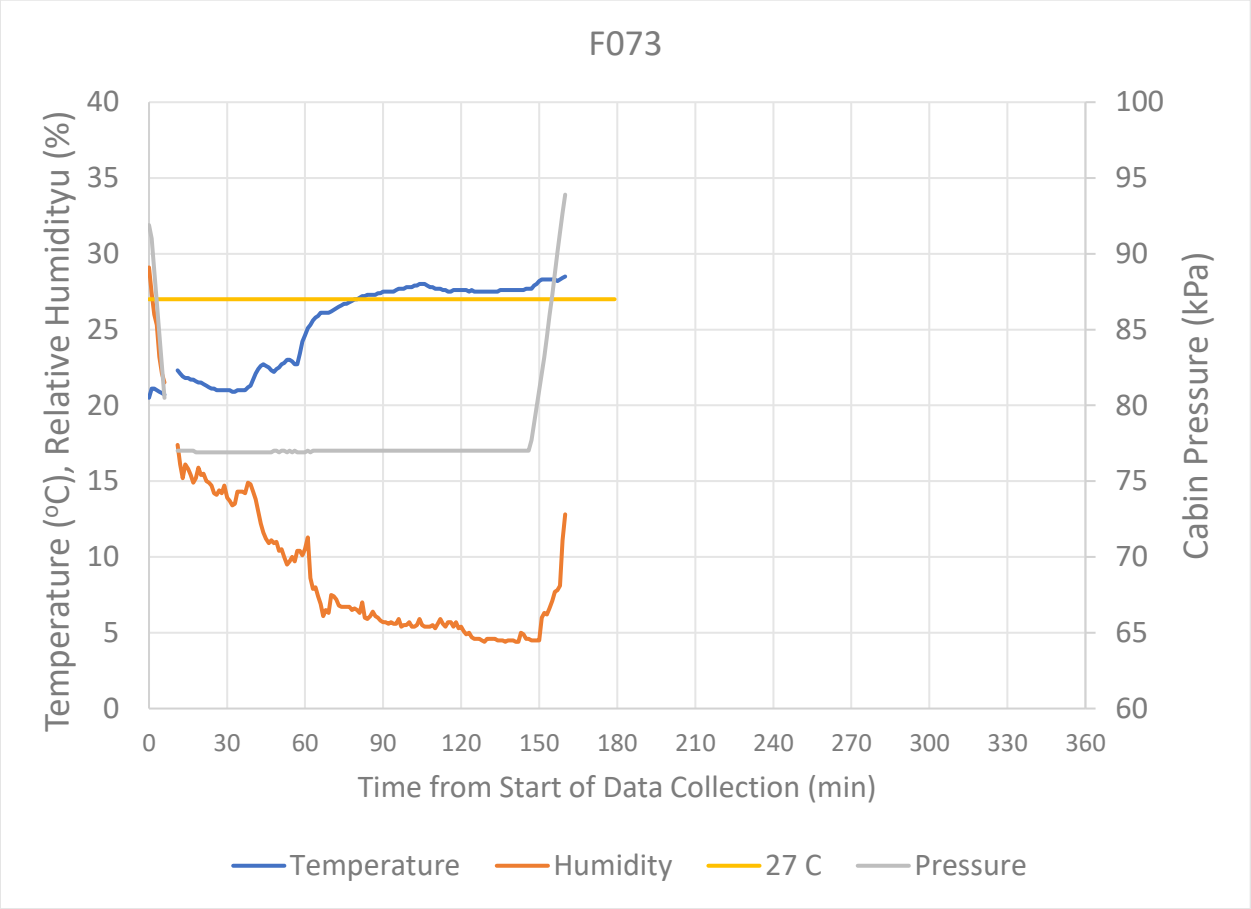

FIGURE B-11 Cabin environment conditions for Flight F073.
NOTE: 27°C (80°F) represents the ANSI/ASHRAE Standard 161-2023 upper allowable limit for in-flight cabin temperature.
SOURCE: Created with data from the ASHRAE-1262 data set (ASHRAE, 2026).

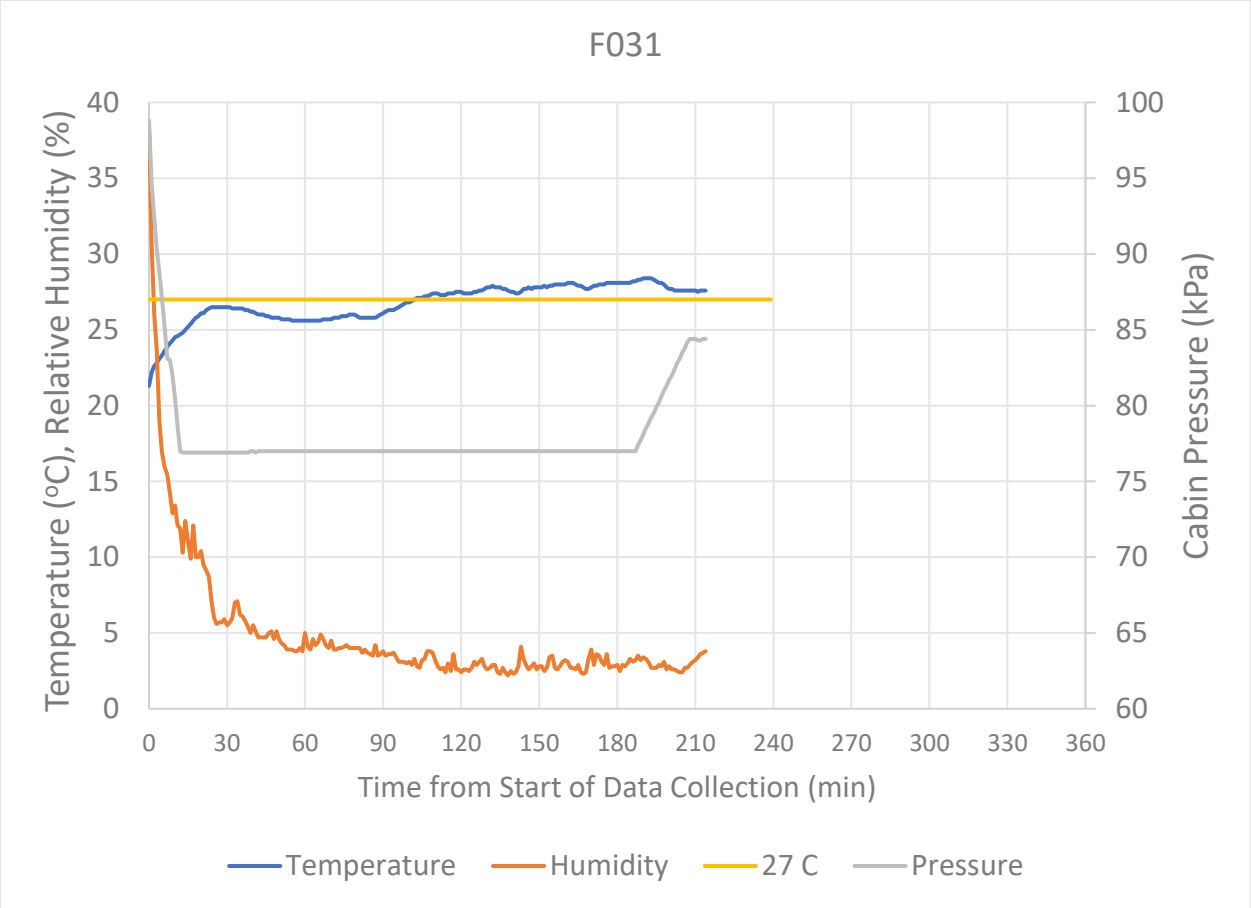

FIGURE B-12 Cabin environment conditions for Flight F031.
NOTE: 27°C (80°F) represents the ANSI/ASHRAE Standard 161-2023 upper allowable limit for in-flight cabin temperature.
SOURCE: Created with data from the ASHRAE-1262 data set (ASHRAE, 2026).

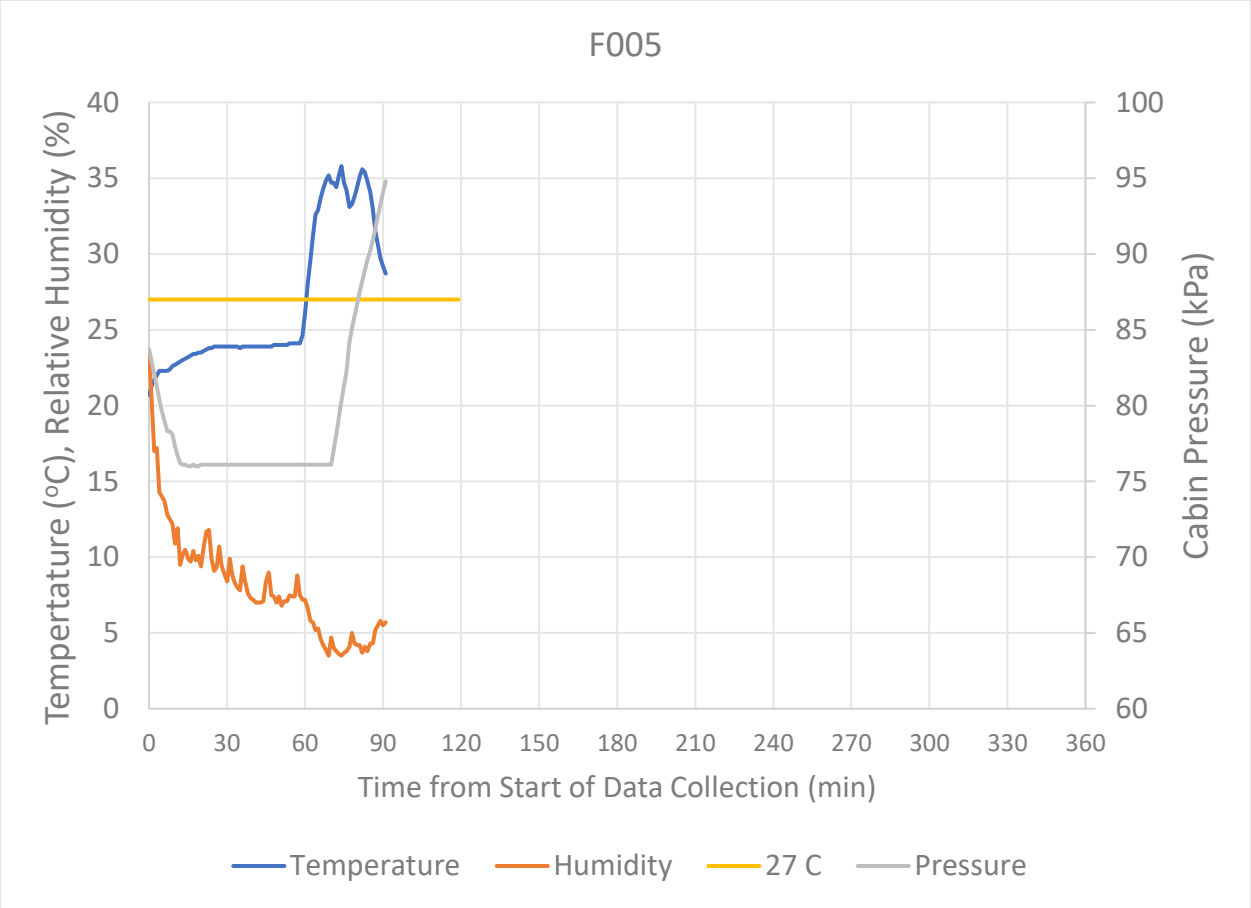

FIGURE B-13 Cabin environment conditions for Flight F005.
NOTE: 27°C (80°F) represents the ANSI/ASHRAE Standard 161-2023 upper allowable limit for in-flight cabin temperature.
SOURCE: Created with data from the ASHRAE-1262 data set (ASHRAE, 2026).

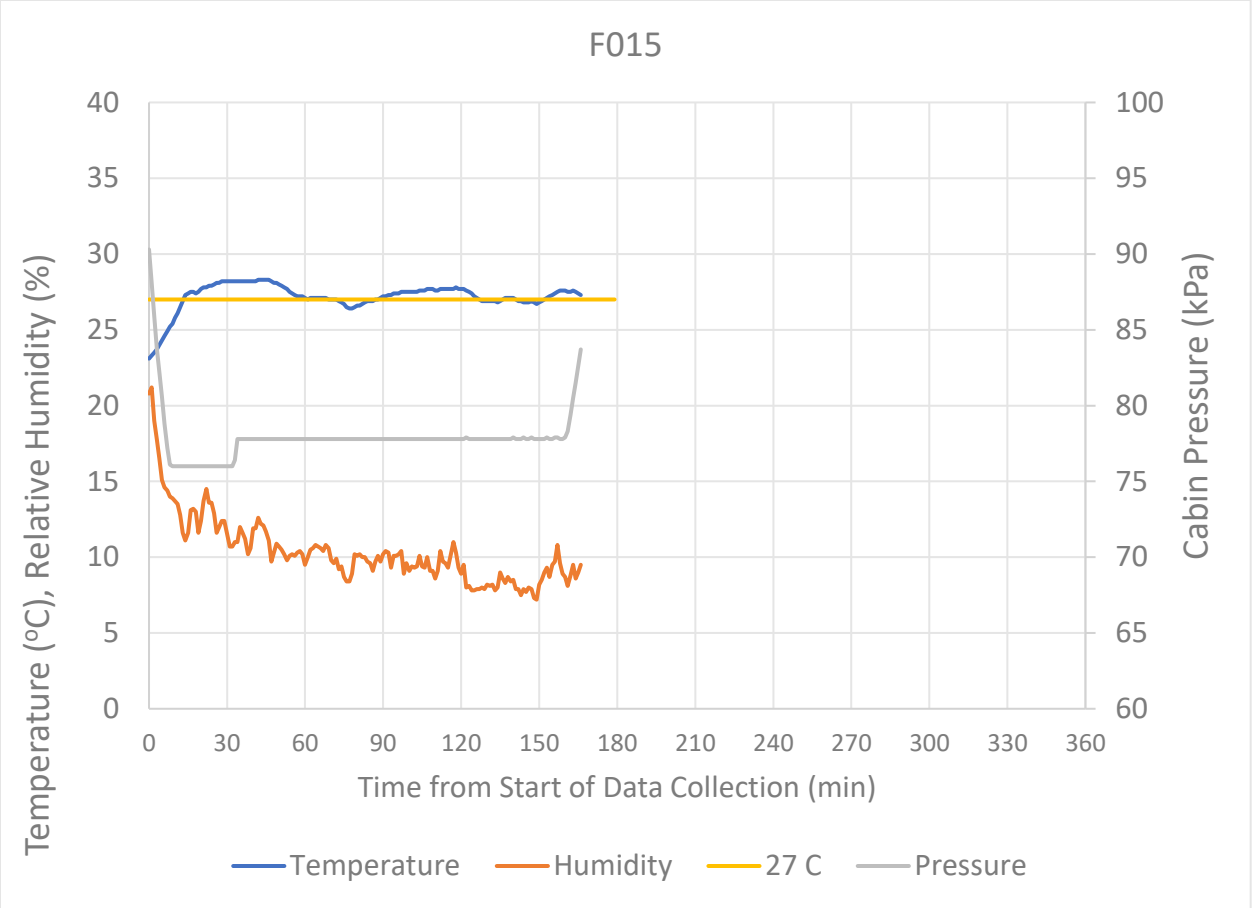

FIGURE B-14 Cabin environment conditions for Flight F015.
NOTE: 27°C (80°F) represents the ANSI/ASHRAE Standard 161-2023 upper allowable limit for in-flight cabin temperature.
SOURCE: Created with data from the ASHRAE-1262 data set (ASHRAE, 2026).

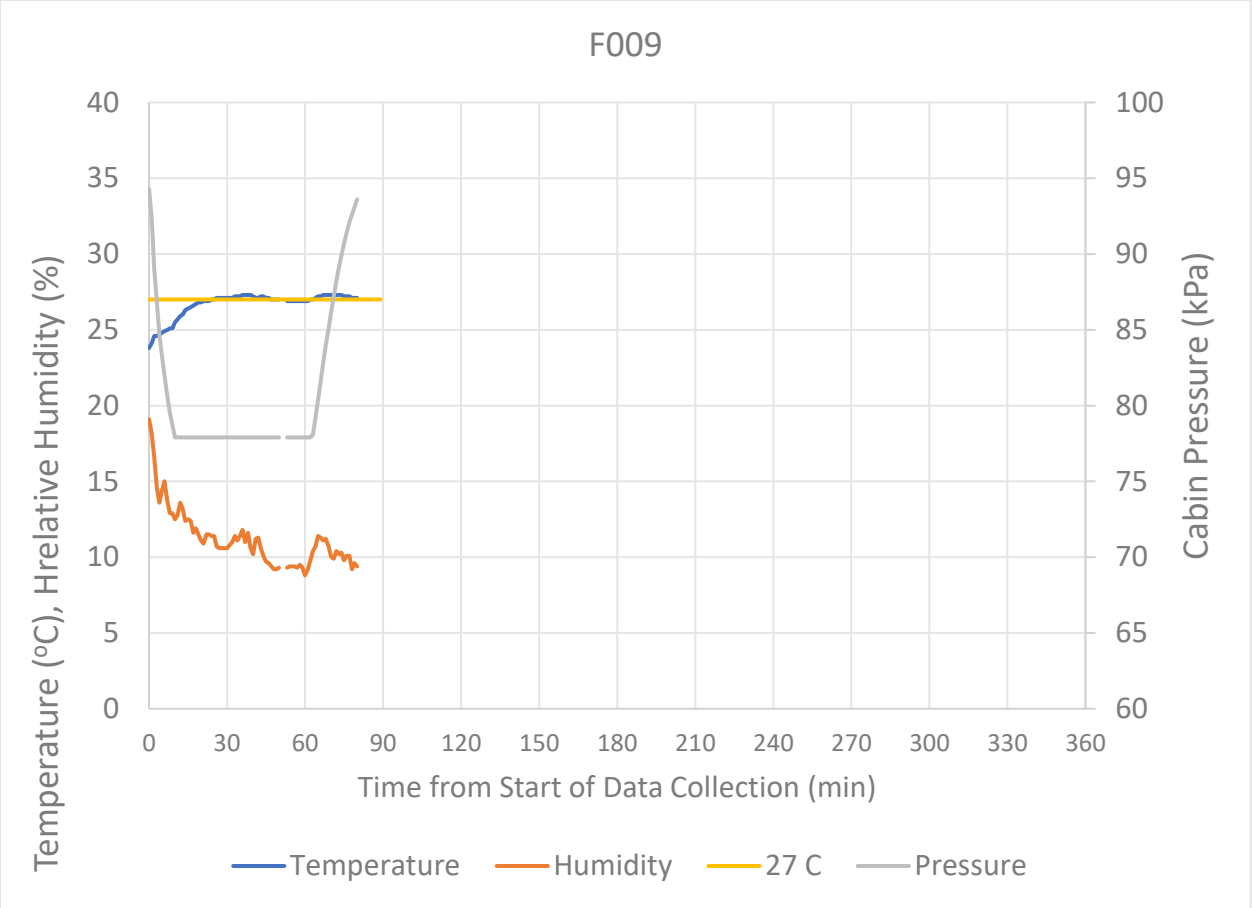

FIGURE B-15 Cabin environment conditions for Flight F009.
NOTE: 27°C (80°F) represents the ANSI/ASHRAE Standard 161-2023 upper allowable limit for in-flight cabin temperature.
SOURCE: Created with data from the ASHRAE-1262 data set (ASHRAE, 2026).

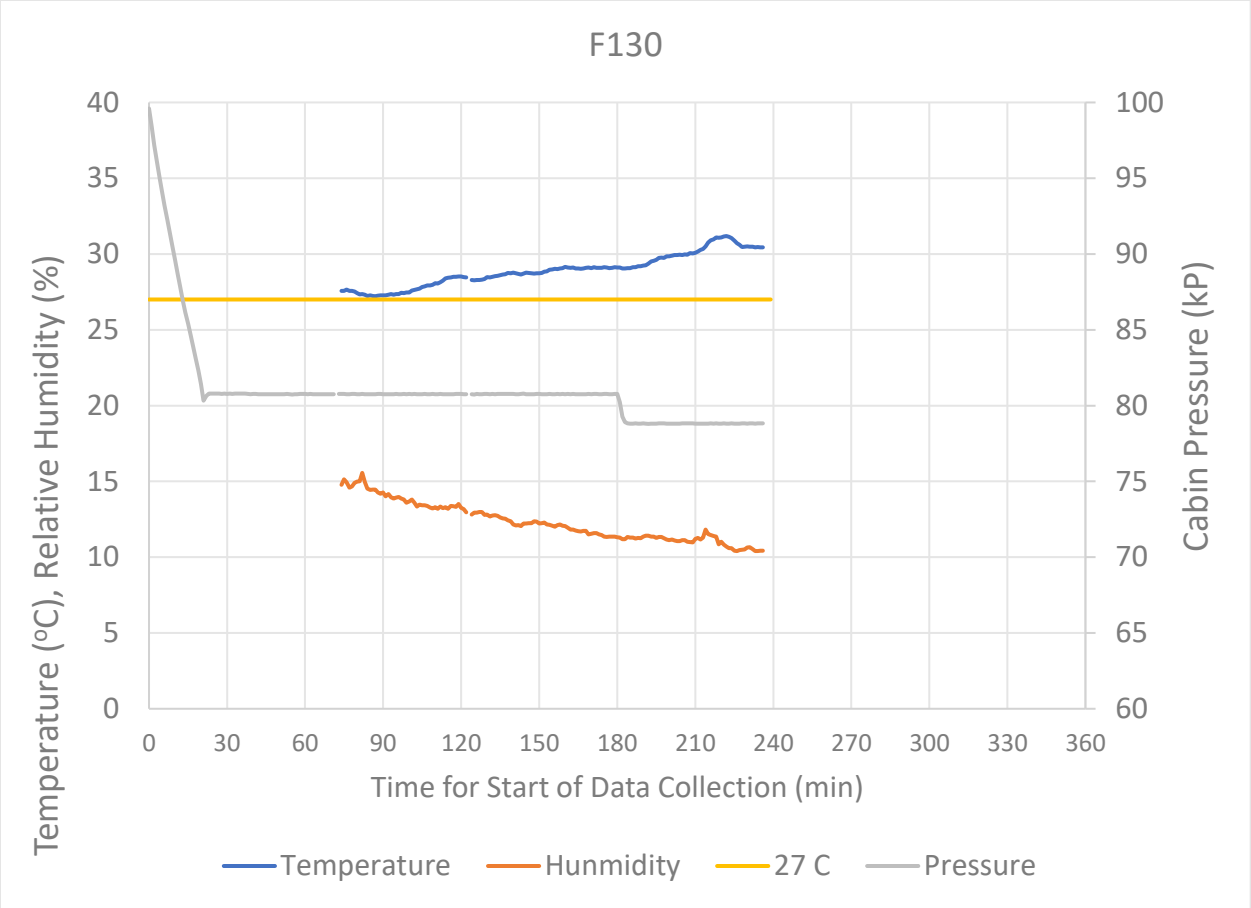

FIGURE B-16 Cabin environment conditions for Flight F130.
NOTE: 27°C (80°F) represents the ANSI/ASHRAE Standard 161-2023 upper allowable limit for in-flight cabin temperature.
SOURCE: Created with data from the ASHRAE-1262 data set (ASHRAE, 2026).

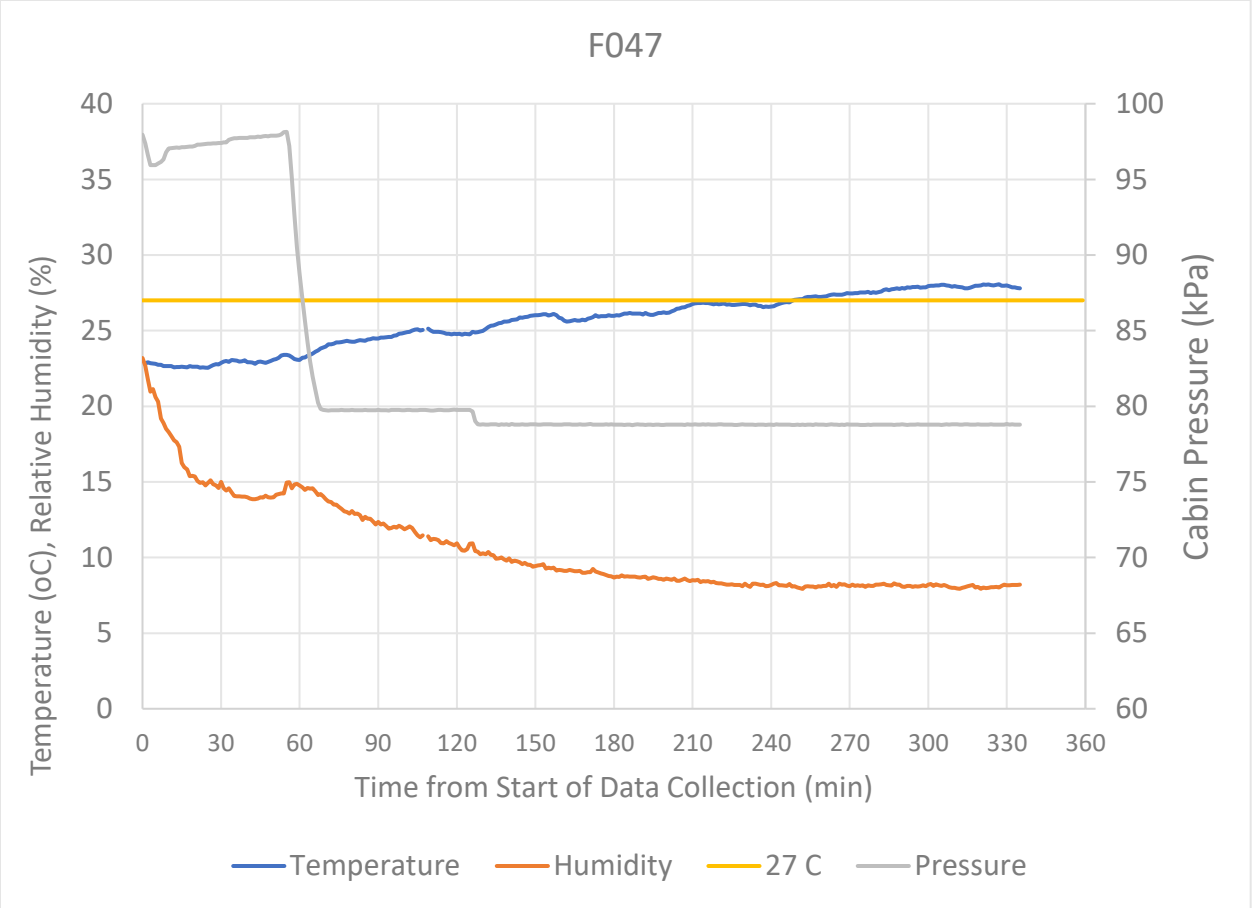

FIGURE B-17 Cabin environment conditions for Flight F047.
NOTE: 27°C (80°F) represents the ANSI/ASHRAE Standard 161-2023 upper allowable limit for in-flight cabin temperature.
SOURCE: Created with data from the ASHRAE-1262 data set (ASHRAE, 2026).

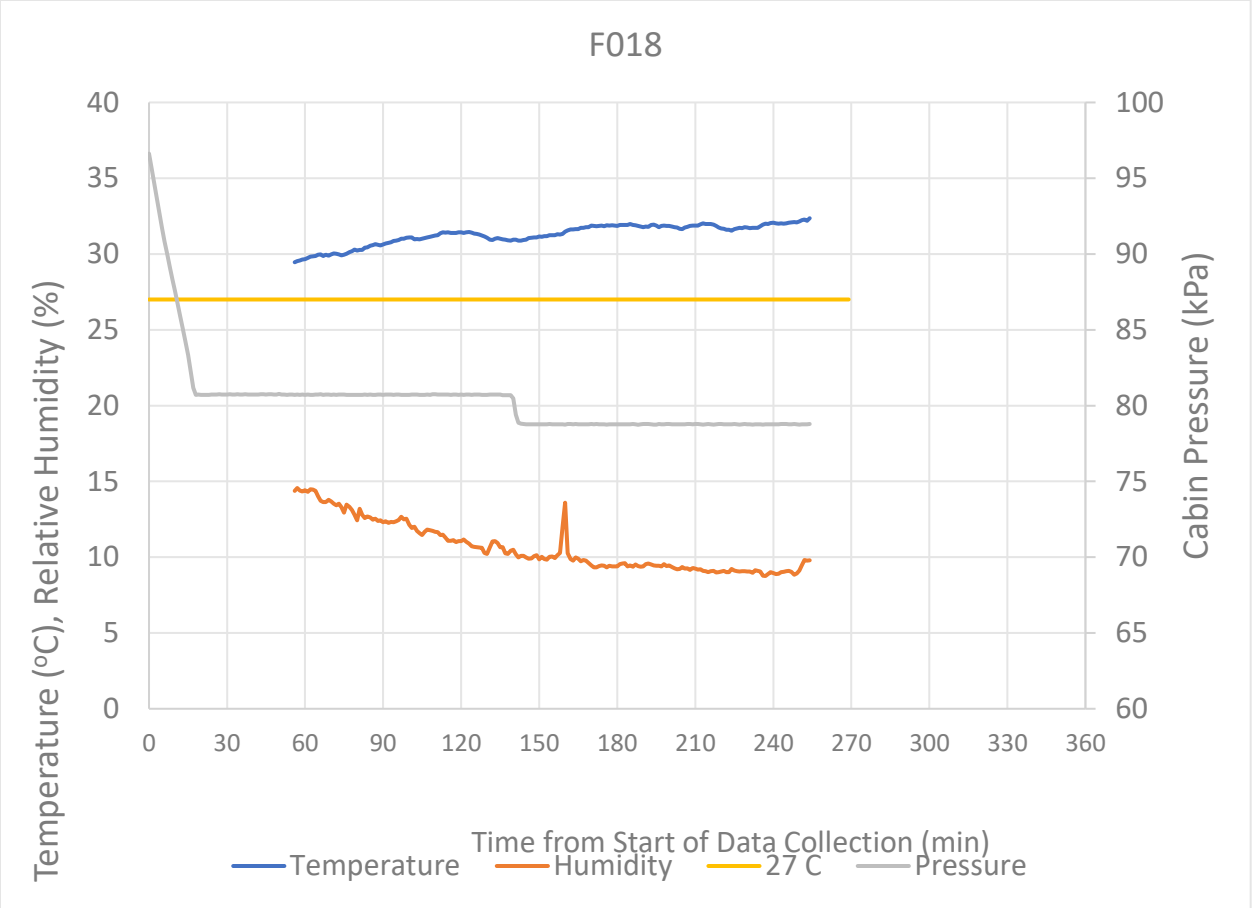

FIGURE B-18 Cabin environment conditions for Flight F018.
NOTE: 27°C (80°F) represents the ANSI/ASHRAE Standard 161-2023 upper allowable limit for in-flight cabin temperature.
SOURCE: Created with data from the ASHRAE-1262 data set (ASHRAE, 2026).

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Appendix C
Committee, Fellow, and Staff Biographical Sketches

David H. Wegman (Chair), is a professor emeritus in the Department of Public Health at the University of Massachusetts Lowell and an adjunct professor at the Harvard T.H. Chan School of Public Health. He also serves as the vice president of the Alpha Foundation for the Improvement of Mine Safety and Health. Dr. Wegman's epidemiologic research has included the study of acute and chronic occupational respiratory disease, cancer risk and musculoskeletal disorders with additional interests in surveillance of occupational conditions and risks, occupational health policy, and, most recently, the prevention of heat impacts on kidney disorders. He is a non-compensated senior scientist and researcher at the La Isla Network, a nongovernmental organization that studies heat impacts on work environments primarily in the agricultural and construction sectors. He is currently directing a study of occupation and chronic kidney disease in sugarcane workers in Nicaragua. Dr. Wegman is a National Associate of the National Academies and has chaired or served on several National Academies committees. He chaired the Mine Safety and Health Administration Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers and previously served on the Boards of Scientific Counselors for the National Institute for Occupational Safety and Health and for the National Toxicology Program as well as on the Environmental Protection Agency Science Advisory Board. In 1998 he was awarded a Fulbright Senior Fellowship for study of health and safety of older workers in Sweden, and in 2006 he was appointed chair of the International Evaluation Group for an analysis of Occupational Health Research in Sweden. His honors include the Jameson Parkinson Memorial Lecturer from the British Society of Occupational Medicine, the Alice Hamilton Lifetime Achievement Award from the Occupational Safety and Health Section of the American Public Health Association, and the EPICOH Lifetime Achievement Award in Occupational Epidemiology. He received his B.A. from Swarthmore College and both his M.D. and M.Sc. from Harvard University.

Fabiano Amorim is an associate professor in and the chair of the Department of Health, Exercise, and Sports Sciences at the University of New Mexico. He previously held a faculty position in Brazil, where he led studies on occupational heat stress and contributed to the development of official government guidelines on heat exposure and worker safety. Dr. Amorim is an exercise and thermal physiologist with extensive expertise in human physiological responses to heat. His research examines the acute and chronic effects of physical work in hot environments, from whole-body to molecular levels. He has conducted applied field studies among laborers, including sugarcane workers in Brazil and construction workers in Kansas and New Mexico, measuring real-world indicators such as core temperature and metabolic rate. He is also investigating the links between heat stress and kidney injury among vulnerable workers. Dr. Amorim has contributed his expertise to public policy, helping to shape the development of New

Mexico's proposed Occupational Heat Rule, currently open for public comment. He received his Ph.D. in exercise physiology from the University of New Mexico.

Catherine Burnett is an expert in cabin safety, with documented success in the aviation industry at various organizational levels. She spent 40 years attaining progressively greater responsibilities at several commercial aviation operators and for the federal government. Most recently, as an aviation safety inspector, she was the senior cabin safety subject matter expert for the Federal Aviation Administration's (FAA's) air transportation policy division, from which she retired in May 2025. Her role included developing and implementing policies, standards, programs, and procedures governing the certification, inspection, surveillance, and operation of air carriers and crewmembers. Prior to her role at FAA, Ms. Burnett worked as a flight attendant and subsequently as a training instructor for two commercial aircraft operators and was certificated on Airbus A319 and A320 aircraft; Boeing 737, 747, 757, and 767 aircraft; and DeHavilland DH-8 aircraft. In 2024 the secretary of the U.S. Department of Transportation presented the Partnering for Excellence Award to Inspector Burnett and other colleagues who made up the "Family Travel Team." She received the FAA's 2023 Commitment to People Award in recognition of her sustained dedication and significant contribution to the FAA mission. She led the Child Restraint Systems Team that received the 2021 Regional Administrator's Award for Team Excellence. In 2019, the FAA bestowed upon Inspector Burnett its Aviation Safety Innovation Award for her work that increased the knowledge about and use of child restraint systems on aircraft. Ms. Burnett is a certified child passenger safety technician. She received her B.A. in education from Arizona State University and M.S. in aviation management from The George Washington University.

Sara Czaja is the Gladys and Roland Harriman Professor of Medicine and a professor of gerontology and the director of the Center on Aging and Behavioral Research in the Division of Geriatrics and Palliative Care at Weill Cornell Medicine. She has extensive experience in aging research, both theoretical and applied, and in the coordination and leadership of multi-site collaborations. She is the principal investigator of the National Institute on Aging–funded multi-site Center for Research and Education on Aging and Technology Enhancement and the co-director of the ENHANCE (Enhancing Neurocognitive Health, Abilities, Networks, and Community Engagement) Center, funded by the National Institute on Disability, Independent Living, and Rehabilitation Research, with a focus on how technology can support older adults living with cognitive impairment. Her research interests include aging and cognition, aging and health care informatics, caregiving, human–computer interaction, training, and functional assessment. She is a fellow of the American Psychological Association (APA), the Human Factors and Ergonomics Society, and the Gerontological Society of America (GSA). She also served as a member of the National Academies Board on Human–Systems Integration. Dr. Czaja is the recipient of the 2015 M. Powell Lawton Distinguished Contribution Award for Applied Gerontology of the APA, the 2013 Social Impact Award for the Association of Computing Machinery, the 2013 Jack A. Kraft Award for Innovation from the Human Factors and Ergonomics Society, The Franklin V. Taylor Award (APA), and the 2020 M. Powell Lawton Award of GSA.

Byron Jones is a professor emeritus in the Mechanical and Nuclear Engineering Department at Kansas State University (KSU). While at KSU, he served as the engineering associate dean for

research, director of the Engineering Experiment Station, and as department head. Prior to joining KSU, Dr. Jones was employed as a senior systems analyst by the Montana Energy and MHD Research and Development Institute. Dr. Jones has extensive research experience with human-body interaction with the thermal environment, having conducted research with thermal manikins, human subjects, and computer modeling. More recently his focus has been on aircraft cabin environments, and he previously served as the technical director for the Federal Aviation Administration Aircraft Cabin Environment Research Center of Excellence. Dr. Jones has worked extensively with the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) where he is a fellow. He chaired the ASHRAE committee that wrote ASHRAE/ANSI Standard 161, *Air Quality within Commercial Aircraft*. He received the Holladay Distinguished Fellow Award, ASHRAE's highest technical recognition. He served on the National Research Council Committee on Air Quality in Passenger Cabins of Commercial Aircraft, which generated the report *The Airliner Cabin Environment and the Health of Passengers and Crew*, published by The National Academies Press in 2002. Dr. Jones received his B.S. in mechanical engineering from Kansas State University and M.S. and Ph.D. degrees in mechanical engineering from Oklahoma State University.

W. Larry Kenney is the Marie Underhill Noll Chair in Human Performance and a professor of physiology and kinesiology at the Pennsylvania State University. His research focuses on human thermoregulation in extreme environments, with an emphasis on aging and other vulnerable populations. Dr. Kenney was awarded the prestigious Faculty Scholar Medal by Penn State for his research contributions and has published multiple editions of two books, approximately 300 journal articles, and dozens of book chapters on the topics of human responses to exercise, heat and cold stress, and dehydration as well as the biophysics of heat exchange between humans and the environment. Dr. Kenney is the primary author of *Physiology of Sport and Exercise*, a best-selling textbook in exercise physiology now in its ninth edition. He served as president of the American College of Sports Medicine (ACSM) from 2003 to 2004. He is also a fellow of the American Physiological Society (APS) and was presented with the Adolph Distinguished Lectureship Award by APS in 2017. He is one of only 10 scientists who have been the recipient of Honor Awards from both ACSM and APS. Dr. Kenney received his B.S. and M.S. in biology and his Ph.D. in physiology.

Eileen McNeely is the founder and executive director of SHINE, the Health and Sustainability Initiative at the Harvard Institute of Quantitative Social Sciences. Dr. McNeely has extensive experience in the areas of environmental epidemiology, occupational and community health, health promotion, health services management and policy, and clinical practice as a nurse practitioner. Her experience spans numerous industries. She previously was a co-investigator for a Federal Aviation Administration–funded Center of Excellence for Research in the Intermodal Transport Environment, which included a study on the Evaluation of Aircraft Cabin Conditions on Health of Passengers and Crew. She started and runs the Harvard Flight Attendant Health Study, the largest cohort study of flight attendants, which received support from the Flight Attendant Medical Research Institute. She is a former intern at the Occupational Safety and Health Administration in Washington D.C., where she evaluated the impact of regulations on the chemical industry. She has consulted both nationally and internationally on the impact of work on well-being and has authored many publications on this topic. Her research is currently focused on work as a platform to improve well-being, putting people and health at the center of

corporate sustainability and business culture. Using a rigorous and applied academic approach, she aims to shine a light on worker health and well-being in the business context and engages companies to understand the impact of workplace culture and practices on well-being. Dr. McNeely's work with companies is intended to redesign how business integrates well-being from an ever-changing programmatic style to an integrated systems approach.

Kimberly Meidenbauer is an assistant professor in the Department of Psychology at Washington State University, where she directs the Social, Cognitive, and Environmental Neuroscience (SCENe) Lab. Her current research focuses on the negative psychological impacts of heat stress, including how it affects emotional states, impulsivity, and aggression. She received her Ph.D. from the University of Chicago in 2020 and worked as a postdoctoral scholar in the Environmental Neuroscience Lab there until beginning her faculty appointment in 2023. Dr. Meidenbauer received her B.S. and M.A. in psychology and Ph.D. in psychology (integrative neuroscience).

Paul Morell is an independent consultant and a retired vice president of safety, security, regulatory compliance, and environmental at American Airlines. His areas of expertise are aviation safety, managing aviation risk, implementing and evaluating the effectiveness of Federal Aviation Administration (FAA) safety management systems to identify and mitigate risks. He was the industry co-chair of the FAA Commercial Aviation Safety Team (CAST) and industry co-chair of the FAA Aviation Safety Analysis and Information Sharing program (ASIAS), programs that use an integrated, data-driven proactive strategy to reduce the commercial aviation fatality risk in the United States. Mr. Morell currently consults for ProSafeT, a company that develops safety management system software that provides comprehensive safety and risk management for airlines, airports, and maintenance repair and overhaul companies. He holds an M.B.A. from National University.

Zachary Schlader is an associate professor of kinesiology at the Indiana University School of Public Health–Bloomington. His research centers on human physiological responses to thermal stress, with a particular focus on heat. The overarching goal of his work is to uncover the mechanisms by which emerging environmental challenges negatively impact human health. Specifically, Dr. Schlader's work is intended to support the development of occupational and public health initiatives designed to protect against the adverse effects of environmental stressors, such as heat and dehydration. His contributions to the field have been recognized by both institutional and professional organizations. Most notably, he was named the 2025 Impact Awardee by the Environmental and Exercise Physiology Section of the American Physiological Society—an honor awarded to a mid-career researcher who has made significant contributions to environmental, exercise, thermal, or applied physiology. These achievements have been made possible through his extensive training in thermal physiology, including training with preeminent physiologists and completing a postdoctoral fellowship at the prestigious Institute for Exercise and Environmental Medicine. Dr. Schlader received his B.S. in health, M.S. in exercise physiology, and Ph.D. in exercise and sport science.

Shalini H. Shah is a practicing board-certified pediatrician, environmental medicine physician, and assistant director for the Boston Children's Pediatric Environmental Health Center and Region I Pediatric Environmental Health Specialty Unit (PEHSU). She completed her residency

in pediatrics at the University of Massachusetts Medical School and her fellowship in pediatric and reproductive environmental health at Boston Children's Hospital. Dr. Shah provides clinical care in primary care pediatrics and in an environmental health clinic for patients with environmental exposures. She is passionate about the intersection of the climate crisis, environmental justice, and children's health. Her research centers on developing and implementing environmental screening (e.g., the Healthy Homes screener) and clinical education tools (e.g., ClimateRx) to strengthen the capacity of families to adapt to environmental and climate-related health risks. Her work has been presented both regionally and nationally. Dr. Shah also co-leads educational programs at the Region I PEHSU, Boston Children's Hospital, and Harvard Medical School to integrate environmental and climate-related education across all stages of medical training. Dr. Shah has additional roles as a national climate advocate for the Massachusetts chapter of the American Academy of Pediatrics and as a co-chair for the Academic Pediatrics Association Environmental Health, Climate Change, and Sustainability Special Interest Group. Dr. Shah received her D.O in osteopathic medicine at the University of New England College of Osteopathic Medicine.

David Space has extensive experience working on issues of air quality, thermal environment, pressure, humidity, ventilation, purification technologies, and multi-factor environmental effects in aviation settings. He retired in September 2024 from Boeing Commercial Aircraft as an associate technical fellow and lead engineer in environmental control systems, specializing in the cabin environment and air quality. While at Boeing, he served as a principal investigator in cabin environment research, including thermal comfort, humidity, air quality, contaminant behavior, ventilation, and air purification. He also led in-flight, laboratory, and controlled human-subject chamber studies in collaboration with airlines, universities, and leading global experts. Mr. Space is the named inventor of several patents related to aircraft environmental control systems, with all ownership rights assigned to The Boeing Company. Mr. Space served as Boeing's focal representative for cabin environment and air quality issues. During his professional career, he served as chair of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Aviation Research Committee, a founding member of both ASHRAE's Aviation Air Quality and European Air Quality committees, and vice chair of the SAE International Bleed Air Committee. He represented Boeing in the Federal Aviation Administration–supported Centers of Excellence for Aircraft Cabin Environmental Research and presented Boeing's perspectives and research findings to the 2001 National Research Council (NRC) Committee on Aircraft Air Quality. Mr. Space has a B.S. in mechanical engineering from the University of Washington.

Millennia Young is the lead of the Statistics and Data Science Capability at NASA Johnson Space Center, within NASA's Human Health and Performance Directorate. For over a decade she has applied her statistical and data modeling expertise to support human health in spaceflight, particularly by quantifying human health risks and impacts using limited data. Her work includes linking environmental exposures to health impacts on the International Space Station and using diverse data sources—such as literature-extracted summaries—to supplement limited human spaceflight data for developing health and performance prediction models. Dr. Young serves on the American Statistical Association's Committee on Professional Ethics and NASA's institutional review board and Flight Institutional Animal Care and Use Committee. She is also a recipient of multiple NASA performance and achievement awards, including the

prestigious Silver Achievement Medal. Dr. Young received a Ph.D. in statistics from Rice University.

NATIONAL ACADEMY OF MEDICINE FELLOW

Roxana Chicas is a Latina nurse, climate scientist, and advocate for workers' rights who has dedicated her career to advancing health equity and labor policies with and for Latino farmworker communities. Her leadership, teaching, prolific writing, and research have helped to cultivate national awareness of climate health threats. Dr. Chicas currently serves as an assistant professor at Emory University's Nell Hodgson Woodruff School of Nursing. In this role she is leading the field-based testing of a wearable biopatch for outdoor workers to gather physiological data, such as skin temperature, respiratory rate, and heart rate, which will eventually help artificial intelligence (AI) predict when a person is at risk for heat-related illnesses. Dr. Chicas conducted the first field-based intervention study of methods to reduce core body temperature using real-time biomonitoring among farmworkers in the United States. As the daughter of immigrant farmworkers and someone who grew up in an outdoor working community, Dr. Chicas' research is informed by lived experience. Her work is continually informed by insights from farmworker communities as well; likewise, she seeks to continually share research findings and solutions with communities. Dr. Chicas has disseminated her findings through various publications, research abstracts and proceedings, invited presentations, and media features, including José Díaz-Balart Reports (MSNBC), the *Washington Post*, and NPR. In addition, she has contributed to policy-focused collaborations with the Alliance of Nurses for Healthy Environment and the Medical Society Consortium on Climate and Health. Dr. Chicas earned an A.S.N. from Georgia Perimeter College, a B.S.N. from Emory University, and a Ph.D. from Emory University Laney Graduate School. She completed her postdoctoral training in the Renal Division of the School of Medicine at Emory University, which positioned her to advance her pioneering body of work on acute kidney injury secondary to extreme heat exposure.

NATIONAL ACADEMIES STAFF

Autumn S. Downey is a senior program officer in the Biomedical and Health Sciences Program Area. She joined the National Academies of Sciences, Engineering, and Medicine in 2012 and is currently directing a National Institute for Occupational Safety and Health–sponsored standing committee on personal protective equipment. She was formerly the director of a State Department–sponsored standing committee on air pollution exposure and mitigation at overseas posts. During her time with the National Academies, Dr. Downey has worked on consensus studies spanning a broad range of topics, including interventions and research priorities for dementia, nonhuman primate models for biomedical research, the return of research results to participants, public health emergency preparedness and response and disaster recovery, trauma care systems, personal protective equipment for inhalation hazards, and workforce health. Dr. Downey received her Ph.D. in molecular microbiology and immunology from the Johns Hopkins Bloomberg School of Public Health, where she also completed a postdoctoral fellowship at the school's National Center for the Study of Preparedness and Catastrophic Event Response. Prior to joining the National Academies, she was a National Research Council Postdoctoral Fellow at

the National Institute of Standards and Technology, where she worked on environmental sampling for biothreat agents and the indoor microbiome.

Ashley Bologna is a research assistant in the Biomedical and Health Sciences Program Area at the National Academies of Sciences, Engineering, and Medicine. In addition to this study, she supports the Standing Committee on Personal Protective Equipment for Workplace Safety and Health, which is sponsored by the National Personal Protective Technology Laboratory of the National Institute for Occupational Safety and Health. The committee provides a forum for the discussion of scientific and technical issues relevant to the development, certification, deployment, and use of personal protective equipment, standards, and related systems to ensure workplace safety and health. She has worked on a number of National Academies consensus studies, including Research Priorities for Preventing and Treating Alzheimer's Disease and Related Dementias and Accelerating Treatments and Improving Quality of Life for Amyotrophic Lateral Sclerosis. She earned her master of science in global health at Georgetown University. She also has a B.A. in international relations and political science from Virginia Wesleyan University.

Bradford Chaney is a senior program officer with the Committee on National Statistics at the National Academies of Sciences, Engineering, and Medicine. Previously he was a senior study director at Westat. Dr. Chaney received his Ph.D. in political science from the University of Rochester.

Alexandra McKay is a research associate in the National Academies of Sciences, Engineering, and Medicine's Center for Health, People, and Places. While at the National Academies she has contributed to multiple consensus studies concerning environmental health, including Guidance on PFAS Testing and Health Outcomes, the Reassessment of the Department of Veterans Affairs Airborne Hazards and Open Burn Pit Registry, the Review of the Department of Veterans Affairs Presumption Decision Process, the Public Health Consequences of Changes in the Cannabis Policy Landscape, the Feasibility Assessment of Veteran Health Effects of Manhattan Project (1942–1947) Related Waste, and Clinical Follow-Up and Care for Those Impacted by the JP-5 Releases at Red Hill. Ms. McKay has also supported other convening activities, including Children's Environmental Health: A Workshop on Future Priorities for Environmental Health Sciences and several other activities. She has also worked for the National Park Service as an interpretation ranger, concentrating on science education and public engagement. She graduated from Yale University, where she received her M.A. in archaeological studies.

Lydia Teferra was a research associate at the National Academies. Ms. Teferra was a staff member on the Roundtable on Genomics and Precision Health and the Forum on Regenerative Medicine at the Academies. Prior to her time at the National Academies, Ms. Teferra interned and volunteered for local nonprofit organizations addressing a number of public health issues. She graduated from Northwestern University in 2020 with a B.A. in psychology and global health.

Appendix D
Disclosure of Unavoidable Conflict of Interest

The conflict-of-interest policy of the National Academies of Sciences, Engineering, and Medicine (https://www.nationalacademies.org/about/institutional-policies-and-procedures/conflict-of-interest-policies-and-procedures) prohibits the appointment of an individual to a committee like the one that authored this Consensus Study Report if the individual has a conflict of interest that is relevant to the task to be performed. An exception to this prohibition is permitted only if the National Academies determine that the conflict is unavoidable and the conflict is promptly and publicly disclosed.

When the committee that authored this report was established, a determination of whether there was a conflict of interest was made for each committee member, given the individual's circumstances and the task being undertaken by the committee. A determination that an individual has a conflict of interest is not an assessment of that individual's actual behavior or character or ability to act objectively despite the conflicting interest.

Mr. David Space was determined to have a conflict of interest because of stock holdings held through December 28, 2025, attributable to his past employment with The Boeing Company, an aircraft manufacturer.

The National Academies determined that the experience and expertise of the individual was needed for the committee to accomplish the task for which it was established. The National Academies could not find another available individual with the equivalent experience and expertise who did not have a conflict of interest. Therefore, the National Academies concluded that the conflict was unavoidable and publicly disclosed it on its website (www.nationalacademies.org).