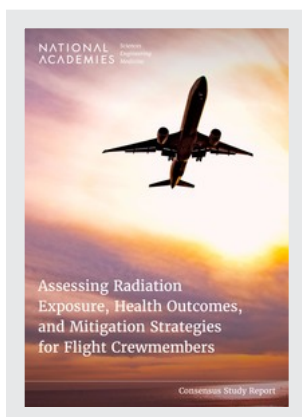


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Assessing Radiation Exposure, Health Outcomes, and Mitigation Strategies for Flight Crewmembers (2026)

DETAILS

232 pages | 7 x 10 | PAPERBACK

ISBN 978-0-309-59996-2 | DOI 10.17226/29261

CONTRIBUTORS

Daniel J. Mulrow and Jonathan M. Samet, Editors; Committee on Assessing Radiation Exposure, Health Outcomes, and Mitigation Strategies for Flight Crewmembers; Center for Health, People, and Places; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

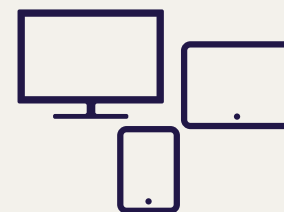
National Academies of Sciences, Engineering, and Medicine. 2026. *Assessing Radiation Exposure, Health Outcomes, and Mitigation Strategies for Flight Crewmembers*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/29261>.

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Assessing Radiation Exposure, Health Outcomes, and Mitigation Strategies for Flight Crewmembers

Daniel J. Mulrow and Jonathan M. Samet,
Editors

Committee on Assessing Radiation
Exposure, Health Outcomes, and
Mitigation Strategies for Flight
Crewmembers

Biomedical and Health Sciences
Program Area

Center for Health, People, and Places

Consensus Study Report

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NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

This study was supported by a contract number 6973GH-25-T-00001 (NAS AWD-002572) between the National Academy of Sciences and Department of Transportation/Federal Aviation Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project.

International Standard Book Number-13: 978-0-309-59996-2

Library of Congress Control Number: 2026945884

Digital Object Identifier: <https://doi.org/10.17226/29261>

This publication is available from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242; <https://nap.nationalacademies.org>.

The manufacturer's authorized representative in the European Union for product safety is Authorised Rep Compliance Ltd., Ground Floor, 71 Lower Baggot Street, Dublin D02 P593 Ireland; www.arccompliance.com.

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Printed in the United States of America.

Suggested citation: National Academies of Sciences, Engineering, and Medicine. 2026. *Assessing Radiation Exposure, Health Outcomes, and Mitigation Strategies for Flight Crewmembers*. Washington, DC: National Academies Press. <https://doi.org/10.17226/29261>.

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**COMMITTEE ON ASSESSING RADIATION
EXPOSURE, HEALTH OUTCOMES, AND MITIGATION
STRATEGIES FOR FLIGHT CREWMEMBERS**

JONATHAN M. SAMET (NAM) (*Chair*), Professor and Former Dean, Colorado School of Public Health, University of Colorado, Aurora

AMIR A. BAHADORI, Professor, Alan Levin Department of Mechanical and Nuclear Engineering, Kansas State University, Manhattan, Kansas

THOMAS A. BURKE, Professor Emeritus and Director Emeritus, Johns Hopkins Risk Sciences and Public Policy Institute, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland

CASEY I. CANFIELD, Associate Professor, Missouri University of Science and Technology, Rolla, Missouri

SARAH S. COHEN, Director of Public Health Research, DLH, LLC, Durham, North Carolina

MARDI CRANE-GODREAU, Independent Research Scientist, Author, and Assistant Editor at *Frontiers in Public Health*, Arlington, Vermont

LINDSAY S. FENWICK, Consultant (retired), Incline Village, Nevada

HEIDI A. HANSON, Senior Scientist and Group Lead of Biostatistics and Biomedical Informatics, Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Adjunct Assistant Professor at University of Utah, Salt Lake City, Utah

BENJAMIN W. MCGEE, Assistant Director of Radiation Safety, Department of Environmental Safety, Sustainability and Risk, University of Maryland, College Park

CHRISTOPHER J. MERTENS, Senior Research Physicist, Space Radiation Group, NASA Langley Research Center, Hampton, Virginia

CHRISTOPHER SCHEIBLER, Chief Flight Surgeon, United States Air Force; Assistant Professor, Uniformed Services University of the Health Sciences, Department of Preventive Medicine and Biostatistics, Bethesda, Maryland; Affiliated Research Scientist, Harvard School of Public Health, Department of Environmental Health, Cambridge, Massachusetts

Study Staff

DANIEL J. MULROW, Study Director

REBECCA A. ENGLISH, Senior Program Officer

NICHOLAS A. MURDOCK, Associate Program Officer (*as of April 1, 2026*)

MADELINE L. JENSEN, Research Associate (*as of October 31, 2025*)

LYDIA TEFERRA, Research Associate (*until October 24, 2025*)

DARLENE GROS, Senior Program Assistant

REBECCA MORGAN, Senior Research Librarian and Team Lead Research Services

LAURA D. LLANOS, Financial Business Partner

CLARE STROUD, Senior Program Director, Biomedical and Health Sciences Program Area

CHARLES D. FERGUSON, Senior Board Director, Nuclear and Radiation Studies Board and Board on Chemical Sciences and Technology (*until December 31, 2025*)

THOMAS MENZIES, Senior Board/Program Director, Consensus and Advisory Studies Division

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.

We thank the following individuals for their review of this report:

ANN BOSTROM, University of Washington

STEPHEN J. CHANOCK (NAM), National Cancer Institute

JOHN-PAUL CLARKE (NAE), The University of Texas at Austin

LAWRENCE DAUER, Memorial Sloan Kettering Cancer Center

SHAHEEN DEWJI, Georgia Institute of Technology

CAPTAIN RONDEAU FLYNN, Allied Pilots Association

MICHAEL MCCALL, PCAire

MARC NICHOLS, DLA Piper

R. JULIAN PRESTON, Environmental Protection Agency

MARY SCHUBAUER-BERIGAN, International Agency for Research on
Cancer

WARREN S. SILBERMAN, Aerospace Medical Association

CHARLES R. WIRA, Dartmouth Medical School

RICHARD D. WOOD (NAS), The University of Texas MD Anderson Cancer
Center

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 **LINDA H. CLEVER (NAM)**, California Pacific Medical Center, and **GAYLE WOLOSCHAK**, Northwestern University Feinberg School of Medicine. 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.

Acknowledgments

This study would not have been possible without the cooperation of many individuals and organizations who assisted with the study's task.

The committee wishes to acknowledge the U.S. Department of Transportation for sponsoring this study. The committee also wishes to acknowledge Federal Aviation Administration (FAA) staff and contractors who provided guidance, expertise, and support to the study: Anthony Tvaryanas, Aerospace Medical Research Division manager, Civil Aerospace Medical Institute (CAMI); Kyle Copeland, health physicist and team coordinator for the Medical Research Team, CAMI; Stacey Zinke-McKee, branch manager, Human Protection and Survival Research Laboratory, CAMI; Hammad Baig, section manager, Life Science Research, CAMI; and Amie A. Simmons, research project manager, Chickasaw Health Consulting, contractor to the FAA Aerospace Medical Research Division. The committee is grateful to the many experts who presented and provided materials during its information-gathering sessions. The committee wishes to acknowledge the following individuals (in order of presentation across sessions): Rondeau Flynn, Allied Pilots Association; Judith Anderson, Association of Flight Attendants-CWA; Lori Vitto Glattly and Hayley Brewer, Association of Professional Flight Attendants; Diego Garcia, Aerospace Medical Association; Zac Dohnal, Air Canada; Francis Heil, Airlines for America; Renaud Fenster, Transport Workers Union (TWU) Local 579; Michael Massoni, TWU Local 556; Marissa Mianzo, Southwest Airlines; Todd Moore, Air Line Pilots Association, International; Alex Schroeder, American Airlines; Brent Weisner, Southwest Airlines Pilots Association; Michael McCall, PCAire; W. Kent Tobiska, Space Environment Technologies; Eric Benton, Oklahoma State University; Les Braby, Texas A&M University; Katherine Monson and Scott McIntosh, Hale SWx; and David A. Savitz, Brown University School of Public Health.

The committee also wishes to acknowledge Francis Heil, Airlines for America, for recommending speakers, providing additional contacts, and coordinating responses to a committee questionnaire to members of Airlines for America.

The committee wishes to acknowledge consultants Meghan Buran and Kevin Naaman, for their support, particularly for the literature assessment and creation of the forest plots in this report, respectively, and Roberta Wedge for her technical support.

The committee also wishes to acknowledge the many individuals, too numerous to list, who assisted with responses to information requests, provided materials for consideration, and shared expertise that informed the committee's information-gathering activities.

The committee is grateful to the staff of the National Academies of Sciences, Engineering, and Medicine (the National Academies) for organizing and facilitating this study. Daniel Mulrow, study director, oversaw the information-gathering process and guided the report through writing, review, and publication. Rebecca English, senior program officer, provided oversight and support throughout the study. Madeline Jensen, research associate, assisted with information and data collection and figure preparation. Lydia Teferra, research associate, assisted with initial background research. Nicholas Murdock, associate program officer, for fact checking of the final report. Darlene Gros, senior program assistant, provided administrative support, including meeting coordination and assistance with report production. The committee also wishes to acknowledge Rebecca Morgan, National Academies Research Center, for performing the literature search and for developing methods and protocols for the literature review.

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Preface

This report addresses the ubiquitous and unavoidable exposure of aircraft flight crew—those in the cockpit and those in the cabin—to naturally occurring galactic cosmic radiation and solar energetic particles. Ionizing radiation is a known cause of cancer and other adverse health outcomes, but the risks of the types of radiation received in-flight are not well characterized. The aggregate doses received during the hundreds to thousands of hours in-flight accumulate over a career may raise concern about increased risk for cancer and other adverse consequences for the health of flight crew. The Federal Aviation Administration (FAA), which has jurisdiction over the health and safety of cockpit crew and flight attendants, has acknowledged that radiation exposure occurs and in response has provided recommendations but no requirements regarding their exposure. This report responds to the need to address radiation safety for flight crew.

This report from the National Academies of Sciences, Engineering, and Medicine, called for in the FAA Reauthorization Act of 2024, provides a description of the radiation received by flight crew, what is known about its consequences, and an approach for moving forward in investigating and mitigating risks. The committee brought together experts spanning airline operations, computational modeling, cancer epidemiology, health physics, occupational health and safety, risk communication, risk assessment, radiation epidemiology, and radiation risk mitigation.

In completing its work, the committee conducted a review of the epidemiologic literature on cancer and reproductive outcomes among pilots and flight attendants, evaluated publicly available computational models used to estimate radiation dose in flight environments, and considered representative flight routes to estimate cumulative occupational exposures over a career. The committee also examined approaches to monitoring and mitigating radiation exposure in aviation settings. Its deliberations were informed by engagement with academic researchers, aircraft manufacturers, federal agencies, instrument developers, labor organizations, and U.S. commercial airlines,

which provided important technical and operational context for interpreting the available evidence.

The committee benefited from the insights and experiences shared by numerous representatives of flight crew organizations, who provided valuable perspectives on occupational conditions and concerns. Pilots and flight attendants are concerned about this exposure. The committee also acknowledges the contributions of Airlines for America, the trade association representing major North American airlines, in supporting information gathering for this study. In addition, the committee recognizes the sustained efforts of researchers working to characterize the radiation environment at aviation altitudes, to develop and refine computational models for estimating radiation exposure, and to better understand the potential associations between radiation exposure and adverse health outcomes. These contributions have been essential to advancing knowledge in this field.

The committee recognizes the complexity of this topic and the importance of continued research on coordination about, and attention to occupational radiation exposure in aviation. It urges coordinated action led by the FAA and involving other relevant organizations.

Jonathan M. Samet, *Chair*
Committee on Assessing Radiation Exposure, Health
Outcomes, and Mitigation Strategies for Flight Crewmembers
March 2026

Acronyms and Abbreviations

A4A	Airlines for America
ACS	American Community Survey
ALARA	“as low as reasonably achievable”
APA	Allied Pilots Association
APFA	Association of Professional Flight Attendants
ARMAS	Automated Radiation Measurements for Aerospace Safety
AU	astronomical unit
Avg	average
AVIDOS	Aviation Dosimetry (software)
BEIR	biological effects of ionizing radiation
BLS	Bureau of Labor Statistics
BTS	Bureau of Transportation Statistics
CAMI	Civil Aerospace Medical Institute
CCMC	Community Coordinated Modeling Center
CDC	Centers for Disease Control and Prevention
CFR	Code of Federal Regulations
CI	confidence interval
CME	coronal mass ejection
CMS	Centers for Medicare & Medicaid Services
CNS	central nervous system
CV	coefficient of variation
DDREF	dose and dose-rate effectiveness factor
DFW	Dallas–Fort Worth International Airport
DOE	U.S. Department of Energy

EPA	U.S. Environmental Protection Agency
ERR	excess relative risk
EU	European Union
FAA	Federal Aviation Administration
GCR	galactic cosmic radiation
GSD	geometric standard deviation
Gy	gray (unit of measure)
HKG	Hong Kong International Airport
hr	hour
HWE	healthy worker effect
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization (a United Nations agency)
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
IGRF	International Geomagnetic Reference Field
INWORKS	International Nuclear Workers Study
JFK	John F. Kennedy International Airport
keV	kiloelectron volt
km	kilometer
LAR	lifetime attributable risk
LAX	Los Angeles International Airport
LHR	London Heathrow Airport
LSS	Life Span Study
LTFU	loss to follow-up
Max	maximum
MeV	megaelectron volt
MHIRJ	
Aviation	MHI RJ Aviation (U.S.), provider of regional aircraft engineering, maintenance, and support services
MIA	Miami International Airport
μSv	microsievert
MOU	memorandum of understanding
MPS	Million Person Study
mSv	millisievert

NAIRAS	Nowcast of Atmospheric Ionizing Radiation for Aviation Safety
NASA	National Aeronautics and Space Administration
NAT	North Atlantic Tracks (officially North Atlantic Organised Track System [NAT-OTS])
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
NOAA	National Oceanic and Atmospheric Administration
NRC	Nuclear Regulatory Commission
OR	odds ratio
OSHA	Occupational Safety and Health Administration
PANDOCA	Professional Aviation Dose Calculator
PBS	preferential bidding system
PCAire	Predictive Code for Aircrew Radiation Exposure
pfu	particle flux unit
PIC	pilot in command
PMR	proportional mortality ratio
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RAA	Regional Airline Association
Rad-X	NASA Radiation Dosimetry Experiment (high-altitude balloon mission)
RoR	run-on-request
RR	relative risk
SA	spontaneous abortion
SC	solar cycle (progression)
SEER	Surveillance, Epidemiology, and End Results program
SEP	solar energetic particle
SIEVERT	French system for evaluating exposure to cosmic radiation in air transport (Système Informatisé d’Evaluation par Vol de l’Exposition aux Rayonnements cosmiques dans les Transports aériens)
SIR	standardized incidence ratio
SMR	standardized mortality ratio
SMS	safety management system
SoT	Statement of Task
SPR	standardized prevalence ratio
Sv	sievert
TWU	Transport Workers Union
UV	ultraviolet radiation types A, B, and C; a form of nonionizing radiation
yr	year

Synopsis

U.S. commercial aviation flight crew are routinely exposed to cosmic ionizing radiation—an elevated form of natural background radiation, consisting of continuously occurring galactic cosmic radiation and sporadic solar energetic particle events, inherent to high-altitude flight—yet the approximately 289,000 affected workers are not afforded regulatory protections comparable to those of other radiation-exposed occupations. Ionizing radiation is known to cause certain cancers and other adverse health outcomes; however, epidemiologic evidence linking occupational exposure to specific health outcomes in flight crew remains limited. Although estimated annual doses for flight crew generally fall below regulatory limits established for other radiation-exposed workers, significant uncertainties persist regarding long-term health risks and total occupational doses received over an entire career. These uncertainties stem from limitations in existing studies, including inadequate information on individual radiation doses and relatively small study populations.

To address this question, the U.S. Congress directed the Federal Aviation Administration (FAA) to sponsor a study by the National Academies of Sciences, Engineering, and Medicine. They assembled a multidisciplinary committee of experts to assess available evidence on health risks, evaluate computational models used to estimate in-flight radiation dose, examine flight paths and plausible worst-case exposure scenarios, determine the feasibility of future epidemiological studies, and recommend strategies for monitoring and assessing radiation exposure among flight crew.

A key message from this committee's report is that radiation exposure in aviation warrants attention as an occupational hazard. Estimated annual occupational doses for flight crew generally fall well below recommended limits; however, cumulative exposures over a career merit monitoring and tracking. Additionally, the tools for monitoring exposure and educating workers are already available but are not uniformly utilized or deployed.

Consistent with these conclusions, the committee recommends that the FAA exert its regulatory authority over ionizing radiation as an occupational exposure that requires oversight to ensure flight crewmember health and safety and improve the accessibility and usability of existing dose-estimation tools. In the near term, the FAA should require U.S. airlines to implement comprehensive radiation safety programs aligned with best practices for radiation protection, including integrating dose considerations into work practices, strengthening training and risk communication, and providing targeted protections for higher-risk groups such as pregnant crew members. Concurrently, interagency collaboration should enhance measurement efforts to support validation of exposure models. Over the longer term, the FAA should lead efforts to refine radiation exposure models, work with relevant agencies to establish a national dose tracking system for monitoring and research, and develop a coordinated research strategy to better understand long-term health risks. Together, these actions provide a practical pathway to improve awareness, monitoring, and management of radiation exposure in commercial aviation.

Summary¹

In the course of their work, flight crewmembers onboard commercial airlines are exposed to naturally occurring cosmic ionizing radiation, consisting of continuously occurring galactic cosmic radiation and sporadic solar energetic particle events. Ionizing radiation is known to cause certain cancers and other adverse health outcomes. However, significant questions and uncertainties remain about the radiation dose these crewmembers are exposed to and associated health impacts specific to this group. To address these questions and their implications, Section 322 of the Federal Aviation Administration (FAA) Reauthorization Act of 2024 directed the FAA to contract with the National Academies of Sciences, Engineering, and Medicine (the National Academies) to conduct an independent assessment of radiation exposure for flight crew.² This assessment considers computational models to estimate such exposure, the state of the evidence on associated health outcomes, the potential for epidemiologic³ studies to be informative, and potential radiation dose mitigation strategies for flight crew onboard aircraft operated under Part 121 of Title 14, Code of Federal

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

² In the same Act, Congress mandated that the FAA contract with the National Academies for two additional health and safety topics—Section 323 on impacts of temperature in aircraft cabins and Section 362 on cabin air safety. These two studies are independent of the study on radiation exposure of flight crew.

³ Epidemiology studies ways that disease and health are spread among groups of people and what factors—such as environments and exposures—are linked to specific health effects.

Regulations, which governs scheduled commercial air carrier operations conducted by U.S. airlines.⁴

In 2023, the U.S. commercial aviation workforce employed approximately 289,000 flight crewmembers (pilots, flight engineers, and flight attendants). Employment in these occupations is projected to grow in the coming decade, reflecting sustained demand for air travel and continued expansion of commercial aviation operations. Under federal regulations, airline pilots may fly up to 1,000 hours per year, with many reaching 700–900 flight hours annually. Flight attendants similarly spend substantial time in flight over the course of a year, with cumulative airborne hours varying by route structure, seniority, and airline scheduling practices. In this report, the combined cohort of pilots and flight attendants is termed “flight crew,” with distinctions made between cockpit crew and flight attendants as appropriate. Members of the general public were not the focus of this study; the committee acknowledges that all individuals are exposed to radiation during air travel, but cumulative doses for members of the public are generally much lower, than those experienced by flight crew owing to less frequent travel.

As an inherent condition of aviation operations, flight crewmembers are routinely exposed to naturally occurring ionizing radiation from cosmic and solar sources. Cosmic radiation arises from two primary sources. One source is the continuously present galactic cosmic radiation (GCR), with origins outside the solar system and intensity varying with the 11-year solar cycle. The second source of cosmic radiation is solar energetic particle (SEP) events, which are rare, occurring three to four times during a given solar cycle, and are associated with violent eruptions on the Sun’s surface that last several hours to days.

These sources of radiation can be modeled to estimate in-flight exposure and translated into occupational dose for flight crewmembers under a range of operating conditions. To address its task, the committee reviewed epidemiologic studies on health outcomes linked to occupational radiation exposure among flight crew. It also conducted a cumulative dose assessment using available computational models. This integrated approach provides a basis for evaluating both the magnitude of exposure and the current state of evidence on associated health risks.

Together, these analyses inform considerations for designing future epidemiologic studies to better characterize health outcomes and the association with radiation exposure, as well as potential strategies for monitoring and mitigating radiation exposure among flight crew.

A key message from this report is that radiation exposure in aviation warrants attention as an occupational hazard. Estimated annual occupational doses for flight crew generally fall well below recommended limits (Conclusion 4-4); however, cumulative

⁴ Part 121 operators are FAA-certified air carriers and for the purposes of this report include only commercial, civilian aviation (e.g., large U.S. airlines and regional air carriers). Military aircraft are not included in the definition of Part 121 operators. While cargo carriers are included in the definition of Part 121 operators, radiation from cargo is out of scope for this report. However, the committee acknowledges radiation as a potential related occupational risk for flight crew for cargo carriers. This report will use the terminology “U.S.-based commercial airlines” or “U.S. airlines” in reference to large U.S. airlines and regional air carriers as Part 121 operators.

exposures over a career warrant monitoring and tracking (Conclusion 4-5). Additionally, the tools for monitoring exposure and educating workers are already available but are not uniformly used or deployed.

COMMITTEE CHARGE AND APPROACH

Based on a request from Congress, the Civil Aerospace Medical Institute of the FAA asked the National Academies to convene a committee to address four primary tasks: (1) assess the scientific literature on health outcomes potentially associated with in-flight exposure to GCR and SEP events; (2) evaluate computational models used to estimate in-flight radiation exposure, including conducting cumulative exposure assessments using multiple models; (3) consider how improved exposure characterization could inform epidemiologic study design; and (4) examine potential mitigation measures and strategies for monitoring, communication, and risk management. The full Statement of Task can be found in Chapter 1 (see Box 1-1; additional specific tasks are listed in Box 1-2).

The committee comprised 11 members with expertise in airline operations, computational modeling, cancer epidemiology, health physics, occupational health and safety risk communication, risk assessment, radiation epidemiology, and radiation risk mitigation. To address these tasks, the committee conducted a comprehensive review of epidemiologic literature on cancer and reproductive outcomes among pilots and flight attendants; evaluated four publicly available computational models used to estimate radiation dose in flight environments; identified bounding and representative flight routes to estimate cumulative occupational doses of flight crew spanning a career; and considered and proposed operational practices relevant to mitigation and monitoring for flight crew. Engagement with labor organizations, U.S. commercial airlines, aircraft manufacturers, federal agencies, instrument developers, and academic researchers informed the committee's deliberations and provided technical and operational context for interpreting the available evidence.

Although the committee evaluates potential risks to flight crew, providing recommendations on "acceptable" risk levels or regulatory policy concerning acceptable risk is beyond the Statement of Task. The committee considered radiation from natural sources only and did not evaluate worst-case scenarios related to nuclear accidents from materials onboard. Additionally, the committee only considered commercial aviation and did not consider military aviation. The report addresses impacts on human health only and does not examine radiation effects on aircraft electronics. In addition, the committee was not tasked with evaluating the FAA's recommended radiation dose limits for flight crew. Finally, the committee focused on ionizing radiation exposure and was not asked to evaluate ultraviolet (UV) (nonionizing) radiation exposure to flight crew and risks for developing malignant melanoma.

CONSIDERING THE EVIDENCE

The committee considered three primary categories of evidence: (1) occupational exposure context and regulatory framework (2) epidemiologic evidence on radiation in the commercial aviation environment and health outcomes, and (3) computational modeling of radiation dose and exposure scenarios. These lines of evidence provide the basis for the committee's conclusions regarding radiation exposure in the commercial aviation environment, associated health risks, and strategies for monitoring and risk management. The following sections describe the committee's major conclusions based on the evidence in these three categories.

Occupational Radiation Exposure for Flight Crewmembers

The committee concludes that flight crewmembers are occupationally exposed to ionizing radiation but are not afforded regulatory protections comparable to those for other radiation-exposed workers (Conclusion 2-1). Stakeholder input indicates that radiation exposure is inconsistently understood, communicated, and managed within U.S. commercial aviation.

While radiation exposure is recognized as an occupational risk for flight crew and the FAA has recommended dose limits, no clear process or systematic way exists for individual flight crewmembers to understand their accumulated dose relative to these limits.

Epidemiologic Evidence

Radiation and its risks to human health have been studied for many decades using experimental and epidemiologic approaches. Exposure to ionizing radiation is a known cause of cancer and other adverse health effects. Risks increase with the dose received, as demonstrated by studies of the atomic bomb survivors and other groups. The radiation dose is relatively small per flight but will accumulate over the course of a worker's career. Evidence linking occupational exposure among flight crewmembers to adverse health outcomes remains inconclusive, in part owing to uncertainty in cumulative dose and limited statistical power at low exposure levels. The committee did find that female flight crewmembers are at increased risk for breast cancer, but the causal factors are uncertain (Conclusion 3-2). For other cancer sites assessed—prostate, brain, and thyroid—and for lymphomas and leukemias, the evidence was mixed and inconclusive (Conclusion 3-3). The committee also reviewed the literature regarding reproductive outcomes and concludes that the available observational studies do not provide adequate evidence on whether flight crew radiation exposure increases risk (Conclusion 3-4).

Models for Estimating Radiation Dose for Flight Crewmembers

The committee was asked to evaluate existing computational models, which may be used to estimate radiation dose received by flight crew, and health risk models.

These computational approaches provide the basis for estimating radiation exposure to flight crew, informing health risk assessments, and supporting operational and regulatory decision-making related to exposure management. Under routine GCR conditions, the computational models evaluated by the committee generally produce comparable dose estimates. However, important differences emerge in the treatment of SEP events. Publicly available aviation radiation measurements allow for the use of these models for general GCR conditions but introduce larger uncertainties for doses accrued during SEP events. Sustained, coordinated measurement and validation efforts are needed to improve model performance and dose estimates (Conclusion 4-1). Variability in the representation of particle energy spectra, geomagnetic storm effects, model inputs, and the calculation of effective dose, including the dose coefficients applied, contributes to divergence in estimated effective dose, particularly for high-latitude and transpolar routes and during periods of elevated solar activity (Conclusion 4-2).

The committee was also asked to apply the models for selected flight paths to develop an understanding of the plausible worst-case radiation exposure for flight crewmembers over their careers. Based on this analysis, the committee found that dose from a flight depends on dose rate across the time spent in the air while on a particular route. While latitudes closest to the magnetic poles are associated with the highest estimated dose rates, routes that spend longer durations in near polar latitudes may result in higher estimated doses than polar routes with shorter durations (Conclusion 4-3). Additionally, pregnant flight crewmembers are the most likely population to potentially exceed dose limits established by the International Commission on Radiological Protection (ICRP) and recommended by the FAA (Conclusion 4-6). If a pregnant worker is caught in a solar storm, the conceptus could receive a dose on the order of several hundreds of Sv⁵ in a single flight (with the recommended limit of 1 mSv during the entire pregnancy).

ACTION AREAS

The committee identifies four areas for action: (1) consider radiation as a regulated occupational exposure for flight crewmembers, (2) require airlines to establish radiation safety programs, (3) advance radiation dose models, and (4) develop dose tracking and research infrastructure.

Consider Radiation as a Regulated Occupational Exposure for Flight Crewmembers

From a regulatory standpoint, risk management and mitigation measures for occupational exposures are established through a framework that evaluates the magnitude and duration of exposure relative to health-based standards or permissible limits. When exposures exceed or have the potential to exceed these benchmarks, regulators require controls designed to reduce risk to acceptable levels. These controls are typically

⁵ The unit for effective dose is the sievert (Sv). Most flights deliver on the order of microsieverts (μ Sv), and many dose limits across occupations are expressed in terms of millisieverts (mSv).

structured according to established principles, such as the hierarchy of controls, to ensure that risks are systematically and proportionately managed.

The FAA first issued guidance recognizing radiation exposure for flight crewmembers in 1990, with the most recent revision being published in 2014. In this advisory circular, the FAA recommends dose limits determined by ICRP. The committee also considered the actions of the FAA compared to those of relevant agencies with jurisdiction over other occupational radiation workers. For example, occupational safety and health for flight crew is shared with the Occupational Safety and Health Administration in certain areas. The committee acknowledges the inherent difference between regulations for workplace safety and health related to manmade hazards (e.g., aircraft performance; safety equipment for emergencies) and potential regulations involving naturally occurring exposures such as GCR.

The comparisons of approaches deployed by federal agencies for radiation-exposed workers reveal multiple gaps (see Table 2-2 in Chapter 2 for full descriptions). First, flight crew are the only occupational group listed without legally enforceable dose limits, despite routine exposure to cosmic radiation. Second, no requirement exists to measure or track individual radiation dose for flight crew. Third, flight crew working across airlines or over decades may accumulate significant dose with no centralized record or cap. These gaps highlight the need to recognize radiation as an occupational exposure subject to oversight to ensure flight crewmember health and safety.

Addressing these gaps will require strengthening the technical and operational foundation for oversight, including improving accessibility and usability of computational tools/models to estimate radiation dose and establishing mechanisms to support consistent exposure management. These elements form the basis for a comprehensive approach to a radiation safety program in commercial aviation.

Require Airlines to Establish Radiation Safety Programs

The committee concludes that flight crew are not covered by a radiation safety program that incorporates systematic dose tracking, structured risk communication, or formal training regarding radiation exposure (Conclusion 6-1). As a result, flight crew are not positioned to make fully informed decisions about their occupational exposure or about the routes they fly, including decisions that may be particularly important during pregnancy.

The committee finds that communication, education, and practical tools for radiation exposure tracking are currently inadequate for flight crew employed by U.S. commercial airlines. Flight crew currently bear responsibility for determining and tracking their own radiation exposure, relying on tools that are difficult to use and without structured training or convenient tracking systems (Conclusion 2-2). These findings highlight the importance of improving the usability and accessibility of existing dose estimation tools to support individual awareness and short-term exposure management.

The absence of a comprehensive radiation safety framework for flight crew stands in contrast to established practices for other radiation-exposed occupational groups. Without enforceable requirements for monitoring, reporting, and education, risk

management remains inconsistent and unaccountable. To address these deficiencies, a set of requirements and implementation protocols will need to be created for airlines to satisfy in their development of a radiation safety program that integrates dose monitoring, operational decision tools, training and risk communication, and accommodations for higher-risk populations, particularly pregnant flight crew.

Overall, the committee concludes that meaningful risk management for aviation radiation exposure requires a shift from informal individual-level tracking to a structured, enforceable system grounded in best practices. The committee frames these measures as foundational elements of a comprehensive radiation safety program capable of supporting informed decision-making, regulatory accountability, and long-term worker protection.

Advance Radiation Dose Models

The aviation radiation environment is complex and composed of multiple particle types, including neutrons, which contribute disproportionately to biologically relevant dose. No single detector can independently characterize all biologically significant components of this environment. Additionally, because routine onboard aircraft dosimetry is not currently conducted by U.S. airlines, the computational models developed both domestically and internationally to estimate the radiation dose in flight environments, if implemented correctly, could serve as the primary means of dose estimation. As a result, computational modeling plays a central role in estimating occupational doses for flight crew.

Chapter 4 compares aspects of the main models used to estimate occupational dose. The committee concludes that the current body of publicly available, systematically collected aviation radiation measurement data is insufficient to fully characterize model uncertainties and biases, particularly for SEP events. Although past flight campaigns, which measured radiation environments at various altitudes, provide important validation benchmarks, sustained and coordinated measurement efforts are necessary to improve model performance and support more accurate dose estimation across the range of operational conditions experienced by flight crew, including different altitudes, latitudes, and solar activity levels. Addressing these limitations will require sustained, coordinated measurement efforts to validate models, particularly for SEP events.

Numerous models for estimating occupational dose are publicly available. The committee chose to perform its analysis using four models: AVIDOS, CARI-7A, NAIRAS, and SIEVERT (see Chapter 4 for more information on individual models). The committee ultimately chose a broad sample of publicly available codes that an individual might encounter to calculate a dose from a flight or that researchers have used in published studies providing dose estimates.

In addition, a systematic comparison of models under realistic operating conditions is needed to better characterize uncertainty and improve dose estimation, particularly for high-latitude routes and SEP events.

An ensemble modeling approach that combines multiple individual models in dose prediction offers a structured method for reducing model-specific bias and characterizing

uncertainty more transparently. Such an approach would help identify conditions under which models converge and diverge as well as what uncertainty bounds should accompany reported dose estimates. This information is important not only for operational decision-making during SEP events but also for communication with flight crew and for regulatory frameworks that may rely on modeled dose estimates.

Overall, the committee found that radiation modeling tools are sufficiently developed to support occupational dose estimation under routine conditions. However, strengthened validation, improved uncertainty characterization, and sustained inter-agency collaboration are necessary to enhance confidence in high-exposure scenarios and to support consistent and credible regulatory implementation. Transparent communication of model uncertainty is particularly important for informing flight crew, regulators, and policymakers about what is known, what remains uncertain, and how uncertainty should inform risk management decisions rather than delay protective action.

Develop Dose Tracking and Research Infrastructure

As covered in Chapter 3, the committee conducted literature searches in PubMed and Scopus to identify and evaluate the evidence on in-flight radiation exposure and associated health outcomes. An initial appraisal of systematic reviews was used to characterize the scope and strength of literature. Based on this assessment, the committee determined that cancer and reproductive outcomes were the categories supported by sufficient original research, appropriate study designs, and reported risk estimates to warrant detailed evaluation.

For cancer outcomes, including breast cancer and cancers of the prostate, brain, and thyroid, as well as lymphomas and leukemias, the evidence regarding GCR exposure and flight crew occupation is mixed or inconclusive, and important uncertainties remain (Conclusions 3-2 and 3-3). While occupational risk of malignant melanoma among cockpit crew is well documented, this is attributed to UV radiation (Conclusion 3-1). Evidence was also insufficient to determine whether cosmic radiation exposure is associated with adverse reproductive outcomes, highlighting the need for a focused research agenda to address these critical gaps (Conclusion 3-4).

However, this lack of conclusive association between cosmic radiation and specific health outcomes reflects major limitations in how exposure and dose have been determined in past studies. Without an established program to monitor and track dose among flight crew, most of the published literature uses occupational surrogates for exposure. The committee concludes that appropriately designed and adequately powered epidemiologic studies are needed to address current evidence gaps (Conclusion 5-1). Establishing a national, standardized, centralized dose repository could substantially improve the timeliness and coordination of research, particularly if integrated with longitudinal health records (Conclusion 5-2). Addressing these limitations requires the development of a centralized, standardized dose tracking system and a coordinated research strategy to support well-designed epidemiologic studies.

The committee carried out calculations of statistical power of potential epidemiological studies, considering the flight crew workforce size and assuming risks

comparable to those generated by health risk models based on the Life Span Study of atomic bomb survivors. The committee concludes that informative epidemiologic studies are feasible for female breast cancer, lung cancer, and potentially other outcomes based on available workforce size and statistical power (Conclusion 5-3). As part of a strategic research plan, pooling existing retrospective cohort studies across airlines, occupational groups, or existing datasets could be done now to improve statistical power for an epidemiologic study that illuminates associations between radiation exposure and specific health outcomes among flight crew. Prospectively, the flight crew workforce is large enough to enable the necessary statistical power to design a study that would address risks for certain radiation-related cancers (Conclusion 5-4).

Overall, while major gaps and limitations remain in the current epidemiologic literature to determine the association between occupational exposure to radiation and adverse health outcomes for flight crew, emerging tools enable large pooled multi-cohort analyses to begin to address this question immediately. Additionally, with proper exposure and health tracking, ideally through a surveillance program, the data needed for future epidemiologic studies could be centralized and standardized, facilitating research in this area.

PATH FORWARD

Collectively, the report finds that flight crew are occupationally exposed to radiation without a comprehensive, enforceable regulatory framework comparable to that for other radiation-exposed workers (Chapter 2). While certain health risks are established, evidence linking cosmic radiation to specific cancers and reproductive outcomes remains limited or inconclusive (Chapter 3). Improvements in dose modeling, sustained measurement efforts to characterize the radiation environment in-flight, centralized occupational dose tracking, and coordinated epidemiologic research are necessary to reduce uncertainty and support risk-informed decision-making (Chapters 4 and 5). The committee ultimately calls for regulatory action, structured monitoring, enhanced worker education, and a radiation safety program to provide consistency, accountability, and informed risk management for flight crewmembers (Chapter 6). Finally, the committee presents its proposed sequencing of recommendations in a path forward (Chapter 7). A coordinated, phased approach led by the FAA, in collaboration with federal partners, industry stakeholders, and flight crew and their labor organizations, will be necessary to implement these actions. The recommendations in this report are actionable and can be implemented to build a comprehensive radiation safety framework.

Recommendation 7-1: The Federal Aviation Administration should take the lead in implementing a collaborative strategy to develop the requirements and the approach for U.S. airlines to implement radiation safety programs.

This recommendation establishes the basis for moving forward and sequencing the committee's recommendations; it also clarifies the role of the FAA in defining requirements to enable implementation by airlines and other stakeholders. The following recommendations are sequenced for action, moving from immediate to longer term.

Sequenced Implementation of Recommendations

Immediate

Recommendation 2-1: The Federal Aviation Administration should exert its regulatory authority over ionizing radiation as an occupational exposure that requires oversight to ensure flight crewmember health and safety.

This action is foundational and enables implementation of all other recommendations.

Recommendation 2-2: The Federal Aviation Administration should improve the usability of the CARI model for estimating radiation dose by developing a user-friendly, web-based application to increase accessibility to dose estimation for flight crew.

This action is a feasible first step as well as interim approach to enhance awareness and provide individual dose tracking while more comprehensive systems are developed. Tracking radiation dose would not be left up to individuals in the long-term.

Shorter-Term

To support the FAA's regulatory authority over radiation exposure, the following actions are recommended in the short-term.

Recommendation 6-1: The Federal Aviation Administration (FAA) should exert its regulatory authority and require U.S. commercial airlines to implement a radiation safety program for flight crewmembers that follows best practices for occupationally exposed workers. FAA should create a set of requirements and implementation protocol for airlines to satisfy in their development of the required radiation safety program. FAA should include the following elements in the agency's set of requirements and implementation protocol:

- **Methods for characterizing radiation conditions in an aircraft (i.e., modeling, monitoring, and dosimetry).**
- **Evidence-based and expert-led training and education programs to inform flight crew about their radiation exposure and potential associated health risks. The training and education program should include specific content about radiation exposure during pregnancy and potential adverse consequences across a life course. This includes a declared pregnant worker process as is done in radiation safety programs for other occupationally exposed workers.**
- **Incorporating radiation exposure considerations into the scheduling systems for flight attendants and pilots. For this purpose, airlines and labor organizations should work together to incorporate solutions for individuals seeking to lower their radiation exposure (e.g., pregnant flight crew), respecting seniority in the scheduling system to the extent possible.**

Concurrently the FAA should collaborate with other agencies to improve radiation dose estimation models and establish a centralized repository for tracking doses.

Recommendation 4-1: The Federal Aviation Administration, in conjunction with the National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration, should collaborate on sustained measurement campaigns with dedicated resources to better characterize radiation environments at flight altitude and validate models, especially for solar energetic particles.

Recommendation 5-1: The Federal Aviation Administration should work with appropriate agencies, such as the Center for Disease Control and Prevention/National Institute for Occupational Safety and Health, to establish a dose-tracking system for flight crew. Such a system would enable U.S. airlines and individual flight crew to monitor doses and to make decisions to manage them. The system would also facilitate epidemiologic research by providing standardized dose information for study participants. Periodic matches of the dose tracking data with health and mortality databases would support assessment of the population health of flight crew.

Longer-Term

While the actions described above should be undertaken promptly, the following recommendations address the longer-term and include efforts to improve computational models for estimating flight crewmember radiation doses and to strengthen the design of studies examining associations between occupational radiation exposure and health outcomes.

Recommendation 4-2: The Federal Aviation Administration, in collaboration with other organizations that develop aviation radiation exposure models, should systematically evaluate computational models under realistic operating conditions to better characterize their uncertainties and biases. This evaluation should establish a methodology for using an ensemble of models to assess variability and improve estimates of flight crew radiation exposure, particularly for transpolar routes and during solar energetic particle events.

Recommendation 5-2: In parallel with developing a dose-tracking system, a strategic research plan for future epidemiologic research on the association between occupational radiation exposure and health outcomes for flight crew should be elaborated by the Federal Aviation Administration and other federal agencies in collaboration with industry and flight crew partners.

1

Introduction

STUDY ORIGIN AND SCOPE

The Federal Aviation Administration (FAA) is the U.S. government agency, within the U.S. Department of Transportation, responsible for regulating and overseeing all aspects of civil aviation, including aircraft safety certification, air traffic control operations, pilot and maintenance personnel licensing, airport infrastructure standards, and the development and enforcement of regulations to ensure the safety and efficiency of the National Airspace System.¹ The FAA Reauthorization Act of 2024, Section 322, directed the agency to contract with the National Academies of Sciences, Engineering, and Medicine (the National Academies) to conduct an independent assessment of radiation exposure, associated health outcomes, and potential mitigation strategies for flight crew onboard various aircraft types operated under Part 121 of Title 14, Code of Federal Regulations.^{2,3}

This chapter begins by providing the context of and background for this assessment, with an overview of the relevant policies for radiation exposure and flight crew, a primer on cosmic and solar radiation relevant to flight, a link between radiation exposure and

¹ The National Airspace System is a complex network of airspace, navigation facilities, and airports in the United States.

² In the same Act, Congress mandated that the FAA contract with the National Academies for two additional health and safety topics—Section 323 on impacts of temperature in aircraft cabins and Section 362 on cabin air safety. These two studies are independent of the study on radiation exposure of flight crew.

³ Part 121 operators are FAA-certified air carriers and for the purposes of this report include only commercial, civilian aviation (e.g., large U.S. airlines and regional air carriers). Military aircraft are not included in the definition of Part 121 operators. While cargo carriers are included in the definition of Part 121 operators, radiation from cargo is out of scope for this report. However, the committee acknowledges radiation as a potential related occupational risk for flight crew for cargo carriers. This report will use the terminology “U.S.-based commercial airlines” or “U.S. airlines” in reference to large U.S. airlines and regional air carriers as Part 121 operators.

health outcomes, and an overview of the demographics of flight crewmembers. This introductory chapter covers the committee's Statement of Task (SoT) and additionally specified contractual tasks, as agreed upon with the FAA. It also describes the general approach taken by the committee to address the SoT and these additional items. This chapter ends with a description of the report's organization.

CONTEXT AND BACKGROUND

The following introductory sections provide an overview of the policy context for this study, radiation exposure during air travel, and flight crew demographics.

Policy Context

Radiation and its risks to human health have been studied for many decades using experimental and epidemiologic approaches⁴. Consequently, much is known about measurement of radiation exposure and the risks associated with different levels of exposure. Around the world, numerous evidence-based protective regulations and practices are in place for the many types of workers exposed to occupational radiation, such as nuclear power plant workers and astronauts, to name a few.

In the United States, flight crewmembers' specific radiation exposure limits have not been established, nor are their exposures monitored; however, the FAA provides information about radiation exposures to flight crew. For example, the FAA's Advisory Circular 120-61B, dated November 21, 2014, informs air carrier flight crew about in-flight ionizing radiation exposure. The circular provides resources for further guidance and training; identifies sources of exposure, such as cosmic radiation and solar storms; and details average annual doses for both the general U.S. population and flight crews, highlighting flight crews as the fourth most exposed occupational group. Recommended exposure limits in the circular are based on international and national guidelines, with specific protections outlined for pregnant flight crew. Tools to calculate individual flight dose are highlighted, as is the principle of "as low as reasonably achievable" (ALARA). ALARA requires that the net benefit of the exposure is maximized through an optimization process that considers economic and social factors in addition to technical ability to further reduce exposure.

Currently, the FAA recommends the adoption of the International Commission on Radiological Protection's (ICRP's) 5-year-averaged dose limit of 20 mSv⁵/year (2,000

⁴ Epidemiology studies ways that disease and health are spread among groups of people and what factors—such as environments and exposures—are linked to specific health effects.

⁵ The unit for effective dose is the sievert (Sv). Most flights deliver on the order of microsieverts (μ Sv), and many dose limits across occupations are expressed in terms of millisieverts (mSv).

1 Sv = 1,000 mSv = 1,000,000 μ Sv

mrem⁶/year) for exposure to ionizing radiation (ICRP 1991)⁷. This value is lower than the current U.S. radiation occupational worker annual dose limit of 50 mSv/year (5,000 mrem/year) but more permissive than the U.S. National Council on Radiation Protection and Measurements' (NCRP's) recommendation of 10 mSv/year (1,000 mrem/year) (NCRP 1993, 1995, 2004, 2018). Additionally, ICRP and NCRP recommend that pregnant members of the flight crew limit ionizing radiation exposure of the conceptus⁸ to no more than 0.5 mSv/month (FAA 2014; NCRP 1987). However, because radiation exposures to flight crew are neither regulated nor enforced, U.S.-based airlines vary in their monitoring of radiation exposure and do not track cumulative exposure. Thus, individual workers currently are left to track their own exposures if they want to ensure that they do not exceed FAA recommendations.

Radiation Exposure During Air Travel

The radiation environment at commercial aircraft–flying altitudes, which typically range between 5 and 11 km (with some exceptions), is derived from cosmic and solar sources. Extraterrestrial energetic charged particles continuously bombard Earth's Geospace environment, a phenomenon known as cosmic radiation. Two sources of cosmic radiation exist: (1) the ubiquitous galactic cosmic radiation (GCR), with origins outside the solar system, and (2) solar energetic particle (SEP) events (or solar cosmic rays), which are associated with violent eruptions on the Sun's surface that last several hours to days. Both types of cosmic radiation⁹ (GCR and SEP) have sufficient energy to penetrate the atmosphere and shielding materials of aircraft. In both cases, the primary cosmic radiation typically collides with particles in the atmosphere to produce secondary radiation. This secondary cosmic radiation dominates the radiation environment experienced by flight crew. This radiation environment could then cause a potential health risk to air travelers and flight crew alike (Mertens and Tobiska 2021). Table 1-1 summarizes the main types of radiation to which flight crew are typically exposed to.

Three independent variables govern the intensity and dynamics of cosmic radiation exposure in the atmosphere (Mertens et al. 2012). The first is the time, or phase, in the Sun's magnetic activity cycle, referred to as the solar cycle (an approximately 11-year pattern of varying solar activity) (Hathaway 2015). The second variable is the vertical cutoff rigidity, which factors in Earth's magnetic field as a shield from incoming cosmic and solar radiation, with the most shielding occurring at the equator and the least

⁶ The roentgen equivalent man (rem) is the centimetre-gram-second system of unit of equivalent dose. 1 rem = 0.01 Sievert. Rem is more commonly used in U.S. regulatory documents, however, the FAA uses the recommended dose limits in Sievert and this report similarly will primarily use Sieverts unless otherwise specified.

⁷ The FAA's most recent Advisory Circular was published in 2014; therefore, the guiding documents from other organizations cited here reflect that time frame. More recent guidance, where available, is also cited as appropriate.

⁸ Any stage between fertilization and birth—this term is cited in the FAA Advisory Circular 120-61B.

⁹ The committee uses the term "cosmic radiation" to mean GCR and SEP, unless otherwise stated for a specific type of radiation.

TABLE 1-1 Broad Categories of Radiation Types in the Aviation Environment

Radiation Type	Origin	Composition	Characteristics	Impact at Aviation Altitudes
Primary GCR	Outer space (galactic sources, including supernovae and distant stars)	Protons, helium nuclei (alpha particles), electrons, heavy atomic nuclei (iron, carbon)	High energy, deeply penetrating, can penetrate metal and dense structures	Rare exposure for flight crew
Secondary Cosmic Radiation (Atmospheric Cascade Products)	Produced when primary particles collide with Earth's atmosphere	Neutrons, pions, electrons, positrons, muons, gamma rays	Less penetrating than primary radiation but more frequently encountered	Constant background exposure; modulated by solar activity; most common form at aviation altitudes
SEPs	The Sun during solar events	Charged particles associated with solar flares and carried with coronal mass ejections	Frequency varies with 11-year solar cycle; higher likelihood during solar maximum with an average 3–4 intense events affecting aviation altitude per cycle	Increased exposure during intense solar activity; affects polar routes more

NOTE: GCR = galactice cosmic radiation; SEP = solar energetic particle.

shielding occurring at the poles. The third variable is areal density or depth within the atmosphere—that is, the altitude at which a plane is flying as the atmosphere provides additional shielding of radiation. Radiation present in the atmosphere at flight altitudes creates the radiation environment to which flight crews and passengers are exposed. When this ionizing radiation interacts with the body, it deposits energy in tissues and produces a radiation dose. The potential health impact depends on the amount of energy deposited, the type of radiation, and the tissue or organ sensitivity to radiation, which together determine the whole-body effective dose.

Thus, the radiation dose received by flight crew during a particular flight depends on the path of the flight and its timing. Across geographic regions, dose rate¹⁰ consistently increases with altitude. The committee calculated the average dose rate¹¹ at multiple altitudes, based on national-level averages within the United States (see Figure 1-1). A typical transcontinental flight from Los Angeles to Washington, DC,

¹⁰ Dose rate is the dose received per unit of time. It is proportional to the intensity of the radiation environment, which increases at higher altitudes.

¹¹ The committee calculated dose rates using the NAIRAS code developed by the National Aeronautics and Space Administration; these were calculated at the solar cycle average (03/02/2011) between Solar Cycle 24 Minimum and Solar Cycle 24 Maximum. The solar cycle is discussed in more detail in Chapter 4 of the report. Dose rates for Denver and at sea level were calculated by dividing the average annual dose received by cosmic radiation by 8,760 hours in a year (EPA n.d.).

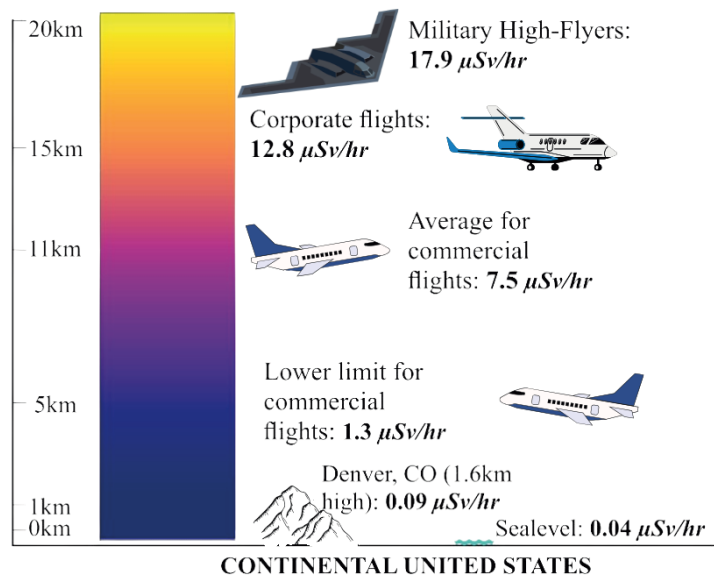


FIGURE 1-1 Committee-calculated average dose rates ($\mu\text{Sv/hr}$) at various altitudes averaged across the continental United States.

NOTE: μSv = microSievert; km = kilometer. For reference 10 km is 350 Flight Level.

takes approximately 5.5 hours, which would equate to a flight dose of roughly $41 \mu\text{Sv}$, equivalent to being in Denver for about 19 days or being at sea level for 42 days.

Intrinsic challenges to determining the quantity and quality of cosmic radiation exposure during flight include technological factors, such as the inability of any one radiation detection technology to “see” the complete range of cosmic radiation particles and energies, and spatiotemporal factors, such as flight path (changes in latitude), altitude of flight, position in the solar cycle, and presence of episodic SEPs.

Flight Crew Demographics

The demographics of the flight crew population are relevant to the SoT, including implications for disease risk and pregnancy outcome. For this report, the committee considers both pilots/cockpit crew and flight attendants/cabin crew as “flight crew,” unless specified otherwise. The two groups differ in their demographics, with implications for the health outcomes of concern and the design of potential epidemiologic studies. Table 1-2 summarizes some of the demographics and operational aspects of relevance to this study when considering potential epidemiologic study cohorts. Table 1-2 reports the three largest groups, percentagewise, within a given occupation and demographic. The estimated size of the flight pilot and flight attendant workforce in 2023 varies based on Bureau of Labor Statistics (BLS) Occupational Employment and Wage Statistics and American Community Survey (ACS) data. The range reflects differences in data collection methods, with BLS relying on employer-reported employment counts and ACS using survey-based self-reported occupation data.

TABLE 1-2 Flight Crew Demographics from 2023

Occupation	Total and Gender % ^a	Age (years)	Ethnicity
Pilots and Flight Engineers	106,360–167,000 (BLS–ACS range) ^b Female: ~9% Male: ~91%	Mean: 43	White (non-Hispanic): ~82%
		Median: 42	Black/African American: ~4%
		Top three largest age groups:	Hispanic/Latino: ~8%
		35–44: ~26%	Asian: ~4.5%
		45–54: ~26%	Other/multiracial: ~2%
		55–64: ~21%	
Flight Attendants	111,801–122,080 (BLS–ACS range) Female: ~78% Male: ~22%	Mean: 41.5	White (non-Hispanic): ~60–62%
		Median: 40	Black/African American: ~15–17%
		Top three largest age groups	Hispanic/Latino: ~15–17%
		25–34: ~21.5%	Asian: ~5–6%
		35–44: ~23.5%	Other/multiracial: ~2–3%
		45–54: ~19%	

NOTE: Gender, age, and ethnicity are derived solely from ACS survey data.

^a Note the total number of workers is reported as a range. The lower number is from BLS, and the higher number is from the U.S. Census Bureau’s ACS.

^b Note that pilot employment totals combine BLS estimates for airline pilots, copilots, and flight engineers with commercial pilots, aligning with the broader ACS category of aircraft pilots and flight engineers to produce a comparable workforce range.

SOURCES: U.S. Bureau of Labor Statistics (2023), U.S. Census Bureau (2023), Data USA (n.d.).

Commercial airline pilots typically range from 25 to 65 years old—the lower bound is approximate and driven by the 1,500-hour flight time requirement¹² for U.S. carriers and the traditional requirement for pilot applicants at major airlines to have a 4-year degree. The upper bound is mandated by the FAA¹³ and the International Civil Aviation Organization retirement rules. Flight attendants can be hired at age 21 and do not have a mandatory retirement age, resulting in an average workforce age of about 49 years.

¹² 14 CFR 61.159

¹³ 14 CFR 121.383

STATEMENT OF TASK

The FAA initiated an agreement with the National Academies and provided the SoT (see Box 1-1) based on the legislative language of Section 322 of the FAA Reauthorization Act of 2024. SoT elements include determining the radiation environments experienced by flight crews, potential impacts on the health of flight crew, and potential mitigation measures.

In addition to the tasks in Box 1-1, the FAA also requested that the committee complete the specific subtasks listed in Box 1-2.

BOX 1-1
Statement of Task

An ad hoc committee of the National Academies of Sciences, Engineering, and Medicine will conduct a study on radiation exposure to crew members onboard airlines operating under a Part 121 certificate of the Federal Aviation Administration. Specifically, the committee will:

- Assess available data and literature on radiation exposure to flight crews.
- Evaluate existing computational models that analyze and estimate radiation exposure and health risks.
- Identify potential harmful radiation sources at aviation altitudes and select a flight path or paths that would provide a bound or bounds on understanding plausible worst-case radiation exposure.
- Determine availability and types of individual exposure information and health data as well as knowledge gaps and limitations for potential epidemiological studies.
- Consider potential mitigation measures that could reduce radiation exposure to flight crews.

Based on its assessment, the committee will develop a short consensus report with its findings and conclusions, and, as appropriate, recommendations to inform strategies for monitoring, assessing, and mitigating radiation exposure levels and any associated health impacts. The committee will engage stakeholders, including manufacturers and operators of Part 121 aircraft, flight crews' associations, and the Civil Aerospace Medical Institute (CAMI) of the FAA, in discussion of levels of radiation exposure, monitoring radiation levels, health risks, and potential mitigations.

BOX 1-2

Additional Contractual Tasks

Task 1: Assessment of Available Data, Computational Models, and Data Limitations

- Solicit input regarding whether Part 121 operators have available data on radiation exposure in their aircraft.
- Assess the availability of evidence on potential health impacts of radiation exposure on flight crew members.
- Characterize available data on radiation exposure on commercial aircraft.
- Solicit input from the Civil Aerospace Medical Institute of the FAA on its computational models on radiation exposure and health risks and any data and analysis it may have available.
- Summarize the findings.

Task 2: Evaluation of Bounding Case Studies and Elements of an Epidemiological Study

- Solicit input on bounding flight routes for the committee's evaluation, considering the likely plausible worst-case radiation exposure routes of transpolar flights at high altitudes while receptive to considering other routes.
- Having selected bounding flight routes, perform cumulative radiation exposure assessments (using at least two different methodologies).
- Identify limitations and knowledge gaps for performing epidemiological studies to relate radiation exposure and health outcomes.
- Summarize the findings.

Task 3: Stakeholder Engagement

- Solicit input from aircraft manufacturers on the feasibility of monitoring and measuring radiation levels in Part 121 aircraft.
- Solicit input from instrument manufacturers and scientists who have done monitoring and measuring radiation with a view toward understanding the differences between measuring cosmic radiation and terrestrial and technological radiation sources.
- Solicit input from Part 121 operators, aviation labor organizations, and other interested parties on the health impacts of radiation exposure and on understanding potential mitigation measures to reduce radiation exposure.
- Summarize the identified opportunities and challenges.

ASPECTS BEYOND THE BOUNDS OF THE STATEMENT OF TASK

Considering the scope specified in Section 322 and the SoT, as well as the FAA's charge to the committee during its first meeting on September 3, 2025, the committee determined that the report's primary purpose is to provide an assessment of current knowledge regarding occupational radiation exposure of flight crew and associated potential health risks. The committee identifies methods to improve radiation dose estimation and to strengthen studies examining the impacts of such exposure on flight crew health. Consistent with the SoT, the committee also provides guidance on potential mitigation measures to reduce radiation exposure.

Although the committee evaluates potential risks to flight crew, providing recommendations on "acceptable" risk levels or regulatory policy concerning acceptable risk is beyond the SoT. The committee considered radiation from natural sources only and did not evaluate worst-case scenarios related to nuclear accidents or acts of war. Additionally, the committee only considered commercial aviation and did not consider military aviation. The report addresses impacts on human health only and does not examine radiation effects on aircraft electronics. In addition, the committee was not tasked with evaluating the FAA's recommended radiation dose limits for flight crew.

Finally, the committee focused on cosmic ionizing radiation exposure, as specified by the FAA in questions and written response (see Appendix D), and did not evaluate ultraviolet radiation exposure to flight crew and the attendant risk for malignant melanoma. The report does, however, highlight the increased risk for this cancer among cockpit crew, which has been documented in epidemiologic studies. Furthermore, relevant findings from ultraviolet radiation exposure studies are discussed where they inform the assessment of associations between cosmic radiation exposure and health outcomes.

COMMITTEE'S APPROACH

To address the SoT, the committee first addressed the potential adverse health outcomes observed in epidemiological studies of flight crewmembers, including pilots and flight attendants, that could plausibly arise from cosmic radiation exposure. The committee was sufficiently constrained by time and resources and was unable to conduct a full systematic review. Instead, the committee conducted three targeted reviews that identified and examined epidemiological studies of flight crews and (1) health outcomes broadly, (2) cancer, and (3) reproductive outcomes. The committee comprehensively searched the literature for relevant reports and summarized the findings.

Second, as specified by the SoT, the committee examined computational models for estimating radiation doses received in-flight and selected four of these models to perform its calculations. As a consideration in the design of epidemiologic studies, flight paths that would yield worst-case (i.e., upper-limit) doses were identified and calculated. The committee also considered common flight paths that were not bounding scenarios. These estimates provided input for the design of epidemiologic studies, particularly the statistical power that could be achieved for various questions about risks.

Third, based on the literature review, the committee considered epidemiological study designs for two health outcomes, cancer and adverse reproductive outcomes.

Cancer was selected as one health outcome of critical concern based not only on this literature review but also on numerous authoritative conclusions on the causation of certain cancers by ionizing radiation. Additionally, there are dose–response relationships derived from epidemiological studies that are embedded in risk models. The generalizability of these models to the cosmic radiation experienced by flight crew is a source of uncertainty. The other group of radiation-related outcomes, non-stochastic events such as cataract and reproductive outcomes, was also considered by the committee in relation to indicators of dose. Because cabin crew are predominantly female and findings of the literature review on reproductive outcomes were mixed, the committee also addressed the design of an epidemiological study of pregnancy-related health outcomes.

The committee then developed an overall framework for estimating the excess risk of cancer associated with the occupational radiation exposure of flight crew. The committee’s framework for cancer has three building blocks that relate to the five elements of the SoT. The first (Model In-Flight Radiation Dose) comprises the modeling tools that are used to estimate the radiation dose (in millisieverts) received in-flight. Some models may incorporate dose from SEP events, which would be higher-exposure events than those for individuals exposed only to GCR but would occur sporadically. As the first component of the committee’s framework, the models can supply dose estimates for individuals and particular flights or for general types of flight patterns (e.g., circumpolar and transatlantic).

The second framework component (Estimate Cumulative Dose for Crewmembers) estimates cumulative doses for individuals or for classes of individuals based on general assumptions about the flight profiles of particular groups (e.g., pilots or flight attendants flying specific domestic or international routes). The input data are comprised of flight history, including the routes flown and the chronological details of the flights. Cumulative dose is estimated by aggregating the doses estimated for each flight from the first component’s underlying model(s).

Finally, the increment in cancer risk is estimated in the third component of the framework (Estimate Excess Cancer Risk). A rich epidemiological literature now documents and quantifies the increased risk of cancer associated with ionizing radiation exposure (e.g., from the studies of the atomic bomb survivors in Hiroshima and Nagasaki). Models are available for this purpose from various authoritative entities (e.g., ICRP). New epidemiological studies could provide risk estimates specific to the exposures of flight crew.

The committee was also asked to consider potential mitigation measures to reduce radiation exposures of flight crew. For this element of the SoT, the committee considered radiation protection practices generally, the regulatory context for Part 121 operators, and steps that could be taken by the industry and by flight crewmembers themselves.

For the additional contractual tasks, the committee undertook a wide range of information-gathering activities, as covered in Chapter 2; a summary of these activities is presented in Table 1-3.

TABLE 1-3 Summary of the Committee’s Information-Gathering Activities

Group	Information-Gathering Activity
Aircraft Manufacturers	• Questionnaires sent to Airbus, Boeing, Embraer, and MHIRJ Aviation
Instrument Manufacturers and Scientists	• Collection and summary of specification sheets for commercially available dosimeters used on aircrafts • Information-gathering session with five invited speakers covering radiation detection and dosimetry in aviation environments, as well as solar weather monitoring and operational science of radiation monitoring of flight crew
Part 121 Operators and Labor Organizations	• Questionnaire sent to Airlines for America and associated members • Information-gathering session with participation from both pilot and flight attendant labor organizations
Other	• Invited presentations and communication from the FAA’s Civil Aerospace Medical Institute • Invited presentation on design of epidemiological studies investigating reproductive health outcomes • Invited presentation from the National Institute for Occupational Safety and Health on past work studying radiation exposure of flight crew and health outcomes

REPORT ORGANIZATION

Chapter 2 is a summary of the stakeholder engagement sessions, encompassing both the groups identified in specific elements of the SoT and additional information requests that the committee deemed necessary to respond to any aspect of its task. Chapter 3 addresses the current understanding of published information regarding radiation exposure of crewmembers and health outcomes, as well as the understanding of data availability to address this topic. Chapter 4 focuses on the computational modeling aspects of the SoT, including evaluation of existing models, radiation sources and considerations for crewmembers, selection of bounding flight paths, and cumulative radiation exposure assessments. Chapter 5 addresses how knowledge gaps and limitations from the literature assessment in Chapter 3 may be used to inform an epidemiologic study to relate radiation exposure of crewmembers and health outcomes. Chapter 6 tackles the final aspect of the SoT, whereby the committee considers potential mitigation strategies through a discussion on risk management, communication, and overarching conclusions. Chapter 7 offers the committee’s path forward based on the synthesis of the report’s conclusions and recommendations.

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2

Evidence Base and Information Gathering

This chapter describes the sources of information gathered to support the committee’s response to the Statement of Task (SoT). It begins by outlining the regulatory landscape relevant to radiation exposure for flight crewmembers, including a comparison to other occupationally exposed workers. The chapter then details the committee’s stakeholder engagement activities, as required by Task 3 (see Box 1-2), including public information-gathering sessions and written requests for information submitted to the Federal Aviation Administration (FAA), aircraft and instrument manufacturers, Part 121 operators,¹ labor organizations, professional societies, and other interested parties. Finally, the chapter summarizes additional information-gathering efforts by the committee to address crosscutting technical and scientific questions identified during its deliberations. The information assembled in this chapter provides context for the committee’s consideration of radiation exposure, risk, and mitigation in the report’s subsequent chapters.

REGULATORY LANDSCAPE

As covered in Chapter 1, the FAA does not have regulations regarding radiation exposure of flight crew. In approaching its SoT, the committee reviewed regulatory documents and the published history of occupational and safety regulations impacting

¹ Part 121 operators are FAA-certified air carriers and for the purposes of this report include only commercial, civilian aviation (e.g., large U.S. airlines and regional air carriers). Military aircraft are not included in the definition of Part 121 operators. While cargo carriers are included in the definition of Part 121 operators, radiation from cargo is out of scope for this report. However, the committee acknowledges radiation as a potential related occupational risk for flight crew for cargo carriers. This report will use the terminology “U.S.-based commercial airlines” or “U.S. airlines” in reference to large U.S. airlines and regional air carriers as Part 121 operators.

flight crew. This information informed the committee's conclusions and recommendations in terms of steps that might be taken to enhance awareness of the radiation exposure received by flight crew and to manage this exposure. The committee also considered the jurisdictional authorities of the FAA and other relevant agencies. The committee recognizes the inherent difference between regulations for workplace safety and health related to manmade hazards (e.g., aircraft performance; safety equipment for emergencies) and regulations involving naturally occurring exposures such as galactic cosmic radiation (GCR) and solar energetic particles (SEPs)—described generally as “cosmic radiation” throughout the report, unless the type of radiation is specified.

The United States has several regulatory authorities and nonregulatory authorities that have direct or adjacent jurisdiction over radiation exposures generally, occupational radiation exposures, and civil aviation. This is relevant to the SoT because any policies to address radiation exposure to commercial flight crew would need to be crafted to ensure that all entities with authorities that touch this issue are considered. For instance, policies surrounding the regulation of occupational radiation exposure for flight crew could involve the FAA and the Occupational Safety and Health Administration (OSHA).

Table 2-1 summarizes the authorities of the FAA and OSHA with respect to occupational exposure to radiation.

Based on the committee's understanding of publicly available information, the FAA has regulatory authority over aviation safety and flight crew working conditions but has not implemented requirements for radiation exposure monitoring or limits. OSHA regulates radiation exposure for workers who are not already covered by regulations of another federal agency but would lack jurisdiction over cosmic radiation exposure of flight crew, who fall under FAA authority.

The FAA first issued guidance recognizing radiation exposure for flight crew in Advisory Circular 120-52, *Radiation Exposure of Air Carrier Crewmembers*, dated March 1990 (FAA 1990). A subsequent circular, Advisory Circular 120-61, *Crewmember Training on In-Flight Radiation Exposure*, was issued in May 1994 and formally acknowledged flight crew as occupationally exposed to ionizing radiation (FAA 1994). The most recent guidance, Advisory Circular 120-61B, *In-Flight Radiation Exposure*, was published in November 2014 (FAA 2014). These documents are issued to inform the aviation community of nonregulatory material in a systematic way. The committee's review of the regulatory landscape shows that U.S. regulatory authorities are fragmented with regard to radiation exposure of flight crew. While radiation exposure is recognized as an occupational risk for flight crew and the FAA has recommended dose limits, the FAA does not have any accountability for tracking doses received in relation to these limits, and no enforced standard exists. The committee found that the historical record of advisory circulars over the past 30 years and the minimal action around radiation exposure of flight crew indicate that most U.S. airlines are unlikely to implement radiation education and monitoring programs unless given a mandate, which would create a dedicated mechanism for accountability.

The committee found that other radiation-exposed workers, or those acknowledged to be occupationally exposed to radiation, are subject to clear regulations with established dose limits and mandatory requirements for monitoring, whereas flight crew

TABLE 2-1 Comparison of FAA and OSHA Authorities Concerning Occupational Exposure to Radiation

Agency	Official Role	Key Public Documentation	Dose Recommendations	Statutory/ Enforceable Limits
FAA	Asserts primary authority over occupational safety and health of crewmembers on aircraft in operation. Provides advisory guidance on in-flight GCR and SEP exposure.	FAA Federal Register notice (FAA 1975); Advisory Circular 120-61B (FAA 2014); FAA/ OSHA Aviation Safety and Health Team report and MOU (FAA and OSHA 2000); FAA policy statement on OSHA applicability (FAA 2013).	Recommends but does not require internationally accepted occupational limits: 20 mSv/ year averaged over 5 years; ≤50 mSv in any single year. Pregnancy guidance: ≤0.5 mSv per month to the conceptus.	The FAA has not established enforceable numeric radiation exposure limits for flightcrew; recommendations are nonbinding. Similarly, no requirements exist for radiation monitoring or tracking of flight crew for airlines or aircraft manufacturers.
OSHA	Establishes enforceable occupational exposure standards for ionizing radiation under OSHA jurisdiction; however, application onboard aircraft is limited where the FAA exercises statutory authority and regulates the relevant working conditions.	29 C.F.R. §1910.1096 (Ionizing Radiation); FAA/OSHA Aviation Safety and Health Team report and MOU (FAA and OSHA 2000); FAA policy statement on OSHA applicability to cabin crewmembers (FAA 2013).	Regulatory limits expressed in rems, including a whole-body limit equivalent to 50 mSv/year, with associated monitoring and recordkeeping requirements.	OSHA exposure limits are enforceable where OSHA has jurisdiction; direct enforcement on aircraft in operation is constrained and coordinated with the FAA.

NOTE: C.F.R. = Code of Federal Regulations; MOU = memorandum of understanding; mSv = millisievert, a unit of measure for radiation dose.

¹ The unit for effective dose is the sievert (Sv). Most flights deliver on the order of microsieverts (μ Sv), and many dose limits across occupations are expressed in terms of millisieverts (mSv).
1 Sv = 1,000 mSv = 1,000,000 μ Sv

only have recommended guidance. Table 2-2 compares federal occupational radiation protection frameworks applicable to radiation-exposed workers whose exposure is regulated by U.S. agencies.

Conclusion 2-1: U.S. flight crews have occupational exposure to ionizing radiation, a known cause of certain cancers and other adverse outcomes. Flight crew are not afforded the same level of regulatory protection as are other radiation-exposed workers. Clear authority is necessary to establish enforceable radiation monitoring and risk management requirements for flight crew; without such authority, oversight and mitigation efforts have lacked consistency and accountability.

TABLE 2-2 Comparison of U.S. Regulatory Agencies and Approach to Occupational Radiation–Exposed Workers

Agency	Covered Worker Populations	Dose Limit Structure (selected)	Monitoring/ Compliance Approach	Notes on Scope and Applicability
OSHA	Workers in general industry where ionizing radiation sources are present and not regulated by another federal radiation authority.	Quarterly whole-body limit of 12.5 mSv (1.25 rem), equivalent to 50 mSv annually, with additional cumulative provisions.	Workplace controls, surveys, posting, training, and personnel monitoring as specified in 29 C.F.R. § 1910.1096.	Framework is source-based and oriented toward employer-controlled radiation sources.
DOE	DOE employees and contractors designated as radiological workers at DOE facilities and activities.	Total effective dose limit of 50 mSv (5 rem) per year, with organ- and tissue-specific limits.	Personnel dosimetry required for workers likely to receive ≥1 mSv annually; comprehensive dose assessment programs.	Requirements established in regulation ¹ and enforced as a matter of law.
NRC	Workers at NRC-licensed facilities, including commercial nuclear power, medical, and industrial licensees.	Total effective dose equivalent limit of 50 mSv (5 rem) ² per year for adult workers.	Individual monitoring required when workers are likely to exceed 10% of annual limits; “as low as reasonably achievable” required.	Applies to licensed activities involving radioactive material or radiation-producing equipment.
NASA	Astronauts and spaceflight crew, including mission-related training and operational exposures.	Career effective dose limit of 600 mSv over a 10-year career, supplemented by mission-specific constraints (NASA 2022).	Continuous monitoring and characterization of the space radiation environment; dose- and risk-based compliance.	Program incorporates an upper limit of 3% risk of exposure-induced death.

TABLE 2-2 Continued

Agency	Covered Worker Populations	Dose Limit Structure (selected)	Monitoring/ Compliance Approach	Notes on Scope and Applicability
FAA	Asserts primary authority over occupational safety and health of crewmembers on aircraft in operation. Provides advisory guidance on in-flight cosmic radiation through Advisory Circulars.	No regulatory limits. Recommends internationally accepted occupational limits: 20 mSv/year averaged over 5 years; ≤50 mSv in any single year. Pregnancy guidance: ≤0.5 mSv per month to the conceptus.	None	None

NOTE: C.F.R. = Code of Federal Regulations; DOE = U.S. Department of Energy; mSv = millisievert³; rem = roentgen equivalent man⁴; NASA = National Aeronautics and Space Administration; NRC = Nuclear Regulatory Commission.

¹ 10 C.F.R. Part 835

² 10 CFR Part 20

³ The unit for effective dose is the sievert (Sv). Most flights deliver on the order of microsieverts (μ Sv), and many dose limits across occupations are expressed in terms of millisieverts (mSv).

Sv = 1,000 mSv = 1,000,000 μ Sv

⁴ The roentgen equivalent man (rem) is the centimetre-gram-second system of unit of equivalent dose. 1 rem = 0.01 Sievert. Rem is more commonly used in U.S. regulatory documents, however, the FAA uses the recommended dose limits in Sievert and this report similarly will primarily use Sieverts unless otherwise specified.

Recommendation 2-1: The Federal Aviation Administration should exert its regulatory authority over ionizing radiation as an occupational exposure that requires oversight to ensure flight crewmember health and safety.

STAKEHOLDER ENGAGEMENT

To address the SoT, the committee solicited input from the FAA, aircraft manufacturers, and instrument manufacturers on the feasibility of monitoring and measuring radiation for Part 121 aircraft. The committee also sought perspectives from Part 121 operators, aviation labor organizations, and other interested parties regarding potential health impacts of occupational radiation exposure and possible mitigation strategies. To obtain this information, the committee conducted public information-gathering sessions with federal agencies, industry representatives, labor organizations, professional

societies, and technical experts, and supplemented these efforts with written requests for input using structured questionnaires distributed to airline associations and manufacturers. In addition, the committee gathered information on commercially available and employed radiation dosimeters (as determined by published literature) to better understand current technical capabilities and limitations.

Soliciting Input from the Civil Aerospace Medical Institute

To address its task to solicit input from the Civil Aerospace Medical Institute (CAMI), the sponsoring office for this study within the FAA, the committee held a public information-gathering session on September 3, 2025. During the session, Anthony Tvaryanas, FAA CAMI, formally charged the committee and presented the SoT (see Boxes 1-1 and 1-2). The committee posed additional questions to clarify elements of the SoT, and responses to these questions are summarized in Appendix D. Notably, the SoT focuses on natural cosmic radiation hazards, which do not include ultraviolet radiation, another recognized exposure relevant to flight crew, particularly cockpit crew.

Kyle Copeland, FAA CAMI, then offered an overview of FAA capabilities for assessing radiation exposure, including computational tools used to estimate in-flight dose. Providing technical background on aviation radiation exposure, he noted that GCR is the primary source of occupational exposure for flight crews. He described the FAA's CARI-7 and CARI-7A software², which model cosmic ray interactions with the atmosphere and magnetosphere to estimate in-flight dose. He indicated that typical annual doses for pilots are on the order of a few millisieverts (generally below recommended occupational limits) but vary as a result of altitude, latitude, and route structure, with higher exposures on transpolar and high-altitude flights. He noted that current exposure levels are not expected to produce deterministic health effects but may contribute to stochastic risks such as cancer. He also observed that emerging flight profiles, including supersonic or suborbital operations, could result in higher dose accumulation over shorter time periods. Following the session, the committee submitted written requests to CAMI to clarify technical aspects of the CARI-7A model, including input and output formats and units.

Soliciting Input from Part 121 Operators, Aviation Labor Organizations, and Other Interested Parties

As part of the SoT, the committee “solicit[ed] input from Part 121 operators, aviation labor organizations, and other interested parties on the health impacts of radiation exposure and on understanding potential mitigation measures to reduce radiation exposure.” To address this part of the SoT, the committee both held an information-gathering session and sent a questionnaire to multiple airline associations.

A second public event was held September 30, 2025, beginning with presentations

² CARI-7A differs from CARI-7 in that it is intended for academic/research-focused users and includes more options (FAA 2025).

from the Allied Pilots Association, the Association of Flight Attendants-CWA, the Association of Professional Flight Attendants, and the Aerospace Medical Association. A moderated community discussion followed, including representatives from Air Canada; Airlines for America (A4A); the Transport Workers Union Local 579 and Local 556; Southwest Airlines; Air Line Pilots Association, International; American Airlines; and Southwest Airlines Pilots Association.

Pilots, flight attendants, medical professionals, and labor representatives broadly agreed that radiation is an established occupational exposure in aviation, but that it is not consistently understood, communicated, or operationally addressed in the United States. Rondeau Flynn, Allied Pilots Association, noted that exposure varies as a result of solar activity, geomagnetic conditions, altitude, and latitude, with SEP events capable of temporarily increasing dose rates (see Chapter 4). While FAA guidance exists, he indicated that understanding and application among pilots are uneven, particularly with respect to cumulative exposure, episodic events, and pregnancy-related considerations.

Flight attendant representatives described similar gaps in awareness and training. Judith Anderson, Association of Flight Attendants-CWA, and Lori Vitto Glattly, Association of Professional Flight Attendants, stated that radiation exposure is generally not included in routine training or communications for cabin crew, and that baseline education, individual monitoring, and standardized protections are not widely implemented. Both emphasized that despite recognition of flight crew as an occupationally exposed population, current practices do not consistently support an understanding of cumulative dose or long-term health implications.

Pregnancy was identified as a key area of concern. Flynn and Anderson emphasized the importance of understanding recommended dose limits for the conceptus and managing exposure following pregnancy disclosure. They noted that uncertainty in risk estimates of aviation exposure levels supports a precautionary approach, particularly during solar events that may temporarily elevate exposure and could warrant operational adjustments.

Speakers also described a gap between scientific knowledge and operational implementation. Vitto Glattly highlighted challenges in accessing and interpreting exposure information, as well as differences between U.S. practices and more standardized international approaches that include dose tracking and notification protocols. Flynn described ongoing efforts within pilot organizations to improve education and operational awareness through aeromedical and space weather initiatives.

Diego Garcia, Aerospace Medical Association, emphasized that discussions of occupational radiation exposure have persisted due to unresolved issues in data, regulation, and education. He noted that limited access to clear, actionable information has constrained progress and that radiation exposure is often not treated as a routine occupational health consideration.

Across discussions, presenting participants consistently reported that most flight crewmembers do not receive structured education on radiation exposure or cumulative dose and that awareness of associated risks varies. Common concerns included long-term cancer risk, pregnancy outcomes, variability associated with space weather, and the feasibility of individual dose tracking. Overall, speakers identified a need for more

consistent communication, improved access to information, and approaches that better connect radiation science to operational decision-making.

Crosscutting Takeaways

The committee heard consistent statements that occupational radiation exposure in aviation is scientifically characterized but not uniformly understood or communicated across the flight crew workforce, particularly among flight attendants, resulting in variable awareness of cumulative exposure, pregnancy considerations, and SEP-related risk.

Conclusion 2-2: Based on concerns voiced by flight crew labor organizations in public meetings, the committee concluded that an unmet need remains for consistency, clarity, and accountability in communications and education from Part 121 operators around the risk of radiation exposure to flight crew. Currently, individuals are responsible for determining and tracking their own radiation exposure, relying on tools that are difficult to use. No training is provided, and convenient tools are not available for storing and tracking accumulating dose.

Recommendation 2-2: The Federal Aviation Administration should improve the usability of the CARI model for estimating radiation dose by developing a user-friendly, web-based application to increase accessibility to dose estimation for flight crew.

Written Requests to Airline Associations

In addition to the committee's public meetings, during which it heard from several in the aviation community, the committee submitted written requests to A4A and the Regional Airline Association (RAA) for information about airline monitoring, tracking, and education of flight crew (see Appendix D for the full list of questions).

The RAA was unable to provide responses from its member organizations. A4A sent the questionnaire to its members, aggregated and de-identified answers, and provided the following summary in response to the committee's request:

Efforts by A4A member carriers regarding radiation exposure monitoring and communication for flight crewmembers vary by individual operator. Crewmember concerns are generally referred to carrier medical departments. Training for crewmembers may be provided at some carriers during initial training periods and reinforced during continuing training periods. Some members contract with radiation health experts as part of their occupational health programs. In response to short-term high-radiation events, routes and altitudes may be adjusted where alerts are issued during space weather events and polar routes are avoided during such times. Additionally, female crewmembers who are pregnant or trying to conceive are advised to exercise caution on polar routes due to higher cosmic radiation exposure at altitude.

The committee found that the variability in approach described by A4A aligns with the statement from labor organizations describing uneven awareness of and reliance on carrier-specific policies rather than standardized requirements.

Soliciting Input from Researchers and Instrument Manufacturers

Also in accordance with the SoT, the committee “solicit[ed] input from instrument manufacturers and scientists who have [monitored and measured] radiation with a view toward understanding the differences between measuring cosmic radiation and terrestrial and technological radiation sources.” To address this part of the SoT, the committee held an information-gathering session and retrieved publicly available information from dosimeter manufacturers’ websites.

The committee obtained specification sheets for certain commercially available dosimeters that have been used in select studies for determining radiation fields and exposure levels, and doses in aviation environments. A summary of the dosimeters and technical specifications is provided in Table 2-3.

TABLE 2-3 Summary of Specifications for Commercially Available Dosimeters Used in Aviation Environments

Parameter	InLight OSL	Micro Dosimeter	Liulin-SET	HAWK (FW-AD1)
Measurement	Integrated dose	Integrated dose	LET spectrum + dose	LET spectrum + dose equivalent
Type				
Primary	Sv (dose equivalent)	Rad (absorbed dose)	MeV (energy deposition)	rem/h (dose equivalent rate)
Unit				
Range	10 μSv–>10 Sv (0.001–>1,000 rem)	0–40 krad (Si) (0–400 Gy)	0.08–20.83 MeV	0.2 keV/μm–2 MeV/μm LET
Dose Rate	Integrating (no rate)	Integrating (0.001–10,000 μrad/s measurable)	Real-time rate	Real-time rate (minute-by-minute)
Capability				
Reference	Landauer (2024)	Teledyne e2v HiRel Electronics (2021)	Space Environment Technologies (n.d.)	Far West Technology, Inc. (2010)

NOTE: GeV = giga electronvolt; Gy = Gray; keV = kilo electronvolt; LET = linear energy transfer; MeV = mega electronvolt; rem – roentgen equivalent man¹; Sv = sievert; TeV = tera electronvolt; μrad/s = microrad per second.

¹ The roentgen equivalent man (rem) is the centimetre-gram-second system of unit of equivalent dose. 1 rem = 0.01 Sievert. Rem is more commonly used in U.S. regulatory documents, however, the FAA uses the recommended dose limits in Sievert and this report similarly will primarily use Sieverts unless otherwise specified.

During the third public meeting, held December 3, 2025, presentations were made by researchers and organizations that develop dosimeters for aviation environments and groups that perform active radiation monitoring in aviation environments.

These presentations highlighted the scientific complexity and operational challenges of characterizing and managing ionizing radiation exposure in commercial aviation. Across the presentations, speakers emphasized that aviation radiation is a mixed, highly variable field shaped by cosmic radiation and modulated by altitude, latitude, geomagnetic conditions, and episodic solar activity. Although measurement technologies, biological research, operational models, and forecasting tools have advanced, limitations in instrumentation, platform access, data integration, and operational implementation continue to constrain progress.

The presentations also highlighted the complexity of the aviation radiation environment and the associated challenges for measurement, modeling, and operational application. Eric Benton, Oklahoma State University, described the radiation field at flight altitudes as a mixed and variable environment produced by atmospheric cascades from GCR. Although photons, electrons, and muons dominate particle flux, he noted that neutrons contribute disproportionately to biologically-relevant dose and remain difficult to measure. Benton emphasized that no single detector can characterize the radiation field fully, motivating hybrid measurement approaches such as combined silicon detectors and tissue-equivalent proportional counters.

Several speakers, including Benton, identified limited access to commercial aircraft for in situ measurements as a constraint on empirical data collection, reinforcing reliance on models and alternative platforms such as high-altitude balloons for validation. Kent Tobiska, Space Environment Technologies, similarly highlighted advances in real-time measurement systems while noting continued limitations in neutron sensitivity that require integration with modeling to estimate total dose.

Les Braby, Texas A&M University, emphasized that radiation exposure assessment is not solely a physical measurement problem but also depends on radiation quality and biological response, which vary with particle type, energy, and dose rate. These considerations underscore the importance of integrating experimental, epidemiological, and modeling approaches in radiation protection.

Operational considerations were addressed by Mike McCall, PCAire, who emphasized that accurate dose estimation depends on detailed flight path data and integration with flight planning systems, and by Katherine Monson, Hale Space Weather Consulting (Hale SWx), who highlighted the role of space weather forecasting in supporting operational decision-making despite inherent uncertainties—particularly during SEP events.

Across presentations, a consistent theme arose: improved coordination among measurement, modeling, and operational systems is needed to support reliable assessment and management of radiation exposure in aviation environments.

Crosscutting Takeaways

The committee heard consistent evidence that radiation exposure in commercial aviation arises from a complex and variably composed atmospheric radiation field that is not fully characterized by existing measurements. Although background conditions can be modeled with reasonable confidence, important uncertainties remain in particle composition, radiation quality, and short-term variability during geomagnetic disturbances. The committee learned that the aviation radiation environment remains incompletely characterized, particularly with respect to particle composition, radiation quality, and variability during space weather events. Multiple speakers emphasized that neutrons contribute disproportionately to biologically relevant dose yet remain among the most difficult components to measure accurately with compact aviation-compatible instrumentation. Aircraft dosimetry is limited, particularly in the United States, which constrains model validation. Current detector technologies cannot independently characterize all biologically significant components of the aviation radiation field, resulting in the need for hybrid detection systems.

Soliciting Input from Aircraft Manufacturers

The committee sent written requests to Airbus, Boeing, Embraer, and MHIRJ Aviation with questions about general radiation protection and monitoring in aircraft design and manufacturing (see Appendix D). Requests were directed to several contacts including environmental control systems experts, airworthiness section chiefs, radiation safety officers, and air management systems specialists.

The committee received a mix of responses including one written response, one telephone response via National Academies staff, one response that information would not be provided, and one entirely missing response. The responders were anonymous to the committee. In general, the responding manufacturers noted that regulatory frameworks are available for monitoring radiation exposure—for example, the European Union’s Directive 2013/59 Euratom. They further stated that radiation exposure per flight may be calculated on the basis of flight data using approved calculation tools. Typically, commercial aircraft do not have built-in detection, or space weather tracking or monitoring incorporated into the aircraft designs. However, specific, albeit nonbinding, guidance exists that may be taken into account during manufacturing for single event effects caused by atmospheric radiation. Single event effects are temporary or permanent disruptions in electronic systems caused by a single high-energy particle (e.g., a neutron, proton, or heavy ion) striking a sensitive part of a microchip; however, these were deemed to be out of scope of the SoT.

IMPLICATIONS FOR POLICY AND PRACTICE

The information presented in this chapter highlights a distinction between the current state of scientific understanding of radiation exposure in aviation and the frameworks in place to manage that exposure operationally. Ionizing radiation is a recognized occupational exposure for flight crew that can be characterized using existing models and measurement approaches. However, in the United States, no enforceable

requirements exist for monitoring, tracking, or managing this exposure that are comparable to those applied to other occupational radiation-exposed worker populations.

This distinction has practical implications for how radiation exposure is understood and managed across the aviation system. In the absence of standardized requirements, approaches to education, communication, and dose assessment vary across operators, and individual crewmembers may have limited access to consistent information regarding cumulative exposure and potential risks. Stakeholder input further indicates that awareness and understanding of radiation exposure are not uniform across the workforce, particularly with respect to variability associated with flight profile and space weather, as well as considerations during pregnancy.

At the same time, the committee identified that relevant technical capabilities, including computational models, measurement technologies, and forecasting tools, are available today, although they are not consistently applied in operational contexts. The findings in this chapter suggest that opportunities exist to improve coordination, consistency, and accessibility of information related to radiation exposure. These observations provide context for the analyses in subsequent chapters, which examine health outcomes; radiation dose estimation; design of future epidemiologic studies; and potential approaches to monitoring, communication, and mitigation.

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3

Assessment of Epidemiologic Literature

Flight crew are routinely exposed to elevated levels of galactic cosmic radiation (GCR) compared to ground-based cohorts as part of the occupational environment. Over the past several decades, a growing body of epidemiologic research has examined whether this exposure is associated with adverse health outcomes among flight crew. These studies focus on a range of outcomes and aim to better understand potential health risks related to occupational radiation exposure in this population.

The Statement of Task calls on the committee to “assess available data and literature on radiation exposure to flight crews.” More specifically, Task 1 asks the committee to “assess the availability of evidence on potential health impacts of radiation exposure on flight crew members.” The committee interprets this task as identifying and reviewing epidemiologic studies of adverse health outcomes among flight crews that are associated with in-flight exposures to GCR and solar energetic particle (SEP) events. Epidemiology studies ways that disease and health are spread among groups of people and what factors—such as environments and exposures—are linked to specific health effects.

LITERATURE ASSESSMENT

Search Strategy and Selection of Health Outcomes

Literature reviews can be categorized in several ways: narrative reviews, umbrella reviews (a compilation of review articles), scoping reviews (systematic identification of literature relevant to a question and description of the studies), and systematic reviews (identification of literature relevant to a question, review for risk of bias, and abstraction of the findings). In considering the type of review to be conducted, the committee acknowledged the limitations posed by available resources and by deadlines for completion of this report. Formal scoping and systematic reviews were not feasible, and based

on a preliminary screening, sufficient high-quality reviews did not appear to be available to support an umbrella review. Hence, the committee settled on the following approach.

The committee performed three searches in PubMed and Scopus to identify relevant literature. The first literature search was intended to provide a broad understanding of the available literature; the committee conducted this search on October 16, 2025, and retrieved systematic reviews on in-flight radiation exposure and any health outcomes. After reviewing the resultant literature, the committee concluded that two major groups of health outcomes had sufficient original research, including relevant study designs and reported risk estimates: cancer and reproductive outcomes. The committee also found reports in the literature identifying other health outcomes potentially associated with radiation exposure, but none had a sufficient body of literature on humans to be summarized further by the committee (Wakayama et al. 2021). Additionally, the committee identified multiple commentaries and reviews that provided background on health outcomes of concerns. Although these are not included in the committee's set of studies, several are referenced as background information (Barish 2004).

A second literature search was conducted on November 4, 2025, and retrieved studies specifically focused on in-flight radiation exposure and reproductive outcomes. The third literature search was conducted on December 2, 2025, and retrieved studies specifically focused on in-flight radiation exposure and cancer outcomes. All search strings were developed in conjunction with a reference librarian (see Appendix E), and PICO Portal software was used to track and manage the review. The searches for reproductive outcomes and cancer were kept separate at each step of the review.

After reviewing the search output for studies on cancer, the committee chose to use the most recent review—from committee member Scheibler and colleagues (2022), which includes studies published through 2021—as the starting point for its assessment of the cancer literature. That decision was based on the large number of citations identified in the search and the need to complete the literature assessment on a tight timeline. Articles published subsequent to the review by Scheibler and colleagues (2022) were identified and screened for inclusion. No such recent review was identified for reproductive outcomes; thus, that search was conducted over all time.

For both outcomes, results returned from the committee's PubMed and Scopus searches were imported into the PICO Portal and deduplicated. The review of studies began at the level of title and abstract. Two committee members independently screened the titles and abstracts of the deduplicated studies using the eligibility criteria to determine relevance. Articles designated as relevant from the title and abstract then proceeded to a full-text review. Each full-text study was assessed by two committee members independently; any disputes regarding inclusion were resolved by consensus after discussion with project staff. Relevant review articles and meta-analyses were identified during the review stages and set aside for hand-searching for additional citations of interest that might not have been identified by the search strings. The numbers of papers reviewed at each step for each health outcome are shown in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagrams in Appendix E (Figures E-1 and E-2 for cancer and reproductive health, respectively). A structured form was developed to extract key study data as the basis for evidence tables. Extraction was performed by project staff and quality checked by committee members.

EVIDENCE SYNTHESIS: CANCER OUTCOMES

Literature Identified

The review by Scheibler and colleagues (2022) included results from 39 studies, with the committee's literature search identifying three further articles, including two published during the span of the review by Scheibler and colleagues and one published subsequently. These studies, along with a few added studies, are described in Tables E-1 through E-8 in Appendix E. Forest plots created by Scheibler and colleagues (2022) were updated to include estimates from the newly identified studies as appropriate using R programming software. Studies were excluded from the forest plots if point estimates were not available for males and females separately, 95% confidence intervals were not provided, or the findings were in letters or journal correspondence. Forest plots were generated for the following cancer sites: breast, brain, leukemia, lymphoma, melanoma, nonmelanoma skin, prostate, and thyroid. The plots were stratified by sex, pilot or flight attendant status, incidence versus mortality, and cancer subtype (when applicable).

Synthesis of Results

The complete set of forest plots and evidence tables are included in Appendix E (Figures E-3 through E-10 and Tables E-1 through E-8). Here, the committee reviews the cancer sites for which the evidence linking cosmic radiation exposure to specific outcomes is most robust. Consistent with the SoT, the committee did not undertake a review of the far larger body of literature addressing ionizing radiation and cancer risk.

Malignant Melanoma

Cockpit crew are exposed to ultraviolet radiation, a well-documented cause of malignant melanoma (Emslie et al. 2025; IARC Working Group 1992). In fact, increased risk for melanoma in pilots was first reported in 1990 and confirmed in later reports (Band et al. 1990; Vågerö et al. 1990). For malignant melanoma, incidence is the most accurate measure of occurrence, as mortality reflects the consequences of detection and appropriate treatment along with cancer development. Additionally, since 1990, strong temporal trends of rising incidence of malignant melanoma have emerged, along with improved survival. Some studies of malignant melanoma in flight crew did include mortality as an outcome, the less useful measure. For incidence, Figure E-3 shows consistently elevated standardized incidence ratios (SIRs). For males, the studies of mortality also show elevated occurrence versus control populations. In male cockpit flight crewmembers, the findings for nonmelanoma skin cancers were complementary in showing increased risk (see Appendix E)¹.

A 2019 systematic review and meta-analysis included 12 studies (Miura et al. 2019). For seven studies on melanoma incidence, the pooled estimate of the SIR was

¹ The committee recognizes that cockpit crew are exposed to UV radiation, a form of non-ionizing radiation and that this exposure represents a known risk. However, this report focuses on ionizing radiation and therefore does not include UV exposure.

2.03 (95% confidence interval [CI] 1.71, 2.40). The pooled estimate of the standardized mortality ratio from three studies was similar at 1.99 (95% CI 1.17, 3.40).

Breast Cancer

Breast cancer, the most common cancer among women, has multiple risk factors, including ionizing radiation (CDC 2025). These other risk factors receive varying consideration in the studies reviewed by the committee. Relevant to the work environment of flight crews, in 2020 the International Agency for Research on Cancer classified night shift work as “probably carcinogenic” (group 2A), noting epidemiological evidence for breast and other cancers (IARC 2020). Given these well-established risk factors for breast cancer, epidemiological studies of breast cancer in flight crew need to fully consider potential confounding by other key risk factors. For example, breast cancer risk rises with older age at first pregnancy; perhaps, flight crew defer pregnancy as they begin their careers. Disruption of circadian rhythm by night shift work is inherent to working as a member of the flight crew.

Thus, epidemiological studies on the breast cancer risk associated with GCR should include both accurate assessment of dose and collection of information on potential confounding and modifying factors, if a specific effect of occupational radiation exposure is to be estimated. The studies of incidence consistently show an increase in risk (see Figure E-5). The consistent association of being a member of the flight crew with increased breast cancer risk likely reflects the confluence of multiple factors including reproductive history, night shift work, and cosmic radiation exposure. To disentangle the effects of these different factors, accurate information is needed so that models can be used to estimate the risk associated with each. Two studies have such information.

Kojo and colleagues (2005) conducted a case-control study nested within a cohort of female flight attendants working for Finnish airlines. Information was collected by questionnaire from 27 women with breast cancer and a matched set of 103 controls. Using CARI-6² for various flight categories and self-reported flight history, individual exposures to GCR were estimated. Radiation exposure was not associated with breast cancer risk, while, notably, sleep disruption was associated with increased risk.

The cohort study carried out by the National Institute for Occupational Safety and Health (NIOSH) also addressed the breast cancer risk associated with GCR estimated with CARI-6P³, with consideration of reproductive exposure and circadian rhythm disruption (Pinkerton et al. 2016). Overall, radiation exposure was not associated with breast cancer risk. With stratification by parity, an increased risk was found for women with parity of three or greater (excess relative risk of 1.60 per 10 mGy⁴, 95% CI 0.14, 6.6).

A recent systematic review and meta-analysis by Weinmann and colleagues (2022) included studies published through January 2022. Nine studies were identified, with

² CARI-6 is an FAA-developed computational model used to estimate cosmic radiation dose, which has since been replaced by the newer CARI-7 model.

³ CARI-6P was developed for NIOSH for these retrospective health studies (see Copeland 2013).

⁴ Gy or Gray is the unit of ionizing radiation dose in the International System of Units. This is a unit for absorbed dose and has not been adjusted for radiation type and relative organ sensitivity.

four included in a meta-analysis. In a risk of bias assessment, one study was considered of high quality and the others of moderate quality. The pooled estimate of the SIR (i.e., the ratio of observed cases to the expected number based on the comparison population) was 1.43 (95% CI 1.32, 1.54). Analyses of the data from the two studies with estimates of GCR dose did not show clear indication of a positive dose–response relationship. Three studies addressed circadian rhythm disruption using surrogate exposure measures. The findings were ambiguous and compromised by small sample sizes in two studies.

Other Cancers

For prostate cancer, the evidence on incidence and mortality is quite mixed. A systematic review and meta-analysis of studies on pilots provided a significant, but small, increase in risk for incidence (Relative Risk 1.20; 95% CI 1.08, 1.33) (Raslau et al. 2016). The evidence was similarly mixed for brain cancer, thyroid cancer, and lymphomas and leukemias (see Appendix E).

Conclusion 3-1: While occupational risk of malignant melanoma among cockpit crew is well documented, the literature attributes this to ultraviolet radiation and not to cosmic radiation.

Conclusion 3-2: Flight attendants are at increased risk for breast cancer, but the causal factors are uncertain. Patterns of known risk factors may be responsible, including disruption of diurnal sleep rhythm. Follow-up research is needed that would consider the full array of known risk factors for breast cancer along with estimates of exposure to galactic cosmic radiation.

Conclusion 3-3: For other cancer sites assessed—prostate, brain, and thyroid—and for lymphomas and leukemias, the evidence was mixed and inconclusive.

EVIDENCE SYNTHESIS: REPRODUCTIVE OUTCOMES

Literature Identified

Reproductive outcomes constitute a diverse set of events that span from pre-pregnancy, (i.e., damage to sperm and ova with infertility) through pregnancy, and finally to the health of the infant at birth and in the perinatal period. Many factors influence the complex processes underlying these outcomes, and measurement of some of the outcomes themselves is challenging (e.g., miscarriage). Examples of such potential confounding and modifying factors for flight crew include use of tobacco products (and historic exposure to secondhand smoke), disruption of circadian rhythm, and workplace stress. The healthy worker effect, the phenomenon that employed populations tend to have better overall health than the general population or other occupational groups and may result in underestimation of health risk for that occupation, is also a consideration when interpreting the epidemiologic literature of an occupational group such as flight crew.

For the committee's assessment of the literature on reproductive outcomes, a total of 15 papers were identified that met its inclusion criteria (see PRISMA diagram in Appendix E for details on all articles identified). The papers were published between 1990 and 2025 and included seven cohort studies and eight cross-sectional studies. Four studies (27%) focused on military populations (some overlapping), while the remaining studies examined civilian flight crew. Most studies were of flight attendants (11 of 15, 73%), including one study that examined pilots as well as flight attendants; the remaining study populations included military aviation officers (N=4). Studies were conducted in the United States (N=9), Europe (N=5), and China (N=1). Across the studies, the reproductive outcomes most investigated were miscarriage or spontaneous abortion (SA), various birth outcome endpoints (including birthweight, preterm birth, and birth defects), sex ratios of offspring, and infertility. Additional outcomes (e.g., menstrual characteristics) were studied in three or fewer studies and are not summarized further in this report.

Synthesis of Results

The complete set of evidence tables is included in Appendix E. Here, the committee reviews the literature on reproductive outcomes and study results.

Spontaneous Abortion

Spontaneous abortion (SA) was the most commonly studied reproductive outcome (N=10). Studies that have monitored pregnancy intensely by tracking human chorionic gonadotropin show that many unrecognized pregnancies are lost during the first trimester; consequently, most epidemiological studies of SA are affected by measurement error related to the outcome (i.e., the outcomes that are measured are those that are identified; earlier losses are often not captured). Most studies (90%) were conducted among flight attendants for commercial airlines, with one study conducted among female aviation officers. The occurrence of SA was most frequently identified from self-report but also from medical records or a mixture of both sources. Surrogates for exposure to cosmic radiation were generally nonspecific and included measures such as "yes/no" to flying during pregnancy, occupational code, and years of work as a flight attendant. The only study to specifically estimate radiation dose was conducted by Grajewski and colleagues (2015), which utilized the Federal Aviation Administration's CARI-6P model. Results of the 10 studies were mixed, with a few showing elevated risks but most reporting no significant association between working as a flight attendant and SA (see Table E-9). For the single study that estimated radiation dose, the odds ratio for SA was 1.7 (95% CI 0.95, 3.2), for a cumulative absorbed total dose of 0.1+ v. <0.1 mGy.

Birth Outcomes

A variety of birth outcomes were examined in seven of the studies, most commonly low birthweight and preterm birth. Five studies included flight attendants only, and two

studies included female aviation officers in the military. Birth outcomes were identified from self-report, via medical records, or through a mixture of both. Only one study estimated radiation dose using the CARI-6P model (Irgens et al. 2003); all other studies used surrogates related to occupation or flight time. As seen in Table E-10, most studies reported nonsignificant results with effect estimates near, or often below, the null value for modeled results or the comparison group for crude comparisons.

Birth Defects

Birth defects were examined in five studies. Three studies included flight attendants only, one study included flight attendants and pilots, and one study included female military aviation officers. Birth defects were reported from a mixture of self-report, registries, and medical records. Only one study estimated radiation dose using the CARI-6P model (Irgens et al. 2003); all other studies used surrogates related to occupation or flight time. A study by dos Santos Silva and colleagues (2009) used air traffic control officers as controls, a group with similar sociodemographic characteristics, medical surveillance, and night shift work to flight crew. Overall, the studies did not report significant associations, with only one study of U.S. flight attendants reporting a statistically significant elevated risk of birth defects (McNeely et al. 2018; see Table E-11).

Sex Ratio

The ratio of male to female offspring among flight crew was examined in five studies, including four studies of flight attendants and one study of male military aviation officers. One study (Daniell et al. 1990) obtained the sex of offspring from medical records, while all other studies relied on self-report from the parent. Surrogates for radiation exposure were utilized in all of the studies. Overall, little evidence was found to indicate a difference in the ratio of male to female offspring among flight crew (see Table E-12).

Infertility

Four cross-sectional studies of flight attendants examined outcomes related to infertility, and all of these studies relied on self-reported outcome information. Surrogate measures related to occupation were utilized in all of the studies rather than direct measures of in-flight radiation exposure. An elevated risk of infertility was observed in one study of U.S. flight attendants; a significant difference was observed in a crude comparison of fertility among Chinese flight attendants versus ground crew, while two other studies reported no significant association (see Table E-13).

Limitations in the Literature

The committee found that studies on reproductive outcomes provide mixed outcomes and are of variable quality. Evidence regarding effects of radiation on reproductive

outcomes in flight crew was limited. The available literature is subject to important methodologic issues including few studies of most individual outcomes, the use of surrogates rather than direct measures of radiation exposure, self-reported outcomes, and cross-sectional survey designs rather than longitudinal designs. For SA—the most-studied outcome and one of great concern—the various approaches to outcome assessment are subject to substantial misclassification, and potential confounding factors are not well addressed. However, after discussion with stakeholders (as described in Chapter 2), the committee noted that adverse reproductive outcomes have been a concern for aircraft flight crew, extending from fertility through to pregnancy outcomes.

Conclusion 3-4: Observational studies on reproductive outcomes do not provide adequate evidence regarding potential health risks in relation to cosmic radiation exposure for any of the outcomes included in this review. A future research agenda is needed to address critical uncertainties for this topic of great concern to female flight crew.

COMMONALITIES AND LIMITATIONS

While many studies have been published on risks for cancer and adverse reproductive outcomes, few of the studies have incorporated estimates of exposure to cosmic radiation. Instead, most have used surrogates, such as duration of employment. Additionally, consideration of potential confounding and modifying factors has been limited. For many of the studies, sample sizes are inadequate, as is manifest in point estimates with wide confidence intervals.

Conclusion 3-5: In general, studies on the risks of galactic cosmic radiation (GCR) for flight crew have been limited by not having information on estimated exposure to GCR or on key potential confounders and modifiers. Inadequate sample size is an additional limitation of many studies. Without addressing these limitations, future epidemiological studies on GCR and solar energetic particle events in relation to the health of flight crew will not be informative on risk.

Chapter 5 of this report considers the feasibility of future epidemiologic investigations and potential study designs for both the cancer outcomes discussed in this chapter and reproductive health outcomes. It addresses how studies should be designed to address the limitations identified in this chapter. Additional cancer sites (e.g., prostate, testicular, and endometrial) and other health outcomes may warrant further study as the evidence base evolves.

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4

Evaluation of Computational Models

This chapter addresses the subtasks in the committee's charge to evaluate existing computational models that may be used to estimate radiation exposure of flight crew as well as health risk models. The Statement of Task includes the specific charges of selecting bounding flight routes to consider plausible worst-case radiation exposure routes due to galactic cosmic radiation (GCR) and solar energetic particle (SEP) radiation, and performing at least two cumulative radiation exposure assessments using different computational models. This chapter offers insight into the development of these radiation exposure estimation codes, parameters and inputs necessary to run such codes, and a comparison of the strengths, limitations, and uncertainties of the codes.

The first section of this chapter provides an overview of information used in computational models to estimate radiation exposures of flight crew and a description of how models are validated. Using the identified parameters, a comparison of selected codes, chosen from commonly cited codes in literature on exposures and risks, is presented. The committee then provides selection criteria to determine the codes used to perform cumulative radiation occupational dose assessments. A description of the methodology used for the exposure assessment follows, with parameters used in the assessments (including the selected flight paths to create bounding exposure scenarios) and inputs for each model. Individual results from each of the scenarios and flight paths are described. A framework for considering an occupational profile for flight crew, which includes pilots and flight attendants, is presented to offer examples of the potential magnitude of cumulative radiation exposure for flight crew.

OVERVIEW OF IMPORTANT PARAMETERS FOR RADIATION EXPOSURE ASSESSMENT OF FLIGHT CREW AND CURRENT VALIDATION OF MODELS

Extraterrestrial energetic charged particles, collectively known as cosmic radiation, continuously bombard Earth's Geospace environment. Two primary types of cosmic radiation exist: GCR, which originates outside the solar system and is always present, and SEP events, which occur sporadically and are associated with violent solar eruptions that can last from hours to days. Both GCR and SEPs have enough energy to penetrate Earth's atmosphere and aircraft shielding, increasing radiation exposure for air travelers and flight crew (Mertens and Tobiska 2021). In this chapter, GCR and SEP will be discussed separately, whereas in other chapters of the report the combination of GCR and SEP is referred to as cosmic radiation.

Three interconnected factors govern the intensity and variability of cosmic radiation in the atmosphere (Mertens et al. 2012). The first is the solar cycle, an approximately 11-year pattern of changing solar activity. The amount of GCR reaching Earth is influenced by competing processes: the outward flow of particles carried by the solar wind and the inward scattering of particles by the Sun's magnetic field, known as the interplanetary magnetic field (Parker 1965). During solar maximum, the stronger solar wind reduces the number of GCR particles reaching Earth, resulting in lesser occupational radiation exposure for flight crewmembers. During solar minimum, the opposite occurs. Many aviation radiation assessment models account for this cycle using a parameter called the solar modulation potential, which reflects the influence of solar activity on incoming GCR (e.g., Mertens et al. 2012). The relationship between the solar cycle and background GCR exposure is shown in Figure 4-1A.

The second factor is the amount of atmosphere above a given altitude, sometimes described as areal density or column-integrated mass. The atmosphere acts as shielding: the more air overhead, the more material cosmic radiation must pass through. As these particles move downward, they lose energy and interact with atmospheric atoms, changing both the energy distribution and composition of the radiation field (Copeland 2014; Matthiä 2009; Reitz 1993).

The component of GCR most relevant for radiation exposure consists of high-energy atomic nuclei that have been stripped of their electrons. These particles include nuclei from many elements in the periodic table. When they collide with atoms in the atmosphere, they fragment into smaller particles and produce cascades of secondary radiation. As a result, radiation levels increase with decreasing altitude until reaching a maximum at about 18 km (approximately 60,000 feet), known as the Pfotzer maximum (Hands et al. 2016). Below this altitude, radiation levels decrease. The general relationship between altitude, i.e. amount of atmospheric shielding, and effective dose is shown in Figure 4-1B.

The third factor affecting radiation exposure at aviation altitudes is Earth's magnetic field. The geomagnetic field provides shielding by deflecting incoming charged particles. This shielding is commonly described using the vertical cutoff rigidity, which is defined as the minimum momentum per unit charge required for a vertically incident

particle to reach a specific location above Earth's surface (Kress et al. 2004, 2010; Smart and Shea 2005). Geomagnetic shielding is strongest near the equator and weakest near the poles (Mertens et al. 2012). As a result, radiation exposure is generally greatest on polar routes and lowest near the equator. Because Earth's magnetic field is tilted and offset from a perfect dipole, cutoff rigidity varies with longitude as well as latitude. Solar-geomagnetic storms can temporarily alter the geomagnetic field and significantly change cutoff rigidities. The relationship between geomagnetic shielding and latitude is shown in Figure 4-1C.

SEP events can produce radiation with a nuclear composition similar to GCR (Mertens et al. 2023a, 2024). However, SEPs typically have lower energies than GCR particles, and only SEP protons substantially affect radiation exposure in the atmosphere. At 1 astronomical unit (AU), Earth's approximate distance from the Sun, GCR consists primarily of protons (about 90%) and helium nuclei (less than 10%), with the remainder made up of heavier nuclei and electrons (e.g., Gaisser 1990; Yang 2022). SEP radiation is likewise dominated by protons, with small contributions from helium and heavier nuclei, such that the similarity to GCR reflects the presence but much lower relative abundance of heavy ions (Mertens et al. 2023a, 2024). Examples of solar processes known to be associated with SEP events are shown in Figure 4-2.

Geomagnetic shielding affects SEP radiation more strongly than GCR radiation because GCR particles generally have higher energies. As a result, GCR exposure changes gradually with latitude. In contrast, SEP radiation is more strongly limited by geomagnetic shielding, and substantial SEP exposure typically occurs primarily at high latitudes. However, during major geomagnetic storms, reductions in cutoff rigidity can allow SEPs to penetrate to lower latitudes. Large geomagnetic storms are often associated with coronal mass ejections (CMEs). In some cases, a phenomenon known as a Forbush decrease occurs, in which the CME temporarily reduces the background GCR intensity while SEPs are arriving. This effect can offset SEP-related exposure in whole or in part and, in some situations, reduce total (GCR + SEP) radiation levels below pre-storm conditions (Getley et al. 2005; Mertens et al. 2023a, 2024).

The number of flight campaigns with publicly available, easily accessible radiation measurements over recent solar cycles remains limited. One key effort, the Radiation Dosimetry Experiment (RaD-X), produced high-quality dosimetric measurements spanning seven altitudes from 0 to over 32 km at a single cutoff rigidity (Mertens 2016; Mertens et al. 2016). These measurements were later used to validate the Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) model version 3 (Mertens et al. 2025).

Additional validation efforts have leveraged in-flight dosimeter data from commercial aviation. NAIRAS version 2, CARI-7A, and the Professional Aviation Dose Calculator (PANDOCA) were compared to measurements collected aboard two European commercial aircraft operating in 2007 and 2013 (Meier et al. 2018). More recently, NAIRAS version 3 calculations were evaluated against Automated Radiation Measurements for Aerospace Safety (ARMAS) dosimeter data from 45 flights conducted between 2022 and 2023 (Phoenix et al. 2024).

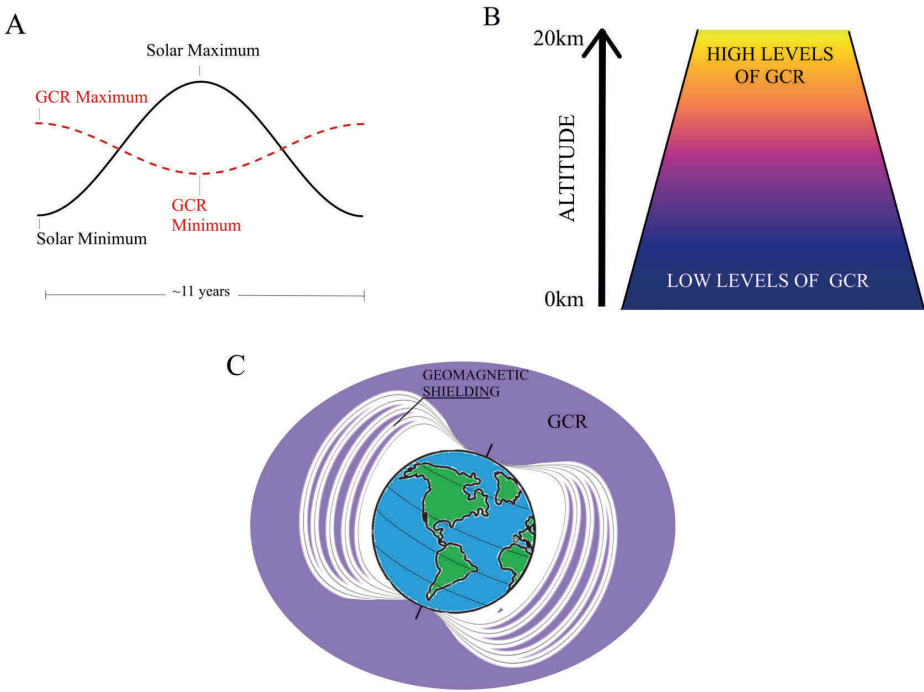


FIGURE 4-1 Important parameters for radiation exposure: (A) the inverse relationship between the solar cycle and GCR, (B) atmospheric shielding, and (C) variances in geomagnetic shielding across the globe with respect to latitude.

NOTES: (A) The solar cycle, impacted by the greater solar system, is influenced by factors such as solar winds and completes one rotation (from minimum to minimum) over an 11-year period. GCR is directly impacted by the solar cycle, and as the solar cycle reaches its maximum, GCR reaches its minimum. (B) In general, GCR exposure increases as altitude increases. (C) Geomagnetic shielding varies with higher latitudes, experiencing, on average, less geomagnetic shielding than lower latitudes. This shielding results in areas like the poles experiencing a greater impact from GRC.

The broader ARMAS data inventory includes more than 1,300 flights since 2013, encompassing National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) research aircraft, high-altitude balloons, commercial suborbital vehicles, orbital satellites, and commercial and corporate aircraft (Tobiska et al. 2016, 2018). To enable consistent comparisons with aviation exposure models, Phoenix and colleagues (2026) filtered the ARMAS database for flights with cruise altitudes between 8 km and 16 km and at least 45 minutes at cruise, yielding slightly more than 500 flights suitable for comparison with NAIRAS version 3.

Despite its breadth and public availability, the ARMAS dataset presents challenges. Most ARMAS altitudes are reported in geometric (i.e., Global Positioning System)

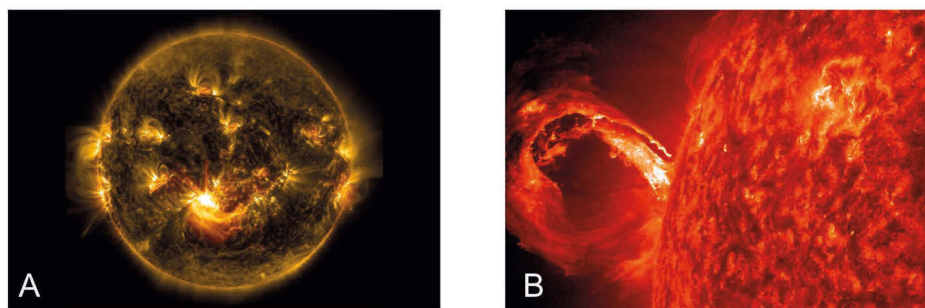


FIGURE 4-2 Solar storms: (A) Solar flares and (B) Coronal Mass Ejections

NOTES: Solar storms occur at random times throughout the solar cycle, with an average of 3.5 events occurring in an 11-year period. The level of radiation released from these events is dependent on both the type of storm and the individual event. (A) Solar Flares: Intense flashes or bursts of radiation from the sun releasing solar particles that can interact with objects like planes or satellites. (B) Coronal Mass Ejections: Large eruptions of plasmas or gas from the sun releasing solar particles that can interact with objects like planes or satellites.

SOURCE: (A) NASA/SDO n.d. (<https://www.nasa.gov/image-article/sun-release-m8-7-class-solar-flare-dec-17-2014/>). (B) Detail from NASA n.d. (<https://svs.gsfc.nasa.gov/10785/>). Credit: NASA's Goddard Space Flight Center/ Solar Dynamics Observatory/Atmospheric Imaging Assembly.

units, whereas aviation radiation models typically output results in barometric (i.e., pressure) altitude or flight levels, reflecting aircraft operations on constant pressure surfaces. This mismatch complicates direct model–measurement comparisons. Additional uncertainties arise from factors that are difficult to quantify, particularly because many measurements were obtained on scientific or experimental aircraft platforms with varying operational profiles. As a result, Phoenix and colleagues (2026) reported that further dedicated flight campaigns are needed, specifically campaigns designed to constrain key sources of uncertainty and ensure consistent altitude frameworks and operational conditions.

Overall, while RaD-X and ARMAS provide valuable validation datasets spanning more than a decade, the limited number of systematically controlled campaigns underscores the need for additional open, well-documented measurement efforts. Open science practices, including publicly accessible measurement databases and transparent, reproducible model runs, are essential to accelerate progress in quantifying aviation radiation exposure and developing predictive capabilities that remain reliable across the full range of GCR and SEP radiation environment conditions at aircraft-relevant altitudes. The committee found that while existing measurement campaigns have provided important benchmarks, the current body of publicly available, systematically collected data is limited and insufficient to fully characterize model uncertainties.

For meaningful model–measurement intercomparisons, effective dose, which is already computed by many models, should be reported consistently because radiation protection limits and recommendations are based on this quantity. Additional quantities,

including absorbed dose in silicon, absorbed dose in tissue, dose equivalent, and ambient dose equivalent, are also important; they interrogate different aspects of the radiation environment and reflect different aspects of either the data collection or modeling process. Accordingly, measurement campaigns that include multiple types of dosimeters capable of capturing these quantities would improve validation capability.

No single dosimeter or detector can fully characterize the aviation radiation environment because it is a mixed field composed of multiple particle types spanning a wide range of energies and differing contributions to radiation dose and health risk. As described in Chapter 2, accurate characterization therefore requires the use of multiple types of dosimeters and detectors, such as tissue-equivalent proportional counters and silicon-based detectors, each measuring different aspects of the radiation field and quantities relevant to radiation protection. In practice, measurement is further constrained by limited access to aircrafts and the impracticality of deploying comprehensive dosimeter and detector suites across commercial fleets. As a result, operational dose assessment in a radiation safety program would likely rely on computational models, with targeted measurement campaigns used to validate and refine model performance. Sustained validation is necessary because the radiation environment varies with the solar cycle and geomagnetic conditions and remains insufficiently characterized during solar energetic particle events. Regular validation campaigns are therefore essential to ensure that models remain representative of current conditions and capable of supporting reliable occupational dose estimates (see also Chapter 6).

Conclusion 4-1: The current body of publicly available, systematically collected aviation radiation measurement data is insufficient to fully characterize model uncertainties, particularly for solar energetic particle events. Sustained, coordinated measurement and validation efforts, supported by adequate long-term investment and interagency collaboration among the Federal Aviation Administration (FAA), the National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA) are necessary to improve model performance and to support more accurate dose estimates for flight crew.

Recommendation 4-1: The Federal Aviation Administration, in conjunction with the National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration, should collaborate on sustained measurement campaigns with dedicated resources to better characterize radiation environments at flight altitude and validate models, especially for solar energetic particles.

COMPARISON OF CODES TO ESTIMATE RADIATION DOSE

The committee derived a list of common considerations and parameters to use when comparing codes for its analysis, as summarized in Table 4-1. The committee utilized information from the International Commission on Radiological Protection (ICRP) and the U.S. National Council on Radiation Protection and Measurements (NCRP).

TABLE 4-1 Considerations for Selection of Computational Models

Consideration	Description
Spatial Resolution	Longitude, latitude, and altitude resolution for which radiation fields and protection quantities are evaluated along flight trajectories.
Geomagnetic Field Model/ Storming	Geomagnetic field and cutoff rigidity models used, including treatment of time-dependent geomagnetic disturbances (storm conditions).
Temporal Resolution	Time resolution of calculations and outputs, including representation of temporal variability in solar and geomagnetic conditions.
Input Requirements	Required operational and environmental inputs, such as flight path and relevant space weather indices.
Output Formats	Reported output forms, including numerical values and distributions of radiation protection quantities (e.g., dose rates and cumulative doses).
Computational Requirements	Computational resources, runtime, and software dependencies required for model execution.
Licensing/Software Acquisition	Accessibility of the model, including licensing conditions, user restrictions, and cost.
Human Phantom	Reference human model used for dose assessment, such as the ICRP reference phantoms and associated irradiation geometries.
Radiation Types	Ionizing radiation components considered including neutrons, protons, photons, electrons, positrons, heavy charged particles, and more exotic particles (e.g., pions and muons).
Energy Range	Particle energy ranges covered in radiation transport and dose conversion calculations.
Atmospheric/Shielding Model	Atmospheric density and composition models used, and treatment of aircraft structural shielding and attenuation.
Dose Quantities	Radiation protection quantities evaluated, such as effective dose, ambient dose equivalent, and organ or tissue absorbed dose, as defined by ICRP.
Verification and Validation Status	Extent of verification and validation against measured aviation radiation data, reference fields, and/or intercomparison benchmarks.
Key References	ICRP and NCRP publications, peer-reviewed articles, and technical reports supporting model development and validation.

While this list is not exhaustive, it provided an initial framework to guide the selection of methods to assess cumulative radiation exposure of flight crew, per the Statement of Task and task 2 in particular.

Selection Criteria for Committee’s Analysis

The committee used the following selection criteria and logic to determine codes to use for its two cumulative radiation exposure assessments with different computational models.

1. Use in existing literature and/or industry to estimate radiation exposure of flight crew.

Codes selected should be used by professionals and researchers in the field to reflect what would typically be done to estimate radiation exposure of flight crews.

2. Public accessibility of the code.

The codes should be easily and publicly accessible. This allows for the committee's analysis to be easily reproduced if desired. The amount of explanation and downloadable documentation of the code/availability of a user manual was also considered.

3. Ability to calculate SEP dose.

SEP events are considered by the committee to be the "plausible worst-case radiation exposure due to galactic and solar radiation." The codes chosen should be able to estimate the dose from these events.

4. Committee familiarity with the code.

This criterion was included to ensure that the analysis could be confidently performed within the time frame available for committee activities.

Based on the above criteria, the committee chose perform its analysis using four codes: AVIDOS, CARI-7A, NAIRAS, and SIEVERT. The committee ultimately chose a broad sample of publicly available codes that either an individual might encounter to calculate a dose from a flight or that researchers have used in published studies that provide dose estimates. Many of the key features discussed in Table 4-1 are summarized for the selected codes in Table 4-2. Code-specific methods used for this study are summarized in Appendix F.¹

CUMULATIVE RADIATION EXPOSURE ASSESSMENTS

Flight Paths

The variation of cosmic radiation with respect to the three variables discussed above provides the basis for selecting commercial aviation flight paths to evaluate the bounding cases of radiation exposure received by commercial flight crew. The altitudes are selected to represent the typical cruise flight levels for each aircraft flight path. Thus, the influence of atmospheric depth was not independently interrogated for flight paths for this study since they are determined by aircraft design, air traffic control, terrestrial weather, and other factors. However, a decrease in flight altitude during a SEP event can significantly reduce the increased exposure above background GCR (Mertens et al. 2012). The flight paths and datetime periods for the radiation exposure test cases are chosen to represent the expected maximum and minimum exposure levels (more detailed information on the datetime periods is in Appendix F). Five flight paths with

¹ Data files, processing code, and detailed methodological documentation are available in the committee's public access file.

TABLE 4-2 Summary of Selected Codes and Comparison of Key Features

Code	Access/ Licensing	Spatial Resolution	Geomagnetic/ Storming	Temporal Resolution	Inputs	Radiation Types	Atmosphere/ Shielding	Dose Quantities and Weighting Factors	Verification and Validation
AVIDOS	Public version available (Seibersdorf Laboratories) Web Interface	Global, cruise altitudes	Geomagnetic effects; storm capability noted	Solar-cycle based	Departure airport, arrival airport, departure time	GCR; SEP (storm- related enhance- ments)	Monte Carlo atmosphere; shielding not detailed	Effective dose; H* (10), ICRP 60, optional use of ICRP 103 (Beck 2015)	Former in-flight measurement campaigns
	Public (French Civil Aviation Authority or DGAC) Web Interface	Global 3-D dose maps	Implicit geomagnetic effects; SEP vis SIGLE	Monthly (GCR); event-based (SEP)	Flight plan	GCR; SEP	Operational transport models	Effective dose, ICRP 60 (Bottollier-Depois et al. 2003)	Institute for Radiation Protection and Nuclear Safety; the Paris Observatory, and the French Institute for Polar Research
CARI-7A	Public (U.S. FAA)	Route-based £300,000 ft	Cutoff rigidity; storm/Forbush options	Monthly to daily/hourly	Route altitude, date/time	GCR; SEP options	MC-derived atmosphere approximate shielding	Various including effective dose; ICRP 103 (Copeland 2021)	FAA documentation and testing - in conjunction with NOAA

continued

TABLE 4-2 Continued

Code	Access/ Licensing	Spatial Resolution	Geomagnetic/ Storming	Temporal Resolution	Inputs	Radiation Types	Atmosphere/ Shielding	Dose Quantities and Weighting Factors	Verification and Validation
NAIRAS	Public (U.S. NASA)	Global Grid Run-on- Request allowing custom trajectory files	Real-time geomagnetic variability	Hourly real-time; custom Run- on-Request trajectories at shorter intervals	Time, location, trajectory	GCR; SEP	Deterministic atmospheric transport	Various including effective dose; ICRP 60 (Mertens et al. 2025)	NASA validation studies through Space Weather Balloon measurement and aircraft measurements

five space weather conditions per flight path are selected for evaluation. The flight durations were chosen to represent realistic commercial flights between the airport city-pairs.

Tables 4-3 and 4-4 summarize the route selection and rationale used by the committee, as well as the solar weather conditions and the rationale chosen by the committee, respectively.

Methodology for Analysis

Four aviation radiation models were run² for the five flight paths (Table 4-3) and five space weather conditions (Table 4-4) using the dates and times listed in Appendix F (see Tables F-1 through F-3).³ Moreover, the model results are reported assuming zero

TABLE 4-3 Route Selection and Committee Rationale for Inclusion in Analysis

Flight Route	Exposure Category	Primary Sensitivity	Why This Route Was Selected
Hong Kong (HKG) to New York City (JFK)	Upper bound (global)	GCR and SEP	This long-duration transpolar flight includes extensive travel over polar regions, where geomagnetic shielding is weakest. It represents a reasonable upper bound for both background (GCR) and storm-driven (SEP) radiation exposure.
Los Angeles (LAX) to New York City (JFK)	Upper bound (U.S. domestic)	GCR and SEP	This long transcontinental flight represents the upper bound of radiation exposure for U.S. domestic routes. During strong solar and geomagnetic storms, SEP radiation can extend into mid-latitudes along this route.
London (LHR) to Los Angeles (LAX)	Intermediate	GCR and SEP	This long transatlantic route includes substantial travel at high latitudes. Radiation exposure is higher than most domestic flights but generally lower than transpolar routes.
New York City (JFK) to London (LHR)	Intermediate	GCR and SEP	Similar to LHR–LAX, this route represents an intermediate exposure case. Radiation exposure is particularly sensitive to geomagnetic storm conditions.
Dallas–Fort Worth (DFW) to Miami (MIA)	Lower bound	GCR	This short-duration, low-latitude flight experiences strong geomagnetic shielding and represents a reasonable lower bound for radiation exposure to commercial flight crew.

² Results were calculated by individual committee members. The documented methodologies for using each model can be found in Appendix F. Subsequently, a minimum of one other committee member checked each calculation and reviewed the input parameters, verifying the outputs.

³ AVIDOS and SIEVERT do not explicitly permit the user to define ascent and descent rates.

TABLE 4-4 Solar Weather Conditions and Committee Rationale for Inclusion in Analysis

Space Weather Condition/ Event	Exposure Type	Relative Exposure Role	Characterization	Why This Condition Was Selected
Solar Cycle 24 Maximum (SC24 Min)	GCR	Lower bound	Solar maximum	Represents a lower bound for GCR exposure, as higher solar activity increases solar wind shielding and reduces GCR intensity near Earth.
Solar Cycle 24 Minimum (SC24 Max)	GCR	Upper bound	Solar minimum	Represents an upper bound for GCR exposure. Solar Cycle 24 exhibited an unusually deep minimum and weak maximum, resulting in elevated GCR exposure relative to earlier solar cycles.
Halloween 2003 Event-E1A (October–November 2003)	SEP	High SEP intensity	High SEP flux, moderate geomagnetic storm	Characterized by the largest solar proton flux during the Halloween 2003 storm sequence, representing a case of high SEP intensity with less extreme geomagnetic suppression.
Halloween 2003 Event-E1B (October–November 2003)	SEP	Expanded spatial exposure	Moderate SEP flux, strong geomagnetic storm	Occurred during maximum geomagnetic cutoff suppression, allowing SEP radiation to penetrate to lower latitudes and expand the geographic extent of exposure.
January 20, 2005, Event (E2)	SEP	Peak SEP exposure	Short-lived, intense SEP event	Characterized by a large, rapid peak in SEP flux and associated radiation exposure, with relatively modest geomagnetic disturbance during the peak.

aircraft shielding. This is a justifiable assumption since the effect of the aircraft structure on the internal radiation environment is smaller than or comparable to the uncertainty of onboard dosimeter measurements at commercial aviation altitudes (Mertens et al. 2016, 2025). The radiation models were run with comparable parameter settings to the extent possible. For example, default NAIRAS SEP predictions include SEP heavy ion contributions to exposure; to ensure consistency with the other models, however, only SEP proton contributions to exposure were included in the NAIRAS SEP computations. Step-by-step procedures for each model run are in Appendix F. Effective dose is a radiation protection quantity related to the overall health risk from ionizing radiation exposure, and it forms the basis for occupational limits and recommendations for occupational radiation–exposed workers (ICRP 1991, 2007). Variations in the definition and implementation of effective dose across models necessitate careful and coordinated comparisons to better understand differences among codes.

Results: AVIDOS

AVIDOS calculations were performed using the European Space Agency Space Weather Service Network interface,⁴ requiring registration to gain access to the public and aircrew versions of AVIDOS.⁵ The public version was used to perform analyses for the flight paths specified in Table F-1 through F-3 by defining the departure city/datetime and arrival city/datetime as appropriate. The effective dose from ICRP Publication 103 was chosen as the output quantity of interest. SEP events are not broken out by GCR and SEP based on the version used. Results are summarized in Table 4-5.

Results: CARI-7A

Maintained by the Federal Aviation Administration (FAA), CARI-7A calculations were performed on a Dell Latitude 7350 detachable laptop running Windows 11 Pro (Intel®Core™ Ultra 7 164U processor with 16 GB RAM). GCR analyses were

TABLE 4-5 Summary of AVIDOS Results (μSv)

AVIDOS	SC24 MIN	SC24 MAX	SEPE1A	SEPE1B	SEPE2
HKG–JFK	76	62	58	58	374
LHR–LAX	57	42	43	43	278
JFK–LHR	35	26	27	27	67
LAX–JFK	22	17	17	17	30
DFW–MIA	8	6	7	7	9

⁴ See <https://swe.ssa.esa.int/avidos-federated>.
⁵ The Public and Aircrew versions of AVIDOS were found to output the same results for a single flight. The Aircrew version allows the user to define multiple waypoints to compute total exposure in the interface. It also allows the user to upload a waypoint file to compute exposures for user-defined trajectories.

performed first for the flight paths specified in Table 4-3 using inputs summarized in Table F-1 through F-3. Default parameters were used for the calculations, and the International Organization for Standardization local interstellar spectra modulated using the CARI-6 heliocentric potential at 1 AU was used as the boundary condition GCR spectrum. SEP analyses were performed for the same flight paths separately by creating boundary condition SEP flux spectrum files from the corresponding analyses in NAIRAS. The effective dose from ICRP Publication 103 was chosen as the output quantity of interest. The calculations performed produced separate GCR and SEP dose components for each SEP event, represented as the GCR dose component plus the SEP dose component, respectively. Results are summarized in Table 4-6.

Results: NAIRAS

The NAIRAS version 3 computations were performed using the Community Coordinated Modeling Center (CCMC) run-on-request (RoR) service (Mertens et al. 2023b). Great circle route trajectory files were constructed based on the flight path information listed in Table F-1 through F-3. The time interval between trajectory points was 1 minute for each flight path. The trajectory files were uploaded to the NAIRAS RoR interface.⁶ The default magnetic field model option was selected, which consists of the International Geomagnetic Reference Field for the internal magnetic field model and the TS05 for the magnetospheric magnetic field model for the datetime periods of the flight computations in this report. The “protons only” option was selected for the SEP model. The output quantities selected were dosimetric quantities computed at the trajectory points and the time-integrated dosimetric quantities accumulated over the total flight path. NAIRAS calculates effective dose based on the weighting factors of ICRP Publication 60 (ICRP 1991; Mertens et al. 2013). The NAIRAS RoR computations for this study are publicly available from CCMC (see Appendix F), and links to detailed reports and publications on NAIRAS version 3 are also accessible via the NAIRAS RoR interface at CCMC. The calculations performed produced separate GCR and SEP dose components for each SEP event, represented as the GCR dose component plus the SEP dose component, respectively. Results are summarized in Table 4-7.

TABLE 4-6 Summary of CARI-7A Results (μSv)

CARI-7A	SC24 MIN	SC24 MAX	SEPE1A (GCR + SEP)	SEPE1B (GCR + SEP)	SEPE2 (GCR + SEP)
HKG–JFK	109	89	91 (73 + 18)	68 (63 + 5)	113 (81 + 32)
LHR–LAX	89	71	71 (59 + 12)	54 (49 + 5)	89 (65 + 24)
JFK–LHR	49	40	33 (33 + 0)	27 (27 + 0)	36 (36 + 0)
LAX–JFK	26	22	20 (20 + 0)	17 (17 + 0)	21 (21 + 0)
DFW–MIA	6	5	5 (5 + 0)	4 (4 + 0)	5 (5 + 0)

⁶ See <https://ccmc.gsfc.nasa.gov/models/NAIRAS~3.0/>.

TABLE 4-7 Summary of NAIRAS Results (μSv)

NAIRAS	SC24 MIN	SC24 MAX	SEP E1A (GCR + SEP)	SEP E1B (GCR + SEP)	SEP E2 (GCR + SEP)
HKG–JFK	196	172	200 (101 +99)	107 (64 + 43)	295 (105 +190)
LHR–LAX	161	136	169 (87 + 82)	92 (53 + 39)	234 (87 + 146)
JFK–LHR	91	78	49 (49 + 0)	38 (30 + 8)	51 (49 + 2)
LAX–JFK	52	45	31(31 + 0)	24 (20 + 4)	31 (31 + 0)
DFW–MIA	13	12	9 (9 + 0)	6 (6 + 0)	8 (8 + 0)

Results: SIEVERT

SIEVERT calculations were performed using the publicly accessible version at the French Authority for Nuclear Safety and Radiation Protection.⁷ Analyses were performed for the flight paths specified in Table 4-3 by defining the departure city/ datetime and arrival city/datetime as appropriate (using information in Table F-1). “Subsonique” was specified for the type of aircraft. The effective dose from ICRP Publication 60 is the default weighting factor used for the output quantity of interest. SEP events are not broken out by GCR and SEP based on the version used. Results are summarized in Table 4-8.

Comparison of Results

The total flight effective doses (herein referred to as total flight doses) for the five flights and the five space weather conditions are shown in Tables 4-5 through 4-8, as computed by the AVIDOS, CARI-7A, NAIRAS, and SIEVERT models, respectively (see Appendix F for all settings and options used for each model; inputs and configurations were kept as consistent as possible).

For each space weather condition, a broad distribution in total flight dose exists depending on the specific flight path. Thus, an individual flight crewmember’s career

TABLE 4-8 Summary of SIEVERT Results (μSv)

SIEVERT	SC24 MIN	SC24 MAX	SEP E1A	SEP E1B	SEP E2
HKG–JFK	120	88	74	74	99
LHR–LAX	95	68	56	56	78
JFK–LHR	51	37	31	31	42
LAX–JFK	35	28	23	23	31
DFW–MIA	10	8	7	7	9

⁷ See <https://www.sievert-system.org>.

exposure depends on the detailed history of career flight profiles (flight dates and times, geographic flight distribution, and solar–geomagnetic conditions). Figures 4-3 and 4-4 compare calculated effective radiation doses across different flight paths (see Table 4-3) using the four committee-selected computational models under the identified solar weather conditions (see Table 4-4). Figure 4-3 shows how dose estimates differ between solar maximum and minimum. Figure 4-4 shows calculated dose estimates during the 2003 Halloween SEP event at two stages of storm intensity for each flight path; Figure 4-5 shows the dose estimates for the high-intensity SEP event in January 2005.

The total flight doses computed by the NAIRAS model for the longest-duration, high-latitude, and low-cutoff flights (HKG–JFK and LHR–LAX) are comparable for the largest SEP proton flux event during the Halloween 2003 storm period (E1A) and the minimum of Solar Cycle 24. This is due to greater GCR exposure during recent epochs of solar cycle activity and is partially attributable to the Forbush decrease during the Halloween 2003 storm period. The CARI-7A model’s SEP computations used an SEP spectrum averaged over the flight durations, due to model interface limitations in specifying a fully dynamic SEP proton flux spectrum within the time frame of the writing of this report. The SEP averaged spectrum will underestimate the effective dose compared to the fully dynamical calculations of NAIRAS because none of the flight paths entirely overlap regions where the SEP radiation is unshielded by the Earth’s magnetic field. Another noteworthy observation from the results in Tables 4-5 through 4-8 is that the total flight dose for the JFK–LHR north Atlantic corridor flight is nearly the same for events E1A and E1B, even though the SEP proton flux is significantly diminished in E1B compared to E1A. The large geomagnetic storm during E1B, which allowed the SEP proton flux to penetrate to lower latitudes, explains this observation. The transatlantic flights between the United States and Europe along the north Atlantic corridor are sensitive to geomagnetic activity during SEP events. The January 20, 2005, SEP event (E2), shown in Figure 4-5, was not accompanied by a large geomagnetic storm, but the SEP proton peak flux was the largest observed in decades and the total flight doses for the long-duration and high-latitude, low-cutoff rigidity flights during this time were the greatest in this study. The global radiation environment is complex and dynamic. Assessing the radiation exposure to flight crew requires sophisticated, well-validated, and thoroughly documented computational models that reliably represent the complex spatiotemporal variability of the cosmic radiation environment and the geomagnetic field.

Model comparisons of effective dose can differ by a greater degree than the measurable quantities, depending on the specific version of ICRP weighting factors used for computing the effective dose. The different ICRP weighting factors reflect the uncertainty in the biological effectiveness of the ionizing radiation field. For example, the uncertainty in the radiation effectiveness, a quantity analogous to the ICRP weighting factors, for a neutron-dominated radiation environment such as the atmosphere is a factor of four (Copeland 2014; Kocher et al. 2005; Matthia 2009). Estimated doses thus demonstrate variations of 20–50 percent across solar weather conditions.

The NAIRAS model provides a conservative calculation of effective dose by using weighting factors from ICRP Publication 60 (ICRP 1991; Mertens et al. 2012, 2013).

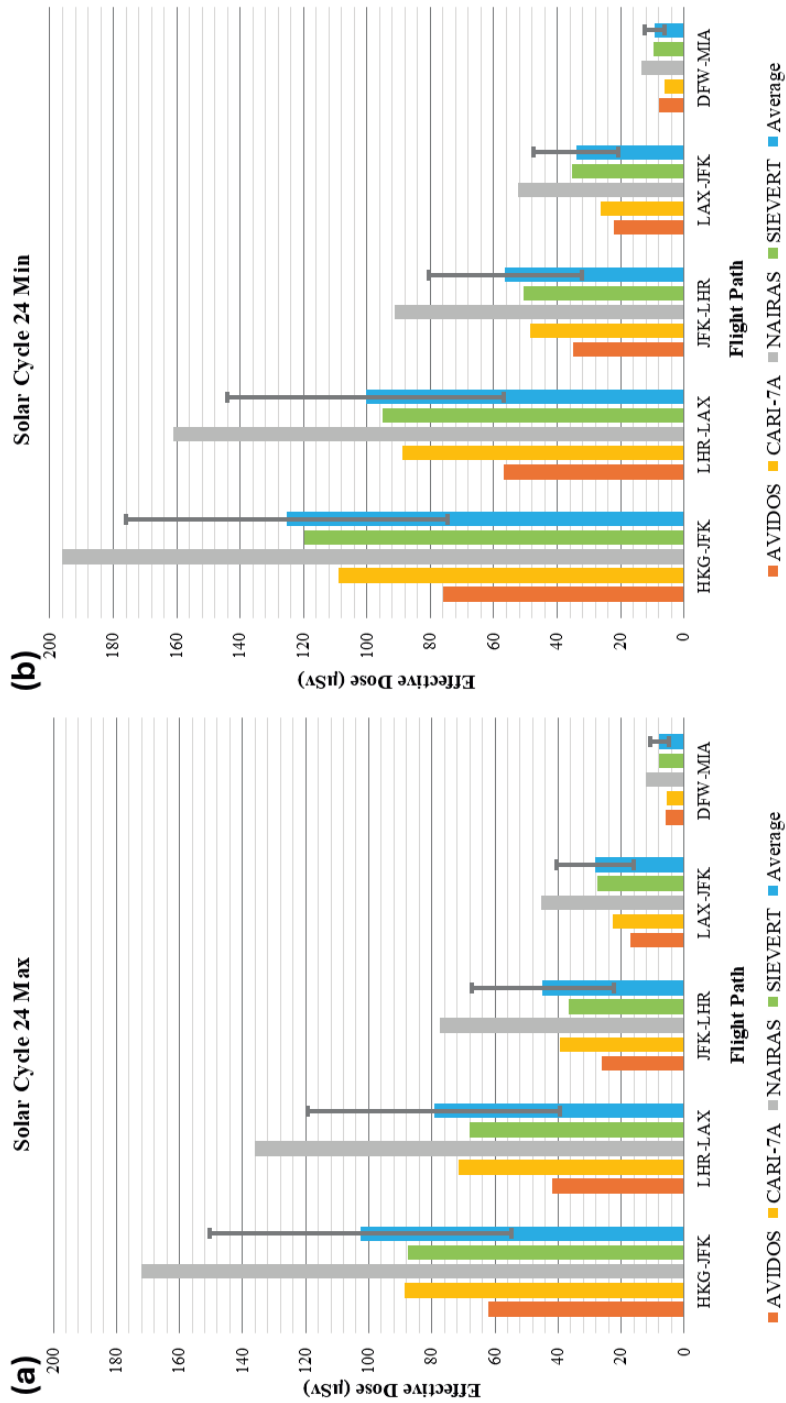


FIGURE 4-3 Effective dose calculated for individual flight paths for each code in (a) Solar Cycle 24 under solar maximum condition and (b) Solar Cycle 24 under solar minimum condition.
NOTE: The error bars for the code-averaged value are the standard deviation.

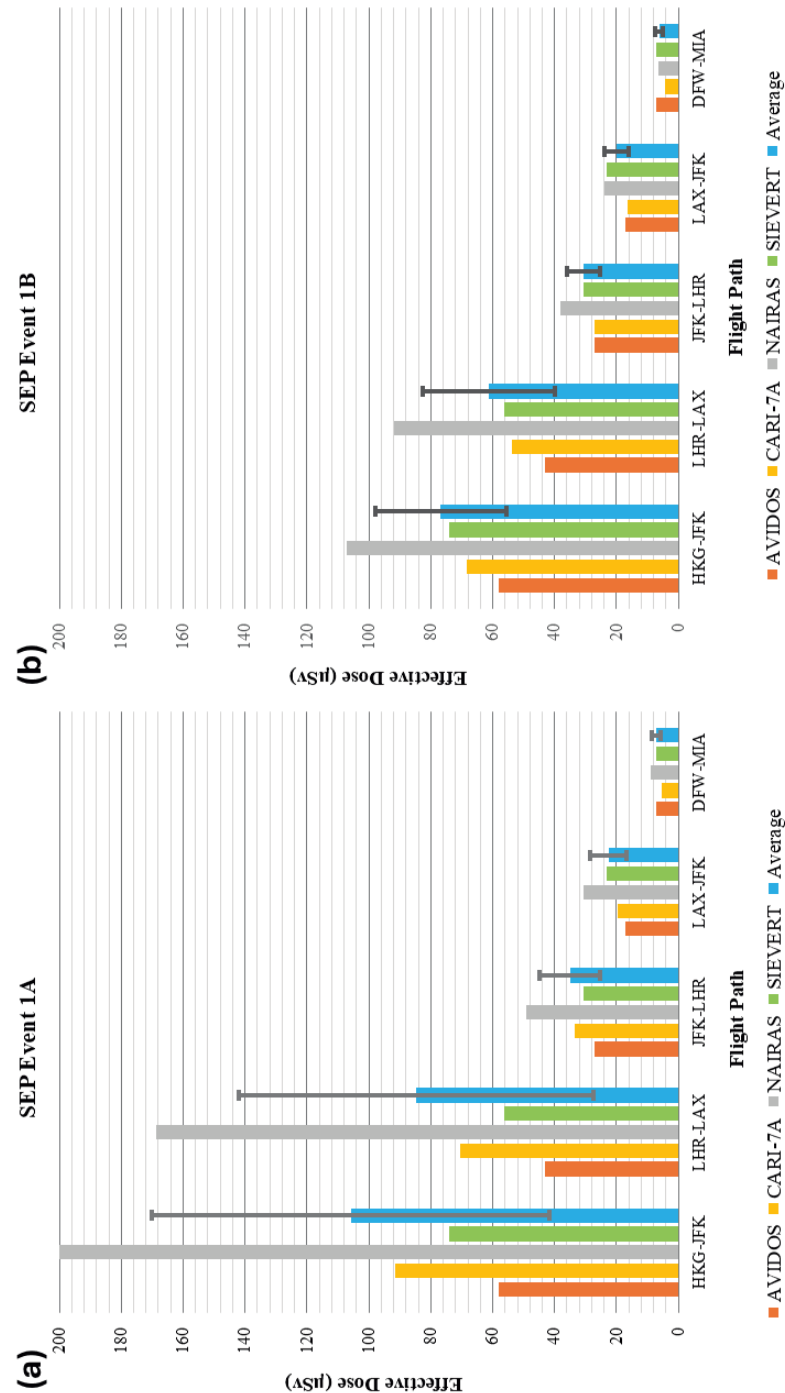


FIGURE 4-4 Effective dose calculated for individual flight paths for each code during the 2003 Halloween SEP event at two different time points: (a) when the storm exhibited strong SEP flux and moderate geomagnetic storming, and (b) when the storm exhibited moderate SEP flux and strong geomagnetic storming.
NOTE: The error bars for the code-averaged value are the standard deviation.

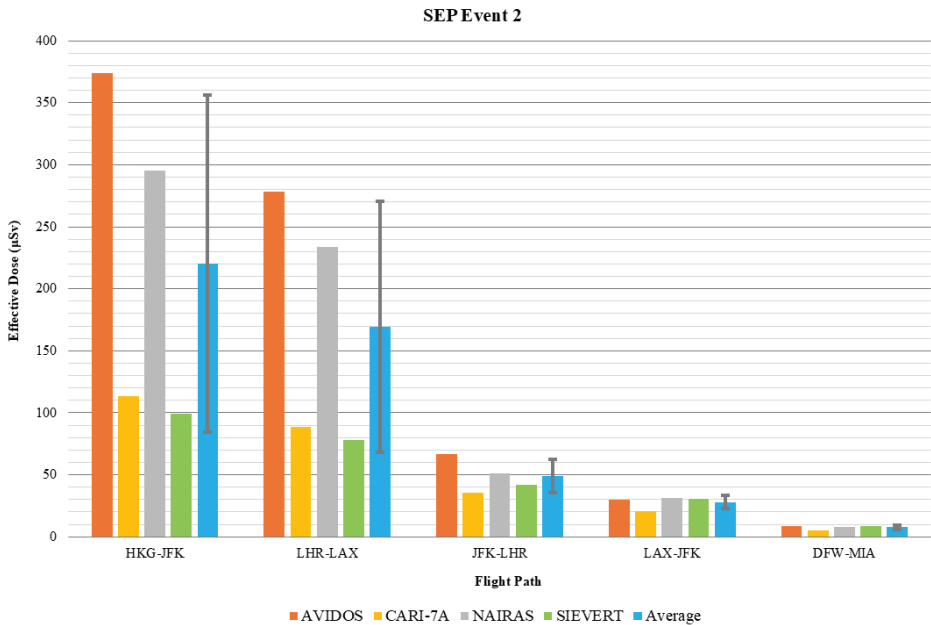


FIGURE 4-5 Effective dose calculated for individual flight paths for each code during the January 2005 event that exhibited a short-lived but intense SEP flux.
NOTE: The error bars for the code-averaged value are the standard deviation.

The CARI-7A results in this report were calculated by using the weighting factors of ICRP Publication 103 (ICRP 2007) because other aviation radiation models are also based on these weighting factors. These different sets of weighting factors alone can account for more than 30 percent of the differences in computed effective dose for GCR conditions (Copeland and Friedberg 2021).

From published literature and other code comparisons, current models that estimate radiation-absorbed dose produce results that are 20–30 percent in agreement with one another for SC24 solar minimum and maximum GCR environments and for measurable quantities (e.g., absorbed dose in tissue, absorbed dose rate in silicon, and ambient dose equivalent), which is the same level of variation in contemporary individual dosimeter measurements (ICRU 2010; Lindborg et al. 2004; Meier et al. 2018; Mertens 2016; Phoenix et al. 2024, 2026). Averaging among model results is one way to account for variations among computational models. Radiation exposure models produce the greatest disagreement when estimating dose during SEP events. This uncertainty is due to limited direct measurements of the solar radiation spectra and the impact of geomagnetic activity on cutoff rigidity during these events to validate the models. Such systematic evaluation could also provide a framework to examine how differing radiation weighting factors (e.g., ICRP Publication 60 and 103) contribute to variability and uncertainty in effective dose estimates across models. Future and more rigorous evaluations should investigate intrinsic aircraft shielding geometry with respect to dose.

Conclusion 4-2: Existing computational models used to estimate aviation radiation exposure differ primarily in their treatment of solar energetic particle (SEP) events. Differences in the representation of particle energy spectra, geomagnetic storm effects, model inputs, and the calculation of effective dose, including the dose coefficients applied, contribute to variability in estimated effective dose for flight crew, particularly for SEP events.

Recommendation 4-2: The Federal Aviation Administration, in collaboration with other organizations that develop aviation radiation exposure models, should systematically evaluate computational models under realistic operating conditions to better characterize their uncertainties and biases. This evaluation should establish a methodology for using an ensemble of models to assess variability and improve estimates of flight crew radiation exposure, particularly for transpolar routes and during solar energetic particle events.

BOX 4-1

Solar Weather Patterns and Contemporary Examples

Solar Cycle 24 (SC24) has the deepest solar minimum and one of the smallest, weakest solar maxima in the Space Age. This pattern appears to be repeating in SC25 (NWS n.d.). As a result, air travelers and flight crew are currently subject to larger radiation exposure rates than in any previous period in the Space Age.

A solar storm erupted on the Sun's surface and produced three X-class solar flares over a 3-day period from November 9, 2025, to November 11, 2025 (Space Weather Prediction Center n.d.). The solar storm was also associated with streaming high-energy protons accelerated by CMEs, which reached the Earth over a period from November 10, 2025, through November 13, 2025. This so-called SEP event began on November 10, 2025, at approximately 11:25 UT when the >10 MeV integral proton flux crossed the threshold of 10 particle flux units (pfu). Another burst of high-energy solar protons, with >100 MeV and >500 MeV integral proton flux exceeding 1 pfu, arrived on November 11, 2025, at approximately 10:20 UT. By 15:00–16:00 UT, the ionizing radiation dose rates at commercial and corporate aviation altitudes (11–15 km) exceeded background levels ranging from a factor of four at 11 km to roughly a factor of 10 at 15 km. At 20 km, the altitude range of high-flying military aircraft, the radiation dose rates exceeded background levels by a factor of 20. For example, if someone flew during this event from HKG to JFK or LAX to JFK at the peak dose rate, the total flight dose received would have been between 400–600 μ Sv (calculated using the NAIRAS model).

FRAMEWORK FOR OCCUPATIONAL PROFILE

The logical underpinning of the development of occupational profiles for aviation flight crews at typical transit altitudes follows the precedent set by the NCRP, both for standard terrestrial radiation–exposed workers and high-altitude flight crews, including numbers of working hours and working years. Specifically, the NCRP issued Commentary No. 12 in 1995, which defined flight crew occupational profiles in terms of estimations of length of time that a given member of the flight crew would be exposed to enhanced levels of ionizing radiation during flight, annually and during the course of a 47-year career (age 18 to 65).⁸ While 14 CFR § 135.265 limits the maximum allowable flight time for any flight crew to 1,200 hours (h) in any calendar year, 14 CFR § 121.471 further limits the maximum allowable flight time for any member of the flight crew involved in domestic operations to 1,000 h in any calendar year. Accordingly, NCRP Commentary No. 12 assumes that flight crews will not exceed 1,000 h of annual flight time, and this forms the conservative basis for the profile of domestic flight crews considered in this work, with a 47-year career defined as 47,000 hr of total flight time. For context, additional profiles will be considered for “representative flight crew,” “frequent travelers,” and “conventional travelers,” at 700 hr, 100 hr, and 10 hr per year, respectively. These categories are intended as illustrative benchmarks for comparison; depending on individual travel patterns (both as a flight crewmember or a member of the public), a given flyer may fall between one of these categories. No distinction is made among pilots and other flight crewmembers because differences in radiation exposure due to geometry and aircraft material shielding are negligible.

Occupational Profile Calculations

The occupational profile comparisons were calculated through an equal-weight,⁹ four-model average of outputs per flight path given time-averaged SC24 solar minimum and maximum conditions, and the tables present a comparison of the annual and career doses for all occupational profiles derived as an equal-weight, four-model average of model outputs for all flight paths, also given time-averaged SC24 solar minimum and maximum conditions. Given study limitations, the committee selected this “averaged” approach as its ideal means of assessing the cumulative flight crew doses produced by the models—that is, the data presented consider a non-real scenario where occupants travel only one flight path back and forth for their entire sum of block hours worked. A more realistic consideration of flight crew exposure, beyond the scope of the present assessment, would assess a more varied set of hours and flight paths flown across a year or career. To produce occupational dose profiles from averaged model outputs, the average values generated were evaluated across the range of temporal intervals reflecting

⁸ The committee acknowledges that commercial airline pilots in the United States typically range from 25 to 65 years old, as stated in Chapter 1. However, it chose to use 1995 commentary as a base comparison.

⁹ Scaling or benchmarking information for performing inter-model flight dose comparisons is not currently available. For general assessments, the four models under consideration were averaged equally to present trends in data outputs.

annual flight time by occupational category, resulting in an average effective dose by occupational class. Note that the career evaluations include the dose contribution of a single worst-case E2 SEP as well as three E1 SEP during the occupants’ total career interval. Table 4-9 presents the solar minimum and maximum averaged as well as the code-averaged single-flight output(s) for comparison with individual outputs presented earlier in the chapter.

Annual Occupational Profile

Table 4-10 and Figure 4-6 represent the projected annual occupational flight profile experienced by various types of flyers. Note that the whole-body effective dose values represented here are doses received beyond doses due to U.S.-average background radiation, which is approximately 3.1 mSv per year (EPA n.d.). According to existing regulatory standards for radiation-exposed workers, the allowable U.S. annual ionizing radiation dose to the public above background from regulated activities is 1 mSv¹⁰; this line is denoted in Figure 4-6.

47-Year Career Occupational Profile

Table 4-11 and Figure 4-7 represent the projected career occupational flight profile(s) received by various types of flyers. These profiles represent bounding (i.e., maximum) scenarios for occupational doses received. Using the 47-year career also takes into account different types of flight crew (i.e., pilots, who have a set retirement age, versus flight attendants, who do not). These results are for discussion purposes; true occupational profiles would require knowledge of the specific flight paths taken and the dates of each flight.

TABLE 4-9 Model-Averaged and Solar-Condition-Averaged Single-Flight Hourly and Total-Flight Whole-Body Effective Dose Received by Occupants for All Flight Trajectories Considered (mSv)

Flight Path	Average Whole-Body Effective Dose Received per Hour (mSv)	Average Whole-Body Effective Dose Received per Flight (mSv)
HKG–JFK	0.009	0.14
LHR–LAX	0.010	0.11
JFK–LHR	0.010	0.06
LAX–JFK	0.011	0.06
DFW–MIA	0.009	0.02

¹⁰ See, for example, 10 CFR § 20.1301 for the Nuclear Regulatory Commission as well as 10 CFR § 835.208 and DOE Order 458.1, Change 3, § 4.b for the U.S. Department of Energy.

TABLE 4-10 Model-Averaged and Solar-Condition-Averaged Cumulative Annual Occupational Flight Profile Doses for All Flight Trajectories (mSv)

Flight Path	Flight Crew (max) (1,000 hr/yr)	Flight Crew (avg) (700 hr/yr)	Frequent Travelers (100 hr/yr)	Conventional Travelers (10 hr/yr) ^a
HKG–JFK	7.4	5.2	0.74	0.07
LHR–LAX	8.1	5.7	0.81	0.08
JFK–LHR	7.9	5.7	0.82	0.08
LAX–JFK	5.7	4.0	0.56	0.06
DFW–MIA	3.3	2.3	0.33	0.03

^a Note that some flight durations exceed 10 hours. These averages are weighted across the entire flight to produce a “per hour” average for that particular trajectory (temporal data are sacrificed), and then that hourly rate is multiplied back across the time range of interest.

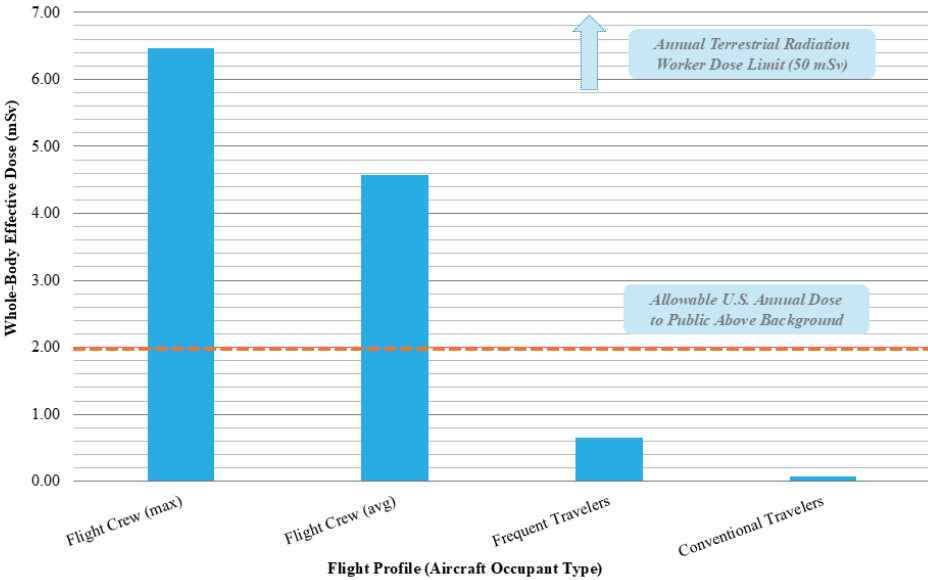


FIGURE 4-6 Model-, trajectory-, and solar-condition-averaged annual doses to aircraft occupants by occupational profile.

NOTES: “Max” refers to 1,000 flight hours per year, and “avg” refers to 700 flight hours per year. Traveler profiles and relevant contextual dose levels are included for reference. The whole-body effective dose is in addition to the dose received from U.S. average background exposures, which result in approximately 3.1 mSv accumulated dose per year.

TABLE 4-11 Model-Averaged and Solar-Condition-Averaged Cumulative 47-Year Career Occupational Flight Profile Doses for All Flight Trajectories Considered (mSv)

Flight Path	Flight Crew (max) (1,000 hr/yr)	Flight Crew (avg) (700 hr/yr)	Frequent Travelers (100 hr/yr)	Conventional Travelers (10 hr/yr)
HKG–JFK	348	244	26	3.9
LHR–LAX	381	267	28	4.2
JFK–LHR	372	203	27	3.9
LAX–JFK	265	186	20	2.8
DFW–MIA	155	109	13	1.6

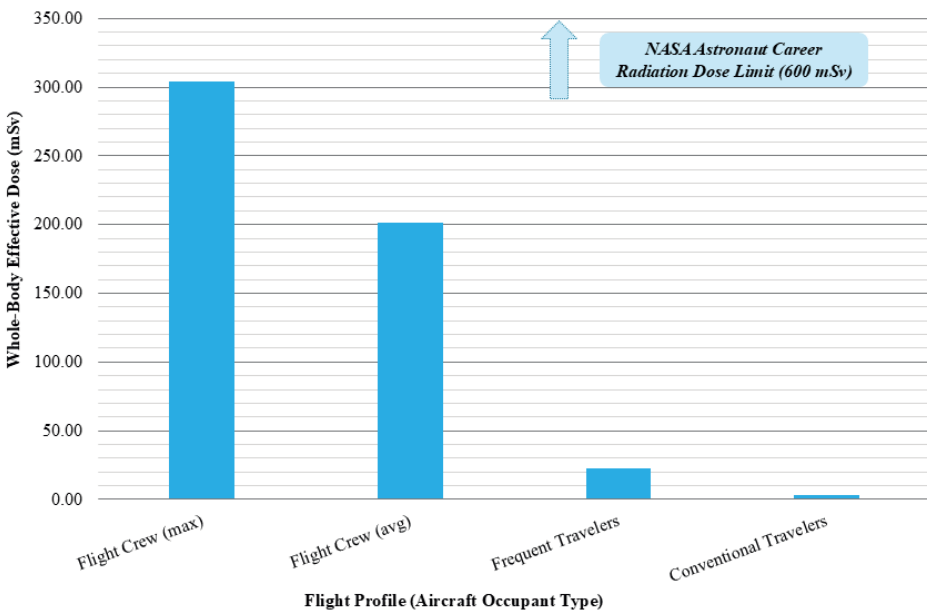


FIGURE 4-7 Model-, trajectory-, and solar-condition-averaged career doses to aircraft occupants by occupational profile.
NOTES: “Max” refers to 1,000 flight hours per year, and “avg” refers to 700 flight hours per year. Traveler profiles and relevant contextual dose levels are included for reference. “Career” is defined for the purposes of analysis as a combination of 47 years’ worth of flight dose plus one E2-type SEP dose and three E1-type SEP doses.

Discussion of Results

The results from the annual and career occupational profiles enable an understanding of the sensitivity of particular flight trajectories and worker profiles to incurred radiation dose. Figure 4-8 presents a depiction of the great circle trajectory and the four-model-averaged flight crew doses for four of the flight paths modeled under averaged solar radiation conditions.

In the context of the model averages, the flight trajectory with the greatest immediate dose environment per flight (HKG–JFK) does not correlate to the occupational profiles with the greatest incurred dose per year or career (LAX–LHR and JFK–LHR);

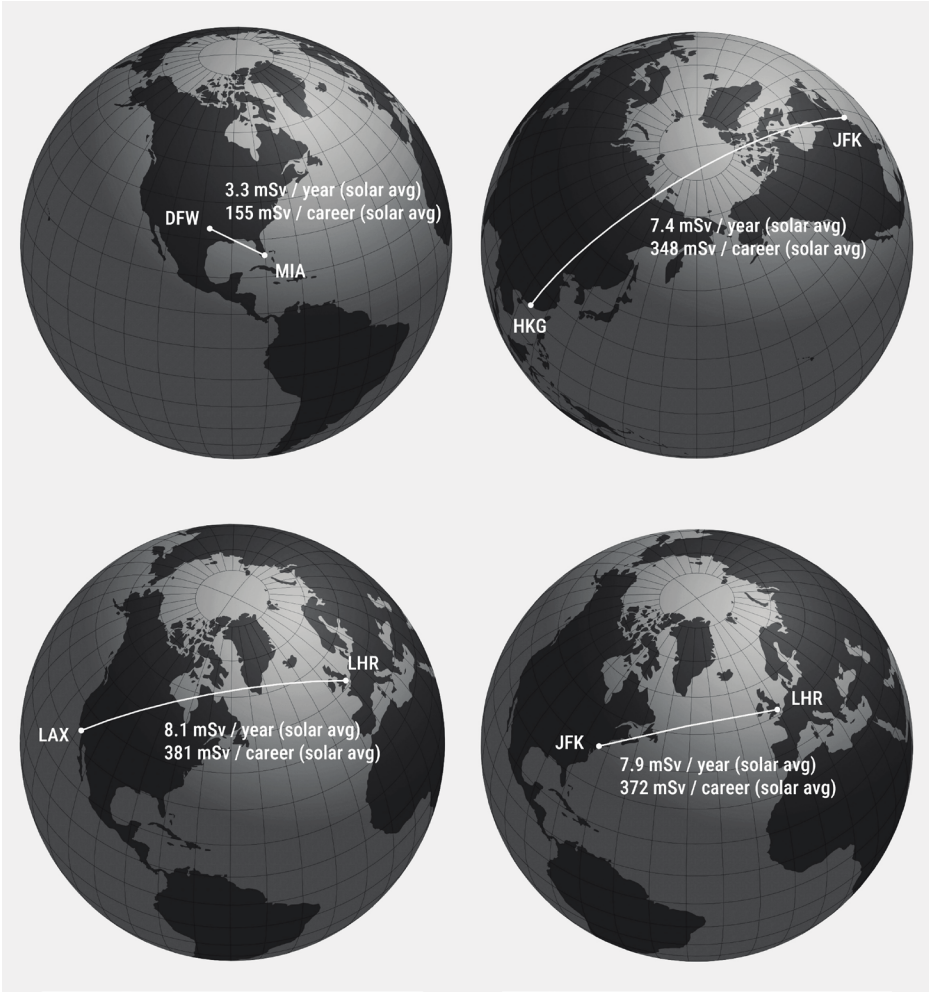


FIGURE 4-8 Great circle trajectories and associated four-model-averaged flight crew doses for each of the four flight paths modeled under averaged solar radiation conditions.
SOURCE: Generated by committee, tool from © 2017-2026 Markus Englund, using GoogleMaps and data from openflights.org.

the high-latitude transpolar and transpacific flight (HKG–JFK) is longer and spends less time in the highest-exposure environment (latitude) compared to the total flight path, and fewer of these flights can be flown in a given year, yielding a lower effective dose per year. Although some artificiality exists in this approach, the salient takeaway is that flights that pass through the greatest physical radiation environment may not operationally result in the highest overall worker doses (e.g., due to spatiotemporal practicalities), and more frequent flights through milder radiation environments might provide the occupational limiting case(s).

Conclusion 4-3: Dose from a flight depends on dose rate across the time spent in the air along a particular route. While latitudes closest to the magnetic poles are associated with the highest dose rate, routes that spend longer durations in near-polar latitudes may result in higher estimated total flight dose than polar routes with shorter durations through regions of the highest dose rates.

Importantly, when considering the 47-year career profile and accounting for the natural frequency of SEP events, the cumulative dose profile is not substantially impacted by these events. However, they do offer a higher dose for a given flight and may be relevant when considering exceeding recommended occupational dose limits for shorter time frames (e.g., bearing in mind pregnant flight crew).

Potential Variability in Occupational Doses

Figures 4-9 and 4-10 and Tables 4-12 and 4-13 explore and contrast the specific model outputs for time-, trajectory-, and solar-cycle-averaged conditions. Again, note that the career evaluation also includes the contribution for a single worst-case E2 SEP event and three milder E1 SEP events during the occupants' 47-year interval.

Conclusion 4-4: Even under conservative modeling assumptions that incorporate realistic worst-case flight paths, the projected annual occupational dose remains well within current FAA-recommended limits for non-pregnant workers.

Conclusion 4-5: Career doses for nominal to conservative projections indicate that workers would benefit from having their occupational doses tracked to better understand long-term exposure and accumulation of relatively small annual doses over the worker's career.

USING CODES TO EVALUATE OCCUPATIONAL DOSE

The committee reviewed numerous publicly available codes that can be used to estimate occupational dose for individual flights. However, no comprehensive ensemble framework currently exists to guide airlines, regulatory bodies, or agencies in selecting among these models to calculate radiation exposure to flight crew. This lack of

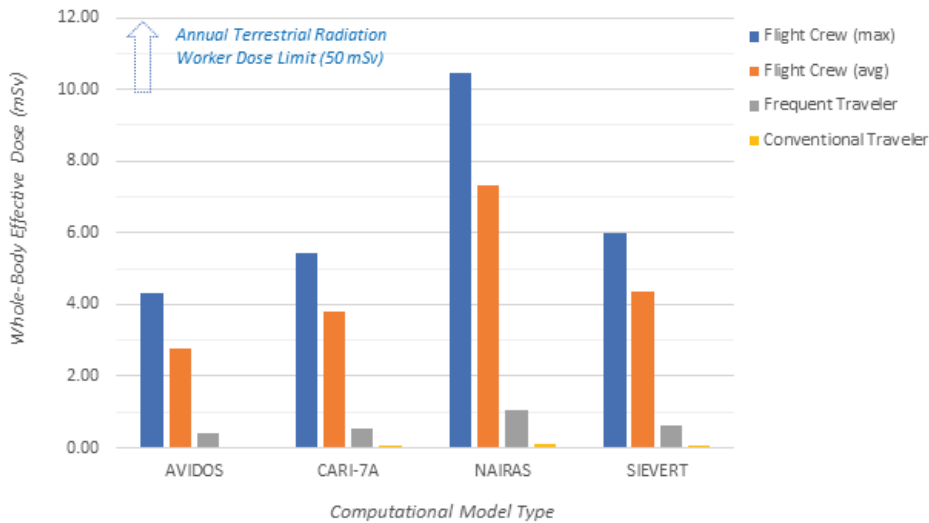


FIGURE 4-9 Comparison of modeled annual doses to aircraft occupants under trajectory- and SC24 solar-cycle-averaged conditions for each occupational profile.
NOTES: “Max” refers to 1,000 flight hours per year, and “avg” refers to 700 flight hours per year. Traveler profiles and the annual regulatory whole-body dose limit for current U.S. radiation-exposed workers (50 mSv) have been included for reference.

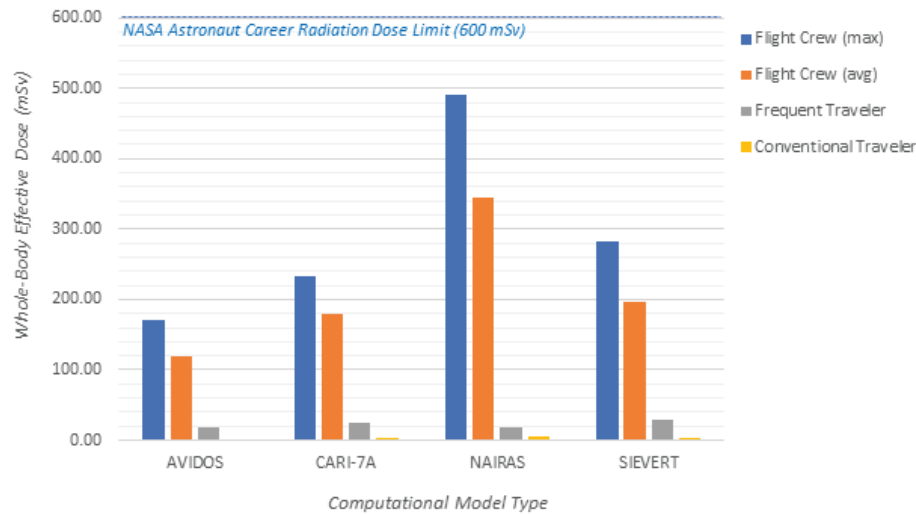


FIGURE 4-10 Comparison of modeled career doses to aircraft occupants under trajectory- and SC24 solar-cycle-averaged conditions.

TABLE 4-12 Annual Occupational Flight Profile Exposures for Time-, Trajectory-, and SC24 Solar-Cycle-Averaged Conditions (mSv)

Model Type	Flight Crew (max) (1,000 hr/yr)	Flight Crew (avg) (700 hr/yr)	Frequent Travelers (100 hr/yr)	Conventional Travelers (10 hr/yr)
AVIDOS	4.3	2.8	0.40	0.04
CARI-7A	5.5	3.8	0.54	0.05
NAIRAS	10	7.3	1.0	0.10
SIEVERT	6.0	4.4	0.62	0.06

TABLE 4-13 47-Year Career Occupational Flight Profile Exposures for Time-, Trajectory-, and Solar-Cycle-Averaged Conditions (mSv)

Model Type	Flight Crew (max) (1,000 hr/yr)	Flight Crew (avg) (700 hr/yr)	Frequent Travelers (100 hr/yr)	Conventional Travelers (10 hr/yr)
AVIDOS	171	120	19	2.1
CARI-7A	233	179	26	2.7
NAIRAS	491	344	19	5.2
SIEVERT	282	197	28	3.0

NOTES: “Max” refers to 1,000 flight hours per year, and “avg” refers to 700 flight hours per year. Traveler profiles and regulatory astronaut career dose limit are included for reference. “Career” is defined for the purposes of analysis as a combination of 47 years’ worth of GCR flight dose plus one E2-type SEP dose and three E1-type SEP doses.

standardization introduces uncertainty in model-based estimates. For its analysis, the committee applied an equal-weighted average of model outputs, reflecting the absence of an established basis for preferential weighting among models and providing a neutral approach for intercomparison.

The committee considers the broader implications of these results in two key areas. First, acute exposure concerns, particularly for pregnant aircrew, underscore the importance of improved characterization and modeling of SEP events, where short-term increases in dose may be operationally relevant. As shown in the section Comparison of Codes to Estimate Radiation Dose and highlighted in Box 4-1, certain flight routes and solar conditions can result in exposures of several hundred μ Sv during a single flight. Although such events are rare, occurring on the order of three to four times per 11-year solar cycle, they approach dose levels of concern for pregnant flight crew.

As noted in Chapter 2, the FAA recommends adopting the occupational dose limits established by ICRP, with current guidance recommending no more than 1 mSv for the

duration of the pregnancy (ICRP 2007).¹¹ However, U.S. policy requires that such limits be applied only if a worker voluntarily declares pregnancy under the Declared Pregnant Worker framework. Established by the Nuclear Regulatory Commission in its revision to 10 CFR 20 in the early 1990s (10 CFR 20.1003) and reinforced by legal precedent (e.g., *UAW v. Johnson Controls* and the Pregnancy Discrimination Act), this framework ensures that reproductive decisions rest solely with the worker. Employers may provide counseling, monitoring, or work modifications only after a formal declaration and cannot impose pregnancy-based restrictions without it, even if a pregnancy is apparent.

Conclusion 4-6: Pregnant flight crew may exceed the more protective pregnant worker dose limits recommended by the FAA; the imposition of limits upon flight crew is bound by the voluntary Declared Pregnant Worker framework.

Second, with respect to long-term exposure, the analysis supports the need for sustained tracking and monitoring of radiation exposure for flight crew. At the same time, the results suggest that existing models are sufficiently mature for this purpose, as SEP-related contributions are unlikely to affect total career dose relative to GCR substantially. The results also indicate that because estimated annual doses are well below recommended dose limits, associated health risks remain within accepted low-risk bounds. These results indicate that the available tools, if implemented appropriately, could support both guidance for pregnant workers and long-term dose tracking for all flight crew.

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¹¹ Note that in the FAA Advisory Circular 120-61B, published in 2014, for a nonpregnant air carrier crewmember, the FAA-recommended limits for exposure to ionizing radiation are the same as those recommended by ICRP. However, in the case of a pregnant crewmember, in addition to the normal occupational limit, the FAA recommends she limit ionizing radiation exposure of her conceptus to no more than 0.5 mSv per month.

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5

Epidemiologic Approaches to Understand Health Risks

The Statement of Task (SoT) asks the committee to “determine availability and types of individual exposure information and health data as well as knowledge gaps and limitations for potential epidemiologic studies.” Epidemiology studies ways that disease and health are spread among groups of people and what factors—such as environments and exposures—are linked to specific health effects. In approaching this element of the SoT, the committee interpreted the charge as asking for an exploration of the feasibility of epidemiologic studies on the health risks posed by cosmic radiation—the combination of galactic cosmic radiation (GCR) and solar energetic particles (SEPs)—to flight crew. In proposing studies to address these questions, the committee recognized that critical limitations of prior studies would need to be addressed, as enumerated in Chapter 3: lack of dose estimates for cosmic radiation, inadequate sample sizes, and insufficient consideration of potential confounding and modifying factors.

This chapter begins by describing why epidemiologic research is needed to address the health outcomes associated with occupational radiation exposure for flight crew. The committee outlines key epidemiologic research considerations, including the feasibility of investigations using flight information and dose models, as well as the need to ensure sufficient statistical power to detect anticipated elevations in risk for critical health endpoints. Next, the committee examines approaches for translating exposures into lifetime risk, emphasizing the importance of improved characterization of cumulative radiation dose across a career through the creation of a program for tracking radiation doses. Building on this foundation, approaches for epidemiologic research, including study designs for cancer and reproductive outcomes to advance understanding of radiation risks, are presented. The chapter concludes with a summary of how epidemiology can strengthen understanding of radiation exposure and health outcomes among flight crew.

EPIDEMIOLOGIC RESEARCH IS NEEDED

Occupational epidemiology examines patterns of disease among workers to identify hazards, quantify their risks in relation to exposures, and inform strategies for prevention (Wegman 1992). Studies of chronic disease etiology have linked workplace exposures, such as asbestos, to adverse health outcomes, providing evidence that has informed protective standards for workers and, in some cases, for the broader population (Stayner et al. 2013). In settings for which regulatory standards are limited or absent, epidemiologic evidence may serve as the primary basis for risk recognition and policy development. This occupational health framework is directly applicable to evaluating potential health risks associated with ionizing radiation exposure for flight crew.

Several reasons exist for considering epidemiologic studies of flight crew: (1) as discussed in Chapter 3, review of the current literature finds that the majority of existing studies use crude radiation exposure proxies, resulting in mixed and limited evidence on critical health outcomes; (2) cosmic radiation creates a distinct environment from the ionizing radiation exposure experienced by the atomic bomb survivors, the main population continuing to inform risk models; and (3) a properly designed epidemiologic surveillance system could become a platform for quantifying the effects of longitudinal exposure to cosmic radiation.

While the evidence reviewed by the committee had methodological limitations, elevated risk for malignant melanoma was documented in cockpit crew, attributed to ultraviolet radiation exposure; the literature also showed elevated breast cancer risk, albeit not specifically linked to radiation exposure. Risks for several other cancers have been examined in epidemiologic studies using occupation as a broad proxy for radiation exposure, but exposure estimates were lacking in these studies. The effects of ionizing cosmic radiation exposure on reproduction and pregnancy outcomes are also a concern for flight crew, but epidemiologic evidence is sparse. As concluded in Chapter 3 (Conclusion 3-5), studies on the risks of cosmic radiation exposure for flight crew generally have been limited by not having information on estimated radiation exposure or on key potential confounders and modifiers. Inadequate sample size is an additional limitation of many studies. Without addressing these limitations, future epidemiologic studies on cosmic radiation in relation to the health of flight crew will not be informative on risk.

Conclusion 5-1: Appropriately designed and adequately powered epidemiologic studies of flight crew are needed to address gaps in the current evidence regarding associations between in-flight radiation exposure and risks for adverse health outcomes.

As context for this component of the SoT, the committee formulated three priority questions that could be addressed through epidemiologic research on flight crew around cancer and reproductive outcomes, the two key health outcomes identified in Chapter 3. The questions were developed based on current understanding of the risks of ionizing radiation, the literature review (see Chapter 3), the committee's public information-gathering efforts, and stakeholder input. These questions are as follows:

- What are the patterns of cancer incidence and mortality in flight crews, and are these patterns associated with ionizing cosmic radiation exposure?
- Do observed excess cancer risks align with estimates from standard epidemiologic radiation risk models, including those based on the Life Span Study (LSS) of Hiroshima and Nagasaki atomic bomb survivors, or do they diverge substantively from those model predictions?
- Do the rates of unfavorable reproductive outcomes differ from expectations based on comparison populations?

EPIDEMIOLOGIC RESEARCH CONSIDERATIONS

Study Designs

Well-established study designs, including those reviewed in Chapter 3, are used in occupational epidemiology. The cohort design is central; it follows workers over time to compare rates of disease in exposed and unexposed groups. Cohort studies may be conducted retrospectively, using employment records and historical data to reconstruct exposures and outcomes, or prospectively, enrolling participants and collecting exposure and other relevant information before disease occurs. Large registry-based occupational cohorts (e.g., Nordic worker cohorts) and agency-based prospective cohorts (e.g., National Institute for Occupational Safety and Health [NIOSH] cohorts) illustrate these approaches. In both designs, accurate exposure assessment was essential, particularly when evaluating exposure–response relationships. Thus, a potential study would require

- the identification of well-defined cohorts of flight crew (e.g., all those working for a particular airline);
- the ability to access, reconstruct, or generate dose estimates for the individuals in the study cohort;
- a mechanism for linking to and/or tracking the health outcomes of interest, such as cancer and adverse reproductive outcomes, even if a flight crewmember moves to a different airline or leaves the workforce;
- consideration of potential confounding and modifying factors for the health outcomes under investigation; and
- longitudinal follow-up, retrospectively and/or prospectively.

In addition to considering these factors, addressing the general challenges of occupational epidemiology is necessary (see Table 5-1). The committee's proposals for potential studies are attentive to these challenges as they apply specifically to epidemiologic research on flight crews.

Tracking Flight Crew Doses

The committee identified a tiered approach to deepen understanding of the risks to flight crew from cosmic radiation. This approach is based on the methods of surveillance and research in occupational health (Koh and Aw 2003). The foundational starting

TABLE 5-1 Challenges in Occupational Epidemiology Studies

Challenge	Considerations
Exposure Misclassification	• Assuming job category is representative of all worker exposure • Lack of individual exposure measurements • Lack of cumulative exposure data • Inaccurate or incomplete historical records or recall
Confounding	• Unmeasured lifestyle and nonoccupational factors • Smoking and smoke exposure status • Reproductive history • Psychological factors: stress
Methodological Limitations	• Potential selection bias • Small sample size • Healthy worker bias • Latency and insufficient time of follow-up • Gender bias

point is to monitor and track doses for individuals to characterize the accumulating dose over time. Subsequently, additional steps are to develop strategies for dose mitigation and to create a research platform. The committee considers the subsequent steps with the establishment of dose tracking, outlined in Table 5-2, as constituting epidemiologic research, albeit sequenced from population-level description of in-flight doses received and the health of flight crew to more focused studies (e.g., on breast cancer and on pregnancy loss).

Population-Based Tracking of Radiation Dose: A Foundation for Future Epidemiologic Research

Epidemiologic surveillance involves the systematic collection, analysis, and dissemination of health data to support the planning, implementation, and evaluation of public health programs (Thacker 2000). In occupational settings, the integration of exposure surveillance and health outcomes research has proven effective in protecting workers’ health, creating a continual feedback loop that enables the identification of hazardous conditions and the assessment of how exposures affect health outcomes (see Table G-1). Outside of the occupational health space, other surveillance programs, such as the National Cancer Institute’s Surveillance, Epidemiology, and End Results (SEER) program, demonstrate how population-based data can generate robust and policy-relevant evidence (Friedman and Negoita 2024).

Historical precedent (e.g., SEER, Centers for Disease Control and Prevention [CDC], and NIOSH surveillance programs) and foundational public-health principles (Thacker 2000) suggest that a national registry-based surveillance program for flight crew cosmic radiation dose could provide a framework for broader and more timely, coordinated, and cost-efficient research than multiple isolated retrospective or prospective epidemiologic studies. Additionally, with advances in data interoperability

TABLE 5-2 Key Elements to Assess Radiation Risks to Flight Crew

Assessment Component	Key Elements	Purpose/Application
Exposure/Dose Monitoring and Estimates	- Personal dose modeling and measurements based on crew flight history, enabling the construction of dose across a career	Characterizes cumulative radiation dose and variability across individuals to support risk estimation and identification of higher-exposure groups
Health Outcome Assessment (as feasible)	- Quantification of flight crew exposure distributions to enable calculation of uncertainty and identification of those at risk of elevated exposure	Enables detection of patterns or elevated risks in flight crew populations
	- Tracking with employee health records for key endpoints of concern, including potential linkage to exposure records	
Descriptive Epidemiology (incidence and mortality)	- Establishing population cohorts to track, assess, and identify flight crew health indicators that differ from those of the general population and flag incidence of health endpoints of concern	Describes disease patterns and generates hypotheses about potential associations with radiation exposure
	- Describing trends for key indicators of flight crew health	
Analytical Epidemiology Studies (exposure–disease relationships)	- Designing comparative analyses of flight crew health compared with nonexposed populations	Tests associations between radiation exposure and health outcomes and supports causal inference
	- Identifying sentinel events and clusters of health outcomes of concern	
	- Prospective and retrospective cohort studies to quantify the relationship between risk of disease and cumulative radiation dose	
	- Targeted case-control studies comparing flight crew with the health outcome of interest to healthy controls, controlling for potential confounding factors	

and health informatics, this is an opportune time to integrate occupational data with longitudinal health records to conduct such research.

The widespread emergence of digital data enables research that leverages existing platforms for the systematic capture of exposure and health data. Carrier employment information or crew management systems can be utilized as a foundational source for cohort formation and subsequently linked to electronic health record systems, administrative databases (e.g., Centers for Medicare & Medicaid Services [CMS] or the National Death Index), cancer registries, and other disease registries.¹ This health information can be paired with cosmic radiation doses estimated using available computational models (see Chapter 4) and maintained in the tracking database to assess hazard and estimate dose–response relationships. Such linkages could be executed periodically to maintain an updated, research-ready data resource.

Conclusion 5-2: A national tracking system to capture and archive radiation doses would provide timely and coordinated evidence to support epidemiologic research, improve risk assessment, and guide risk management decisions. With advances in data interoperability and health informatics, this is an opportune time to integrate occupational dose data with longitudinal health records.

Recommendation 5-1: The Federal Aviation Administration should work with appropriate agencies, such as Centers for Disease Control and Prevention / National Institute for Occupational Safety and Health, to establish a dose tracking system for flight crew. Such a system would enable U.S. airlines and individual flight crewmembers to monitor doses and to make decisions to manage them. The system would also facilitate epidemiologic research by providing standardized dose information for study participants. Periodic matches of the dose tracking data with health and mortality databases would support ongoing assessment of the population health of flight crew.

Study Population

Chapter 1 provides an overview of the demographics of current and past flight crew populations. Here, the committee reviews the number of potential participants for conducting epidemiologic studies, considering current and past workers. Determining that a study population of sufficient size is available is a key step in deciding whether an epidemiologic study should be done. To identify potential flight crew participants, researchers would need to collaborate with one or more major U.S. airlines and with unions representing flight attendants and pilots.

Estimates of the percentage of pilots by airline were derived from publicly available Bureau of Transportation Statistics (BTS) Air Carrier Financial Schedule P-10 data (Bureau of Transportation Statistics 2024). Multiple annual datasets were compiled and combined, and the total number of pilots was aggregated by airline and year. Percentages

¹ See <https://www.nih.gov/health-information/nih-clinical-research-trials-you/list-registries>.

were then calculated by dividing the number of pilots for each airline by the total number of pilots in the corresponding year. Person-year estimates were developed using baseline employment counts for pilots and flight attendants from the U.S. Bureau of Labor Statistics, combined with assumptions about workforce growth, tenure, and follow-up (Bureau of Labor Statistics 2025a; 2025b) over a 24-year period. Assumptions regarding flight attendant tenure were informed by published epidemiologic literature (e.g., McNeely et al. 2014), and pilot career duration was based on minimum entry age and mandatory retirement age (Bureau of Labor Statistics 2025b). Multiple scenarios were evaluated using different growth rates, mortality assumptions, and loss-to-follow-up rates to reflect uncertainty in workforce dynamics and long-term tracking. Across these scenarios, person-year estimates were calculated by projecting cohort expansion over time and summing annual contributions from both initial and newly entering workers, providing a range of plausible estimates for cumulative follow-up time.

Using this approach, the committee estimates that approximately 350,000–370,000 individuals worked as flight attendants between 1999 and 2023. The corresponding estimate for commercial pilots is approximately 48,000–54,000. When expanded to include all aircraft pilots, copilots, and flight engineers, the estimate increases to approximately 145,000–161,000 individuals. If all flight crew employed during this period could be identified and followed for outcomes, the maximum population potentially available for study would be approximately 531,000 individuals, representing approximately 4.6–6.3 million person-years² of observation between the years of 1999 and 2023, depending on how well individuals can be followed after they leave the workforce—ranging from no follow-up after leaving the workforce to up to 24 years of follow-up, accounting for mortality, right censoring in 2023, and a low attrition rate. These estimates are summarized in Table 5-3. Note that they do not account for individuals who left and later re-entered the workforce. Additionally, the demographics in Table 1-2 offer the 2023 estimated totals compared to this estimate of cumulative workforce that could be followed for a potential study.

According to Bureau of Transportation Statistics (2024) data, the airlines with the largest proportion of the pilot/copilot workforce between 1990 and 2020 were American Airlines Inc. (13.6%), Delta Air Lines Inc. (13.4%), and United Airlines Inc. (11.3%). Using these numbers, the committee estimated the approximate number of individuals who could be included in a study conducted within a single airline. Assuming the proportion of flight attendants to pilots is stable across airlines, a retrospective study of American Airlines or Delta Air Lines flight crew from 1999 to 2023 would have approximately 72,000 individuals with 626,000 person-years, and a study of United Airlines would have approximately 60,000 individuals with 520,000 person-years. A combination of all three major carriers would yield a study with approximately 204,000 individuals and 1.8 million person-years.

² Person-years represent the total amount of time that individuals in a study population are observed and at risk for the outcome of interest. One person-year represents follow-up of one individual for 1 year or multiple individuals for a cumulative total of 1 year.

TABLE 5-3 Estimated Cumulative Number of Flight Crew Potentially Available for Epidemiologic Research, United States, 1999–2023

Occupational Group	Estimated Total Individuals	Key Assumptions
Flight Attendants	350,000–370,000	2- to 7-year average career; 9% annual attrition (Bureau of Labor Statistics 2025b)
Commercial Pilots	48,000–54,000	25- to 35-year average career; 4% annual attrition (Bureau of Labor Statistics 2025a)
All Pilots, Copilots, and Flight Engineers	145,000–161,000	Expanded cockpit crew definition
Total Flight Crew (maximum)	~531,000	~4.6–7.6 million person-years. Estimates do not account for individuals who left and subsequently re-entered the workforce.

Exposure/Dose Assessment

In order to conduct any meaningful next-generation epidemiologic studies of flight crew, individual radiation dose estimates would be required for each participant and accumulated across their work history. If dose is measured with random error, real relationships between radiation and health effects can be more difficult to detect. Surrogate exposure indicators used in prior studies, such as employment status, duration of employment, block flight hours, or era- or domicile-specific exposure matrices, are subject to substantial exposure misclassification and therefore constrain the ability to detect associations with health outcomes. Instead, a model-based approach that generates flight-specific dose estimates for each employee and updates cumulative dose over time would be more appropriate for supporting future studies. As discussed in Chapter 4, well-characterized computational models are available for this purpose. As recommended by the committee in Chapter 4 (Recommendation 4-2), the Federal Aviation Administration (FAA), in collaboration with other organizations that develop aviation radiation exposure models, should systematically evaluate computational models and establish a methodology for developing and using an ensemble of models to improve estimates of flight crew radiation exposure.

The committee does not suggest routine use of individual dosimeters for all employees as it may pose operational challenges and may not substantially improve upon model-based estimates. Chapter 4 recommends an ensemble approach that should reduce uncertainty from variations in dose error as models are refined. An optimal dose assessment strategy for epidemiologic research would also account for SEP events and work-related exposures outside conventional block hours, such as extended ground holds and commuting flights. If a new initially retrospective epidemiologic study is initiated, historical exposures would need to be reconstructed using airline employment and flight records, as self-reported work histories have been shown to overestimate

block time and number of flight segments (Grajewski et al. 2004). These records could be linked to model-based dose estimates. Such an approach would require careful evaluation of the availability, completeness, and reporting standards of these records.

Potential Confounding and Modifying Factors

In addition to radiation dose, epidemiologic studies of flight crew would need to account for potential confounding and modifying factors relevant to the outcome under investigation. Because flight crewmembers are exposed to multiple occupational and environmental factors simultaneously, isolating the effects of any single exposure is challenging. These factors include circadian rhythm disruption, occupational or work-related chemical and physical exposures, historical exposures unique to certain subgroups, and gender-related factors that may influence disease risk. These exposures and considerations are summarized in Table 5-4.

Flight crew have irregular work hours and diets and patterns of recreational sun exposure that may differ from those of the general population. Flight crew also have a unique lifestyle profile and tend to be healthier than the general population, further complicating comparisons. Comparisons between pilots and other populations usually exhibit a strong healthy worker effect (as described in Chapter 3) based on the more rigorous initial medical qualification and annual occupational surveillance requirements, leading to lower mortality and morbidity than other populations. Additionally, required medical evaluations could lead to earlier or more frequent detection of cancers or other medical conditions, resulting in earlier diagnoses and potentially inflated incidence rates.

TRANSLATING EXPOSURES INTO LIFETIME RISKS

*Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2*³ (National Research Council 2006) based its quantitative cancer risk projections primarily on epidemiologic findings from the LSS of Japanese atomic bomb survivors. This is considered the most comprehensive dataset available for evaluating radiation-related cancer risks across a wide range of doses and ages at exposure. Using these cohort data, the committee developed risk models to estimate lifetime measures such as lifetime attributable risk (LAR).⁴ The most recent estimates of radiation-associated excess relative risk (ERR)⁵ from the survivors were used to infer the dose–response relationship for the simulation framework to project cancer risk (Brenner 2025). Briefly, the ERR

³ This consensus study report is part of a series of publications on the biological effects of ionizing radiation (BEIR).

⁴ LAR refers to the estimated probability that an individual will develop or die from cancer over a lifetime as a result of a specific exposure (e.g., radiation), above the risk that person would have had without that exposure.

⁵ ERR is a measure of how much higher the risk of disease is in an exposed group compared to an unexposed group, expressed as a proportion of the baseline risk. For example, an ERR of 0.5 indicates a 50 percent increase in risk relative to the unexposed population.

TABLE 5-4 Potential Confounding and Modifying Factors in Flight Crew Studies

Category	Considerations
Circadian Disruption	• Night shift work classified as “probably carcinogenic to humans” (IARC 2020) • May vary by route structure (e.g., east–west vs. north–south flights)
Occupational or Work-Related Exposures	• Fuel fumes and hydraulic fluids • Ozone • Noise and vibration • Electromagnetic fields • Infectious disease exposures • Pesticides
Historical/Legacy Exposures	• Secondhand tobacco smoke exposure among flight attendants and pilots prior to smoking bans • Military aviation exposures among pilots with civilian–military overlap
Gender-Related Factors	• Higher rates of nulliparity • Older age at first birth

estimates were created using longitudinal data (1958–2009) from the LSS cohort of survivors of the atomic bombings in Hiroshima and Nagasaki, Japan. The estimates were generated by fitting a statistical model that accounts for both radiation exposure and smoking. The authors evaluated multiple dose–response functions and found that the dose–response shape varied by sex. Although limitations and scientific debate persist regarding dose–response relationships at low doses and low-dose rates, these models remain the principal framework for translating radiation exposure into projected lifetime cancer risk. Accordingly, they were used in this study to inform power calculations and to estimate potential lifetime risks associated with occupational exposure for flight crew.

Estimates of risk from the LSS are based on exposure to acute mixed field including neutrons and high-energy photons, and their relationship may not be directly transferable to chronic exposure in environments, such as the aviation radiation environment, with different distributions of linear energy transfer, a measure of how radiation deposits energy in tissue (Kocher et al. 2018). Substantial uncertainty remains concerning the quantitative difference in damage between the two types of radiation (Wakeford 2019).

Another uncertainty is dose-rate for in-flight radiation exposure. Some assessments adjust high-dose data to a low-dose situation by applying a dose and dose-rate effectiveness factor (DDREF) to account for these differences.⁶ While the DDREF distribution, developed by Kocher and colleagues (2018), could be used to generate multiple scenarios for power calculations, the committee chose to assume it was equal to 1 for simplicity. The assumed value, 1.0, is lower than the point estimate of 1.3 but within the bounds of the confidence intervals for solid cancers (0.47, 3.6).

⁶The rate at high doses (RH) is divided by DDREF to calculate the rate at low doses (RL).

FEASIBILITY AND DESIGN CONSIDERATIONS FOR EPIDEMIOLOGIC STUDIES

This section considers potential epidemiologic study designs for two categories of health outcomes—cancer and reproductive health—based on gaps identified in the existing literature (see Chapter 3). These outcomes have been evaluated more extensively in relation to ionizing radiation than others and therefore provide a foundation for assessing the feasibility and potential value of additional study. Although other outcomes may warrant consideration, the existing evidence base for cancer and reproductive effects allows clearer evaluation of study design options.

Considerations for Cancer Study Designs

Cancer was selected as an exemplar health outcome for epidemiologic research of stochastic radiation effects, for which the probability of occurrence increases with dose rather than the severity of disease. It was also selected because cancer risk is a primary concern among flight crew, as highlighted in public engagement sessions. The committee developed an overall framework for estimating the excess risk of cancer associated with the occupational radiation exposure of flight crew that follows the general “Red Book” risk assessment framework: hazard identification, description of exposure, selection of a dose–response relationship, and risk characterization (National Research Council 1983).

The committee’s framework for cancer as the hazard of concern (see Figure 5-1) has three building blocks that relate to the five elements of the SoT. The first (Model In-Flight Radiation Dose) comprises the modeling tools (e.g., the FAA’s models CARI-7 and CARI-7A) that are used to estimate the radiation dose (in mSv) received in-flight. These models reflect the dose received from GCR, and some models may incorporate dose from SEPs, which would be higher exposure events but would occur infrequently during an 11-year solar cycle (see Chapter 4). As the first component of the committee’s framework, the models supply dose estimates for individuals and particular flights or for general types of flight patterns (e.g., circumpolar and transatlantic).

The second component (Estimate Cumulative Dose for Flight Crewmembers) builds estimates of cumulative doses for particular individuals or for classes of individuals based on general assumptions about the flight profiles of particular groups (e.g., pilots or flight attendants flying specific domestic or international routes). The input data comprise the flight history, including the routes flown and the chronological detail of the flights. Cumulative dose is estimated by aggregating the doses estimated for each flight from the first component’s underlying model(s). In the future, such dose data would be provided by the proposed system for tracking occupational doses.

Finally, the increment in cancer risk is estimated in the third component of the model (Estimate Excess Cancer Risk). A rich epidemiologic literature is now available that documents and quantifies the increased risk of cancer associated with ionizing radiation exposure (e.g., from the studies of the atomic bomb survivors in Hiroshima and Nagasaki, as noted). Models are available for this purpose from various authoritative

**Estimating Radiation Dose and Cancer Risk
for Aviation Flight Crew Members**

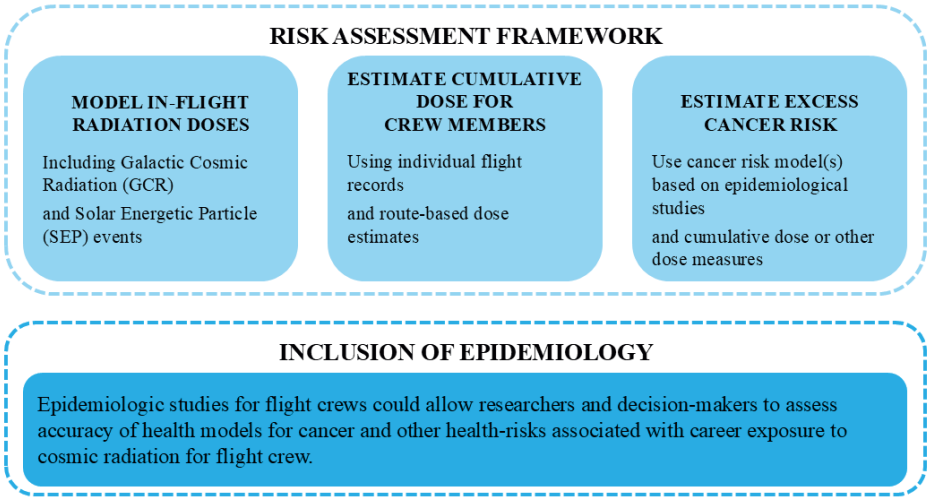


FIGURE 5-1 Framework for cancer risk assessment associated with radiation exposure of flight crew.

entities—for example, the International Commission for Radiological Protection. Future epidemiologic studies of flight crew could provide dose–response relationships specific to cosmic radiation exposures of flight crew.

Statistical Power for Investigating the Risk of Cancer

The statistical power of an epidemiologic study is critical in deciding whether study results will be sufficiently robust to inform measures taken to mitigate risks that are judged unacceptable. Multiple statistical packages can be used to calculate power and sample-size requirements for epidemiologic studies; however, no simple formula exists for studies with complex time-varying exposures and longitudinal designs. Consequently, the committee performed Monte Carlo simulations to calculate power and sample-size requirements. The standard steps for calculating power with Monte Carlo simulations are as follows: (1) generate a dataset, assuming cosmic radiation exposure follows the same pattern as LSS ERR estimates; (2) test the null hypothesis using the dataset; (3) save the results of the test; and (4) repeat steps 1–3 many times, retaining the results. Once this process is complete, the proportion of times the null hypothesis is rejected is the estimate of statistical power. This approach enabled power calculations that incorporated the following methodologically rigorous features, which are explained in more detail in the technical documentation found in Appendix G:

- Attainment of age as the timescale with time-varying dose accumulation and cancer-specific exposure lag periods
- Constraint of dose distributions to realistic values that are dependent on length of employment, flight crew type (pilot vs. flight attendant), and flight route
- Addition of Berkson and classical measurement error for dose uncertainty
- Consideration of the healthy worker effect in modeling through incorporation of frailty and frailty convergence
- Cancer-specific confounding adjustment, such as smoking, circadian disruption, and reproductive factors
- Inclusion of realistic distributions of occupation and career length

Several key assumptions were made when designing the synthetic dataset for the power estimation. These assumptions are summarized in Table 5-5 and explained in detail in Appendix G. The committee's intention is not to assert that this is the only way to conduct an epidemiologic study but rather to provide a conceptual framework for assessing the feasibility of future research. LSS estimates were used to inform sample-size estimation for this framework and were not intended as a sensitivity analysis. All parameters and assumptions made in the power calculations are adjustable, and the committee recommends conducting more rigorous simulations, and considering other risk estimates from other cohorts, before making a definite decision about the value of an epidemiologic study and the needed sample size.⁷

Considerations for Reproductive Outcomes Study Designs

Reproductive outcomes were selected as an exemplar for epidemiologic research of the noncancer outcomes of ionizing radiation exposure in flight crew. As concluded in Chapter 3 (Conclusion 3-4), observational studies on reproductive outcomes do not provide adequate evidence on whether cosmic radiation exposure increases risk for any of those outcomes included in this review. A research agenda is needed to address critical uncertainties for this topic of great concern to female flight crew.

The committee's framework for reproductive outcomes is similar to the framework for an epidemiologic study of cancer risk (see Figure 5-1), with three components: (1) model in-flight radiation dose received, (2) estimate cumulative dose, and (3) assess the effect of estimated dose. The key difference is the treatment of time, as acute exposures over a certain threshold and at a specific time during pregnancy may have a direct biologic impact in a short period of time. These critical windows of vulnerability (Burggren et al. 2015) are difficult to identify, especially because pregnancy losses before a clinically recognized pregnancy often go unrecorded or unrecognized. Given these limitations, study design must be planned carefully to draw reliable conclusions about the relationship between cosmic radiation and pregnancy outcomes. A prospective study designed to assess the timing of exposure and conception accurately would

⁷ An 80% power threshold is a widely accepted standard benchmark in epidemiologic and statistical practice.

TABLE 5-5 Key Assumptions Used in Simulation Modeling

Key Assumption	Summary	Key Limitation
Flight Route Assignment and Exposure Estimation	Flight crew were randomly assigned to route types (short-, medium-, long-haul; polar). Annual radiation dose was estimated by sampling from route-specific effective dose ranges derived from Chapter 4 and informed by Bureau of Transportation Statistics T-100 Segment data (see Appendix G). Annual flight counts by route type were used to calculate yearly exposure statistics (Table G-5).	Assumes random route assignment and does not reflect operational factors such as bidding systems or seniority that may influence cumulative exposure.
Population Characteristics	Occupational, demographic, health, lifestyle, and employment characteristics were compiled from multiple national data sources to construct a synthetic cohort. Because no single dataset provides joint individual-level data, marginal distributions were combined to approximate the population.	May not preserve correlations among exposures, confounders, and time due to use of aggregated data.
Radiation Risk Model Assumptions	Cosmic radiation exposure was assumed to follow ERR estimates from the LSS. Simulations were conducted using both the ERR point estimate and the upper bound of the 95% confidence interval from Brenner (2025).	The upper bound of the 95% confidence interval yields a lower bound on required sample size; together with the point estimate, this defines a planning range for study design.

allow the full spectrum of reproductive outcomes to be assessed (Tingen et al. 2004). The optimal study design would collect detailed data on female flight crew and their partners, allowing researchers to account for the timing of pregnancy and the complex biologic processes. While such a study would be costly, it would be necessary to expand understanding of the effects of cosmic radiation on pregnancy outcomes.

Results of Power Calculations

Three sets of simulations were conducted for each cancer type: one using ERR per gray equal to the LSS point estimate and one for each of the lower and upper bounds of the 95% confidence interval for these estimates. These three points capture sample-size estimation across the full range of uncertainty in the ERR estimates. Across this full range, the following studies would be powered at 80 percent: all solid cancers (female), brain (male), breast (female), prostate (male), colon (male), and lung (male and female) with potentially achievable sample sizes. The results are summarized in Table 5-6. For each cancer, 200 simulations were run with sample sizes from 25,000 to 250,000. The range of sample sizes was based on a combination of incidence rate in the general population and ERR. Estimates for leukemia and melanoma are not available from Brenner (2025). Based on the results presented in Chapter 3, the committee decided to generate power estimates for these two cancers. The leukemia parameters were based on the values published by Hsu and colleagues (2013), and the melanoma value for ERR was arbitrarily set at 0.50 for descriptive purposes.

An epidemiologic study aimed at assessing the relationship between radiation exposure and lung cancer risk would be the best powered, with power reaching the 80 percent threshold for a cohort of 26,000 women. The next most powerful study would be aimed at assessing the relationship between radiation exposure and female breast cancer risk. Notably, the precise dose–response relationship for chronic exposure to radiation environments relevant for flight crew is unknown. While this uncertainty is built into the simulations using Berkson and classical error, a DDREF scalar correction was not applied. A full landscape of simulations was outside the scope of this report but could be conducted to provide a more complete understanding.

Conclusion 5-3: Based on the committee’s analysis of the sample size and power calculations, informative epidemiologic studies are feasible for female breast cancer, female lung cancer, and potentially other cancers for both sexes. The sample sizes needed would generally involve the workforce of several major airlines.

Because of the multiplicity of study design and health endpoints, the committee did not carry out power calculations for studies of reproductive outcomes.

APPROACHES FOR EPIDEMIOLOGIC RESEARCH

The committee presented several approaches for epidemiologic research. Current gaps in flight crew exposure must be addressed. The committee’s preferred foundation for the options presented below is a next-generation, digitally enabled tracking platform

TABLE 5-6 Results of Power Calculations

Cancer	Sex	Estimated ERR		Lower 95% CI ERR		Upper 95% CI ERR	
		Estimated Sample Size	Power (95% CI)	Average Sample Size	Power (95% CI)	Estimated Sample Size	Power (95% CI)
All Solid	Female	65,000	0.68 (0.61, 0.75)	130,000	0.62 (0.55, 0.70)	52,000	0.83 (0.78, 0.89)
	Male	72,000	0.11 (0.17, 0.05)	120,000	0.28 (0.21, 0.36)	120,000	0.15 (0.09, 0.22)
Brain/CNS	Female	130,000	0.14 (0.08, 0.2)	130,000	0.1 (0.04, 0.16)	130,000	0.5 (0.42, 0.57)
	Male	120,000	0.77 (0.71, 0.83)	120,000	0.2 (0.13, 0.27)	48,000	0.91 (0.88, 0.95)
Breast/Prostate	Female	52,000	0.84 (0.79, 0.9)	130,000	0.70 (0.63, 0.76)	26,000	0.88 (0.84, 0.93)
	Male	120,000	0.59 (0.52, 0.67)	120,000	0.16 (0.09, 0.22)	48,000	0.9 (0.86, 0.95)
Colon	Female	104,000	0.14 (0.08, 0.21)	104,000	0.12 (0.05, 0.18)	104,000	0.52 (0.44, 0.59)
	Male	96,000	0.48 (0.4, 0.55)	96,000	0.13 (0.07, 0.2)	72,000	0.79 (0.73, 0.85)
	Female	130,000	0.22 (0.15, 0.3)				
Leukemia	Male	120,000	0.64 (0.57, 0.64)			—	
Lung	Female	26,000	0.82 (0.77, 0.88)	78,000	0.83 (0.78, 0.88)	26,000	1 (0.99, 1)
	Male	120,000	0.28 (0.21, 0.34)	120,000	0.11 (0.07, 0.16)	96,000	0.93 (0.89, 0.97)
Melanoma	Female	130,000	0.06 (0.01, 0.11)				
	Male	120,000	0.19 (0.12, 0.26)			—	

NOTE: CI = confidence interval; CNS = central nervous system.

for flight crews that integrates population-scale dose and health data to identify, precisely quantify, and mitigate occupational hazards before they lead to disease. While this is the ideal prospective data collection platform, it will not alone provide the data needed to study longitudinal outcomes, such as cancer, and may be costly. Multiple study designs for data-forward epidemiologic approaches aimed at studying the relationship between radiation exposure and cancer incidence and morbidity are presented below.

Large-Scale, Well-Characterized Multi-Cohort Study

A large-scale multi-cohort study design that pools data from retrospective and prospective cohorts allows evaluation of both long-term effects of past cosmic radiation exposure and the ongoing risk associated with continued exposure. This design also allows for a larger sample size with longitudinal follow-up and enables the capture of a more complete picture of the effects of radiation exposure in flight crew. Chronic diseases, such as cancer and cardiovascular disease, have long latency periods and are diagnosed years after exposure. The retrospective component will enable the inclusion of decades of exposure profiles and of individuals who may already have cancer. The prospective component will provide more precise exposure estimates, biological sample collection, and newly diagnosed conditions. This is the same logic that underpinned highly influential occupational surveillance/cohort successes (e.g., the International Nuclear Workers Study [INWORKS] and Million Person Study [MPS] for nuclear workers), where retrospective exposure records plus ongoing registry linkages produced regulatory-relevant dose–response evidence.

Cancer rates do not start to increase until later ages and as a result, individuals enrolled into a prospective cohort would not have high rates of cancer until decades after the study begins. A purely retrospective approach will likely suffer from sparse data on confounders and bias in the reconstruction of cumulative exposure. Figure 5-2 is a committee-generated Lexis diagram that shows why a multi-cohort approach is needed for a robust and timely epidemiologic study of the relationship between radiation exposure and cancer. The horizontal axis shows calendar year, and the vertical axis shows age. Each “step” represents a group of people who are the same age in the same year; moving diagonally up and to the right follows the same birth cohort as it ages over time. The vertical line marks the beginning of the study; everything to the left is retrospective, while everything to the right is prospective. The band near the top labeled “Cancer Rates Start to Increase” highlights that cancer becomes more common at older ages. Flight crew who are already older at the start of the study (orange) will contribute the most cancer cases, because cancer risk rises with age. Therefore, inclusion of a retrospective component will increase the power of the study. Flight crew who will turn 65 or older after the study starts (gray) will be the most valuable because they will contribute to the prospective data collection but will also have rich historical exposure data.

A multi-cohort study of flight crews would provide a versatile framework for studying long-latency outcomes, like cancer and cardiovascular disease, and emerging biomarkers of cosmic radiation exposure. For example, the Nordic pilot cohort study, which is comprised of various pilot registries linked to national population and cancer

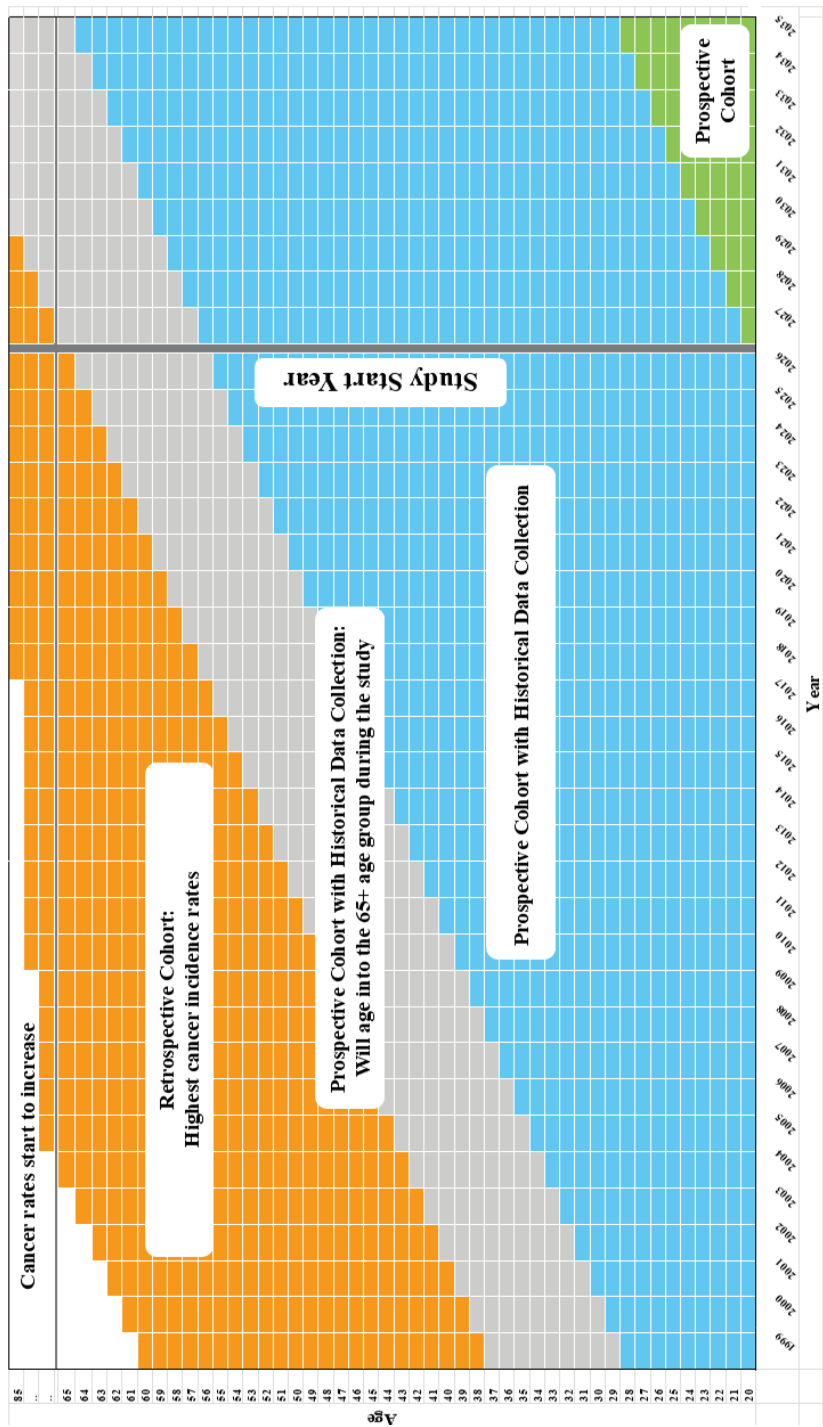


FIGURE 5-2 Lexis diagram showing the longitudinal follow-up of different cohort types and the motivation for a multi-cohort design.

registries, enabled the evaluation of cosmic radiation exposure and cancer outcomes (Pukkala et al. 2002). The multi-cohort design expands the utility of the retrospective and prospective designs by increasing the ability to establish temporal relationships between potential risk factors and outcomes, increasing the precision of exposure metrics, providing a platform for repeated biomarker measures, and assessing the effects of SEP events. Temporal inference is strengthened by establishing a well-defined and comprehensive timeline between cosmic radiation exposure and changes in disease status over time while supporting mechanistic insights into disease development.

The novelty and utility of the study could be increased through longitudinal collection of biomarker data and the establishment of a biobank. Repeated measures of molecular, epigenetic, proteomic, and cytogenetic markers of cosmic radiation exposure would help characterize the natural history of disease development and provide mechanistic insight into radiation-related health effects. Such a platform could also enable rapid biomarker collection following acute-exposure SEP events, improving understanding of biological responses to short-term, low-dose exposures. A cohort study of sufficient size could provide a detailed characterization of flight crew; however, careful selection of recruitment strategies will be essential to maximize statistical power and ensure robust, reproducible findings. The integration of radiobiology with radiation epidemiology to better understand dose–response relationships and health effects has been emphasized in prior publications, including *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2* (National Research Council 2006), earlier BEIR reports, and *Leveraging Advances in Modern Science to Revitalize Low-Dose Radiation Research in the United States* (NASEM 2022).

In parallel with these advances in study design and data collection, careful consideration of how longitudinal radiation exposure is represented in statistical models is also important for interpreting dose–response relationships. The BEIR VI framework, originally developed for radon-exposed cohorts, provides an established approach for modeling longitudinal radiation exposure by partitioning cumulative dose into time-since-exposure windows within an ERR framework (National Research Council 1999). This approach allows risk to vary with timing of exposure while maintaining an interpretable structure and is well suited to retrospective studies where exposure histories are summarized over defined periods.

Simpler approaches that rely on cumulative dose at a single point assume that this value alone determines risk at a given time, without considering how that dose was accumulated. As a result, two individuals with very different exposure patterns over time but the same cumulative dose, and the same baseline characteristics, would be predicted to have the same risk, even though the timing of their exposures may differ. The BEIR VI framework addresses this limitation in part by incorporating timing of exposure through discrete time windows, allowing risk to vary depending on when exposures occurred. An alternative approach is to model radiation dose as it occurs over time, so that risk depends on the full pattern of exposure rather than a single cumulative total or predefined groupings of past dose. This allows the contribution of exposure to vary depending on its timing. In practice, when exposure data are recorded year by year, as

would be enabled by recommended dose tracking systems, this approach can use those yearly values directly to reflect how exposure accumulates and changes over time.

Several strategies can be implemented to help maximize statistical power given the hypothesized size of the effects, which are generally anticipated to be small to moderate in relation to background risks. Prioritizing the recruitment of participants at the cosmic ionizing radiation exposure extremes (“low” vs. “high,” normalized by time as flight crew) can help maximize statistical power by maximizing the contrast and making it easier to detect a difference in disease risk. By employing a negative-control design, this approach leverages the shared characteristics and causal structure between both groups to detect bias and is less affected by sample size (Lipsitch et al. 2010; Prasad and Jena 2013; Yang et al. 2024).

To further strengthen this design, a population-based comparison group could be drawn from the All of Us Research Program (All of Us Research Program Investigators 2019) to provide unexposed controls. This blended cohort structure would increase statistical power and enable assessment of dose–response relationships within flight crews and the general population at minimal cost. Utilizing an existing research infrastructure would substantially lower costs and logistical burden. Similar large-scale initiatives, such as the UK Biobank, demonstrate the feasibility and scientific value of this approach, enabling efficient integration of population-level data with occupational cohorts while minimizing resource burden (Ge et al. 2024; Wang et al. 2025).

Pooling data from other occupational cohorts with radiation exposure could improve power and increase understanding of the relationship between exposure and health outcomes. INWORKS and MPS exemplify the value of pooling multiple cohorts to create a statistically robust resource for examining the relationship between low-dose radiation exposure and mortality (Boice et al. 2022; Boice et al. 2024; Richardson et al. 2023). In the future, these cohorts will also be linked to administrative records, like the CMS data, creating a resource that can be used to investigate a range of health outcomes (Boice et al. 2022; Boice et al. 2024; Dauer et al. 2024). Future flight crew studies should consider integrating data from international cohorts to increase statistical power. Pooled analyses combining data from MPS and future flight crew studies would also increase statistical power and allow for a more comprehensive assessment of the relationship between different modes of low-dose radiation exposure and health outcomes.

Conclusion 5-4: Pooling existing retrospective cohort studies across airlines, occupational groups, or existing datasets could be done now to improve statistical power for an epidemiologic study that illuminates associations between radiation exposure and specific health outcome among flight crew. Prospectively, the flight crew workforce is large enough to enable the necessary statistical power to design a study that would address risks for certain radiation-related cancers.

Assessing Fertility Issues and Adverse Reproductive Outcomes Among Flight Crew Exposed to Cosmic Radiation

Short-term elevations in radiation exposure may increase the immediate risk of decreased male fertility or of an adverse pregnancy outcome (e.g., miscarriage or stillbirth). These exposures may be a cluster of high-dose flights during a critical gestational window or a single exposure during an SEP event. Carefully planned prospective studies provide a powerful solution for studying environmental exposures and fertility outcomes. A detailed prospective preconception cohort study with biospecimen collection would be ideal for a rigorous study of pregnancy loss, as a large proportion of pregnancies can end before the pregnancy can be detected clinically (Tingen et al. 2004; Wilcox et al. 1988). This type of study requires the recruitment of prospective parents, biomonitoring during critical windows, and careful tracking of menstrual cycles. Conducting this type of study, however, is expensive and requires consent to pause participation if pregnancy occurs, careful planning, risk mitigation, and a safety monitoring plan with stopping rules if unexpected harms emerge.

A multi-cohort framework is an alternate, but not ideal, solution that could leverage both retrospectively and prospectively collected flight exposure and pregnancy outcome data. While both study designs are subject to strong limitations when studying reproductive outcomes, retrospective studies are more limited because they suffer from underreporting of miscarriage and recall bias. Study designs such as within-person or case-crossover can be a powerful replacement to a costly prospective study because they can net out time-invariant confounders such as genetics, maternal age, and obstetric risk factors. This design has been widely used to assess the relationship between acute exposures and adverse birth outcomes (Maclure and Mittleman 2000). If a detailed prospective study design is not possible, integrating complementary multi-cohort study designs with precise exposure assessment and stringent ethical safeguards may produce reliable evidence on cosmic radiation-related reproductive risks.

SUMMARY: UNDERSTANDING RADIATION EXPOSURE AND HEALTH OUTCOMES THROUGH EPIDEMIOLOGY

In this chapter, the committee examines key gaps and limitations of the scientific evidence that limit current understanding of flight crew exposures and potentially related adverse health outcomes. Epidemiologic studies have shown increased risk for some cancers; however, direct evidence is insufficient to support a causal link with cosmic radiation specifically. These studies share several common challenges faced by epidemiologic studies of small but real risks that are meaningful when experienced by substantial populations (Lilienfeld 1983):

- Exposure misclassification—lack of dose/exposure measures
- Statistical power and sample size
- Potential confounding factors
- Long latency periods

The committee examined the literature with consideration of each of these challenges and identified key elements to be addressed for informative epidemiologic assessment of flight crew risks. Tracking of flight crew radiation dose is fundamental to addressing these gaps. Lack of systematic collection of flight crew radiation dose levels has been a major limitation of epidemiologic studies. Developing more informative studies will depend upon improved measures of flight crew dose levels.

To assure adequate study population size, the demographics of the national flight crew population are presented. Sample size and power calculations were done for key health endpoints, and the flight crew workforce is large enough to provide necessary statistical power for informative studies of breast cancer, lung cancer, and potentially other radiation-related cancers.

To address the challenges of potential confounding and latency, approaches to epidemiologic study design are presented, including an in-depth examination of the large-scale multi-cohort approach to cancer outcomes. Both retrospective and prospective methods are described to examine the risks of past exposures and to follow study cohort members forward to identify emerging disease outcomes. The committee recognizes the sensitivity of medical disclosure, especially among flight crew, and notes that future studies should account for privacy concerns and potential underreporting in their design.

The committee concludes that appropriately designed and adequately powered epidemiologic studies of flight crew are feasible and essential to address the limitations and gaps in the current evidence regarding the association between in-flight radiation exposure and risks for adverse health outcomes. To address these gaps the committee proposed two recommendations for the FAA: (1) establish a dose tracking system for flight crew and (2) concurrently invest in developing a strategic epidemiologic research plan to elucidate potential health outcomes among flight crew for occupational exposure to radiation.

Recommendation 5-2: In parallel with developing a dose tracking system, a strategic research plan for future epidemiologic research on the association between occupational radiation exposure and health outcomes for flight crew should be elaborated by the Federal Aviation Administration (FAA) and other federal agencies in collaboration with industry and flight crew partners.

Epidemiology is essential to advancing an understanding of the relationship between radiation dose and adverse health outcomes. It can provide the evidence base necessary to quantify risks, guide decisions to improve risk management, and ultimately improve protection of the health of flight crews.

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6

Managing and Communicating Radiation Risk for Flight Crew

This chapter addresses the final subtask in the committee’s charge to “consider potential mitigation measures that could reduce radiation exposure to flight crews.” In an occupational context, mitigation refers to actions taken to reduce or minimize the harmful effects of an exposure, either by avoidance, thus preventing the exposure from occurring, or by lessening the severity of damage to health from that exposure. This chapter discusses mitigation measures primarily in the form of changes to airline operational management systems and communication and education for flight crew.

Building on the evidence and the committee’s conclusions from previous chapters, this chapter begins with the committee’s three primary justifications for recommending action on radiation exposures for flight crew. The chapter then discusses the elements of radiation safety programs and mitigation options in U.S. aviation, as well as challenges and opportunities in risk communication efforts for flight crew. The committee’s recommendations for action on radiation exposure monitoring and mitigation appear at the end of the chapter.

JUSTIFICATION FOR ACTION

The committee determined that radiation exposure to flight crew is a manageable risk worthy of action. The committee identified three primary justifications for taking action on cosmic radiation exposure to flight crew of U.S. Part 121 operators¹: (1) the

¹ Part 121 operators are Federal Aviation Administration–certified air carriers and for the purposes of this report include only commercial, civilian aviation (e.g., large U.S. airlines and regional air carriers). Military aircraft are not included in the definition of Part 121 operators. While cargo carriers are included in the definition of Part 121 operators, radiation from cargo is out of scope for this report. However, the committee acknowledges radiation as a potential related occupational risk for flight crew for cargo carriers. This report will use the terminology “U.S.-based commercial airlines” or “U.S. airlines” in reference to large U.S. airlines and regional air carriers as Part 121 operators.

well-studied increased health risk (specifically, cancer risk) from cumulative radiation exposure in other populations; (2) the lack of education to support informed choices for flight crew to manage their radiation exposure; and (3) the lack of action from U.S. regulatory agencies over the past 30 years regarding radiation exposure and U.S. flight crew.

Increased Health Risk from Cumulative Radiation Exposure

Presently, flight crew are among the occupational groups most exposed to ionizing radiation, with an average effective dose surpassing that of other radiation-exposed workers in the United States, excluding astronauts (ICRP 2016). While flight crew are acknowledged as occupationally exposed to radiation by numerous U.S. agencies, they are not classified or regulated as radiation workers in the United States, meaning they lack the protections, monitoring, and dose limits required for other radiation workers, as discussed in Chapter 2.

Radiation represents a health risk that accumulates over time—a lifetime/career exposure that increases dose over time. For flight crew, cumulative exposure and dose also depend on routes flown and duration of employment. Concern about risks also depends on an individual's perception of the radiation hazard and tolerance for risk. A pregnant flight crewmember may be especially risk averse due to concerns that radiation exposure will harm the developing fetus.

Some flight crew may receive radiation exposure while commuting to their base of operations. Based on the experience of members with careers in the airline industry, the committee recognized that many U.S. pilots and cabin crew commute to work, sometimes involving several hundred miles of travel or even coast-to-coast flights. Such additional exposures would need to be considered by the airlines in the development and implementation of radiation protection practices.

Although uncertainty exists about the magnitude of health risks from radiation exposure for flight crews, exposure to galactic cosmic radiation (GCR) and solar energetic particles (SEPs) is known to pose some risks. Groups at particular risk (e.g., pregnant flight crew) have stricter dose limits that could be exceeded in a single flight during an SEP event (see Chapter 4, Conclusion 4-4). As discussed in Chapter 3, available epidemiologic evidence does not clearly characterize the radiation risks for flight crews. Furthermore, as described in Chapter 5, there are significant challenges and limitations to conducting an epidemiologic study to determine more definitively the health risks associated with radiation exposures in flight crew. However, extensive evidence on radiation risks in other populations is available, and risk models based on atomic bomb survivors are widely used. Such models predict increased cancer risks from radiation exposures received by flight crew. Additionally, other pooled cohort analyses, such as the International Nuclear Workers Study or the Million Person Study, have found that nuclear workers receiving cumulative doses of 100+ millisieverts (mSv) over decades show a statistically significant increased cancer risk (Rühm et al. 2022); such doses are feasible for flight crewmembers whose careers span multiple decades.

Lack of Education to Support Informed Choices for Flight Crew

The committee found that radiation exposure for flight crew is not addressed uniformly among U.S. commercial air carriers, and some carriers may not be addressing it at all. Currently, individual flight crewmembers have little information on their received dose of radiation, nor are they able to determine or manage their exposure through flight choices. Box 6-1 describes the practical limitations for flight crew using the FAA CARI7 model (referred to as the CARI model throughout the chapter). Currently, flight crewmembers wanting to know their radiation exposure are advised by the Federal Aviation Administration (FAA) to use the CARI model to estimate their radiation dose for an individual flight (FAA 2014). The FAA does not regulate or require the integration of the CARI model into airline operations. The committee recognizes the value of computational models, such as CARI, to estimate radiation doses for flight crew but acknowledges that these models are not easily approachable to untrained individuals and are not readily used by flight crew without specific training. The committee found that

BOX 6-1 Practical Limitations in the Use of the CARI Model for Flight Crew

The FAA's CARI model is a well-established and scientifically validated tool for estimating radiation dose from GCR during flight. The model reflects decades of development and represents a significant investment in computational capability to support aviation radiation assessment.

However, the practical use of CARI by individual flight crewmembers is limited. Use of the model requires downloading and installing software, reviewing technical documentation, and manually entering flight-specific parameters such as route, altitude, and timing. Interpreting model outputs and converting them into cumulative exposure estimates requires familiarity with radiation dose concepts. In addition, individuals must independently maintain records over time if they wish to track cumulative exposure.

As a result, although CARI is an effective tool for estimating radiation dose, it is not readily accessible for routine use by flight crew without training, institutional support, or integration into airline systems. These limitations highlight the gap between available technical capability and practical implementation. Addressing this gap would improve accessibility of dose information and support informed decision-making by flight crew, consistent with Recommendation 2-2. As described later in this chapter, the creation of a radiation safety program would appropriately place the responsibility for monitoring and reporting radiation dose for individual flight crewmembers with the airline. Each airline would be able to select the desired method for characterizing the radiation conditions in its aircraft—that is, via modeling, monitoring, or dosimetry (Recommendation 6-1).

flight crew do not have adequate tools or training available to track the accumulating radiation doses received during their careers.

Lack of Action on Flight Crew Radiation Exposure in Recent U.S. History

As discussed in Chapters 1 and 2, the FAA recognizes flight crew as being occupationally exposed to radiation and provides nonregulated guidance through advisory circulars. While recommendations by the FAA have been in place since 1990 (FAA 1990), the committee finds they have largely not been implemented by U.S. airlines. The current Advisory Circular 120-61B provides background information plus links to sources of more detailed information that can be used to improve U.S. air carrier programs' efforts to inform flight crew about in-flight ionizing radiation exposure (FAA 2014). Adherence by airlines to the guidance contained in advisory circulars is voluntary rather than compulsory.

Although the FAA has developed dose estimating software, such as the CARI-7 suite, airlines may interpret recommended dose limits and implement mitigation measures at their discretion in the absence of enforceable requirements. The committee received information during this study (see Chapter 2) that some U.S. air carriers have been more proactive in understanding and educating flight crew on radiation than others, although no U.S. carriers monitor and manage the risk for individual flight crewmembers to the extent required in Europe or practiced voluntarily by some in Canada (Air Canada 2013; EU 2013). Given that the airline industry has been aware of crew exposure to ionizing radiation for more than 30 years, and despite encouragement from the pilot and flight attendant unions, the historical record of advisory circulars over the past 30 years and the absence of action indicates that the airlines will not implement radiation education and monitoring programs in the absence of a mandate (see Conclusions 2-1 and 2-2).

International Examples of Radiation Monitoring of Flight Crew

In other countries (e.g., European Union [EU] countries and South Korea), flight crew education on radiation exposure as well as exposure tracking are regulated and required for airlines based in those countries.

For European airlines, radiation safety programs are governed by EU directive, providing broad guidance across the region that is executed by individual airlines at their respective national levels (EU 2013). The EU requires that aircrew radiation exposure be managed as a planned occupational exposure situation, using a tiered perspective. Under this construct, aircrew are assessed for whether planned exposure will result in an annual effective dose above 1 mSv. For aircrew who are estimated to exceed the 1 mSv threshold, requirements are triggered including assessing individual exposure; considering exposure when organizing work schedules, with the aim to reduce doses for highly exposed aircrew; and informing workers of health risks related to their work and individual dose. Additionally for pregnant aircrew, once the pregnancy is declared the worker must be protected such that the effective dose to the unborn child

is “as low as reasonably achievable” (ALARA) and unlikely to exceed 1 mSv for the remainder of the pregnancy. Aircrew expected to exceed 6 mSv per year require stricter occupational exposure management. This includes exposed worker categorization, individualized dose monitoring, medical surveillance, education and training, and exposure recordkeeping requirements. In addition to the specialized guidance for aircrew, the EU directs a general occupational dose limit of 20 mSv per year. Under these overarching EU-directed requirements, airlines can integrate standardized risk mitigation processes into safety systems while maintaining oversight at the national authority level. Complementing these regulatory structures, the European ALARA Network promotes the principle of ALARA by supporting coordination among regulators, industry, and scientific stakeholders.

In Germany, as is typical of other EU countries, this obligation is formalized through national legislation: flight personnel must undergo mandatory monitoring if they may receive more than 1 mSv annually from cosmic radiation (Bundesamt für Strahlenschutz 2018). Aircraft operators are required to calculate dose values, adjust crew scheduling and flight routes to reduce exposure, and report data to a national dose registry that tracks occupational and lifetime dose limits.

The United Kingdom requires civil aircraft operators to assess individual crew-member exposure using approved computational models, incorporate dose considerations into scheduling to reduce exposure among highly exposed crew, and educate flight crewmembers about the health consequences of radiation (United Kingdom 2019). South Korea caps annual exposure for cabin crew at 6 mSv and 1 mSv for pregnant crew, and requires airlines to review individual flight routes and workloads to minimize radiation exposure (DongA Science 2021). Canada recommends—but does not mandate—that air operators establish cosmic radiation management programs (TC 2001), although major Canadian airlines have voluntarily implemented monitoring programs using commercial service providers (Air Canada 2013). Australia has guidance on flight crew radiation exposure for some operators (Australian Radiation Protection and Nuclear Safety Agency n.d.), but its largest airline has voluntarily instituted a monitoring program through a third-party provider, reflecting an industry-led rather than legislatively required approach (Qantas n.d.).

FAA Collaborations

The committee is aware that collaborations among the FAA and multiple participants (e.g., airlines, aircraft manufacturers, and labor groups) have, in large part, contributed to the high-quality safety record of commercial aviation in the United States. In particular, the work of the global Commercial Aviation Safety Team, along with new aircraft, regulations, and other activities, reduced the fatality risk for commercial aviation in the United States by 83 percent from 1998 to 2008 (FAA 2018). Other key partnerships involving the FAA and industry include the Aviation Safety Information Analysis and Sharing system, Flight Operational Quality Assurance (also known as flight data monitoring), and Aviation Safety Action Program, which encourage voluntary self-reporting. The committee recognizes the success of these partnerships involving

the regulator and industry as well as the implications for crafting a potential radiation hazard mitigation program. In addition to the collaborative nature of these initiatives, notably, some aspects of these safety partnership programs, especially data management and recordkeeping, can be outsourced by the airlines. During its information gathering, the committee found that external partners exist that could facilitate adoption of radiation monitoring, solar weather forecasting, and operational implementation (see Chapter 2). As the committee was not tasked with evaluating such partnerships, additional effort would be needed to determine the best path forward for how the FAA or airlines could incorporate practices and what collaborations would be best to undertake. The committee previously recommended that the FAA should exert its regulatory authority over ionizing radiation as an occupational exposure that requires oversight to ensure flight crewmember health and safety (Recommendation 2-1). Together, these factors indicate that radiation exposure in aviation is a manageable occupational risk that can be addressed through a structured radiation safety program.

Conclusion 6-1: Flight crew are not covered by a radiation safety program that incorporates tracking of dose, and risk communication and training concerning radiation exposure. Consequently, they cannot make informed decisions about their radiation exposure and the routes that they fly.

ELEMENTS OF A RADIATION SAFETY PROGRAM

In other occupational settings where workers have known exposure to radiation, the radiation exposure is monitored and managed through a radiation safety program. An occupational radiation safety program in the United States is a structured system of policies, procedures, and controls designed to protect workers from exposure to ionizing radiation in the workplace. While such programs may incorporate the safe use of radioactive materials and radiation-producing equipment, their primary purpose in many industries is to manage occupational exposure from naturally occurring sources, including radon (subject to the radiation safety program administered by the Occupational Safety and Health Administration) and cosmic radiation (covered for astronauts by the National Aeronautics and Space Administration [NASA] but not for flight crew).

Effective governance and oversight are essential to program success. Organizations typically designate a qualified subject matter expert, such as a radiation safety officer or health physicist, who is responsible for implementing protective measures. This role is supported by management and, where appropriate, a safety committee to ensure accountability and integration with broader occupational health and safety systems.

A core operational component is the establishment of exposure assessment and monitoring strategies, as recommended by the committee in Chapter 5 (Recommendation 5-1). Monitoring radiation exposure levels for flight crew—measuring, estimating, or tracking exposures to calculate dose—is a necessary first step before taking actions to manage radiation exposure (i.e., mitigation). This can be in the form of using computational models (discussed in Chapter 4) or dosimetry. This may include personal monitoring, area surveys, and environmental measurements, depending on the source and

work environment. As noted in Chapter 4, the mixed radiation field at aviation altitudes cannot be well characterized or assessed by a single dosimeter. Instead, computational models trained on validation campaigns, or a series of experiments used to characterize this mixed field, would offer an operationally feasible alternative to individual or aircraft dosimeter deployment.

Worker training and hazard communication are also critical elements. Employees must be informed of radiation risks, including those associated with naturally occurring sources, and trained in protective measures, proper procedures, and response to unusual conditions. These programs also maintain individual dose records over time and establish procedures to incorporate radiation exposure considerations into operational decisions.

The purpose of this program is worker protection, and it emphasizes integrating hazard identification (i.e., radiation in the flight environment), exposure monitoring or dose estimating and tracking, training, and continuous evaluation. Such a program would provide a practical and adaptable framework for flight crew as well as manage the potential risk of occupational exposure to radiation. These programs are guided by the principle of ALARA. This is achieved through a combination of engineering controls, administrative controls, and safe work practices.

These elements can be translated into the aviation context to illustrate how a radiation safety program could be implemented within airline operations (see Table 6-1). The following sections describe how these program elements could be implemented through potential operational and engineering mitigation strategies in aviation.

TABLE 6-1 Elements of a Radiation Safety Program and Application to Commercial Aviation

Program Element	Description (General Occupational Context)	Application in Commercial Aviation (Airlines)
Program Oversight and Governance	Designation of a qualified individual (e.g., radiation safety officer or health physicist) responsible for program implementation, supported by management and safety systems.	Airline designates a responsible expert (internal or contracted) to oversee radiation risk management, integrated within the safety management system and coordinated with medical and operational teams.
Hazard Identification	Identification of sources of radiation exposure in the workplace, including naturally occurring sources.	Recognition of cosmic radiation (GCR and SEP) as an occupational hazard associated with altitude, latitude, and space weather conditions.
Exposure Assessment and Monitoring	Measurement or estimation of worker exposure using personal dosimetry, area monitoring, or environmental measurements.	Use of validated computational models (e.g., CARI, NAIRAS [see chapter 4 for more information]) to estimate dose for flights; targeted measurement campaigns to validate models and characterize the radiation environment.

TABLE 6-1 Continued

Program Element	Description (General Occupational Context)	Application in Commercial Aviation (Airlines)
Dose Tracking and Recordkeeping	Maintenance of individual exposure records over time to support compliance and risk management.	Airline systems track cumulative radiation dose for individual crewmembers across flights and over time, enabling annual and career dose assessment.
Training and Education	Worker training on radiation risks, safe practices, and procedures for normal and unusual conditions.	Integration of radiation education into initial and recurrent flight crew training, including cumulative exposure, SEP events, and pregnancy-related considerations.
Hazard Communication	Communication of risks, exposure levels, and protective actions to workers.	Provision of accessible, individualized dose information and clear communication tools to support informed decision-making by flight crew.
ALARA Implementation	Application of ALARA principles using engineering and administrative controls.	Use of administrative controls such as route selection, altitude adjustments when operationally feasible, and crew scheduling to reduce exposure, particularly for higher-risk individuals.
Operational Controls and Procedures	Development of procedures to reduce exposure and respond to abnormal conditions.	Integration of radiation considerations into flight planning, dispatch, and real-time operations, including response to space weather alerts and SEP events.
Program Evaluation and Continuous Improvement	Periodic review of program effectiveness and updates based on new data, technology, and scientific understanding.	Ongoing evaluation of models, validation campaigns, and operational practices to ensure alignment with current radiation environments and evolving science.

SOURCE: OSHA (n.d.).

MITIGATION OPTIONS IN U.S. AVIATION

Three primary methods exist to reduce radiation exposure generally: reduce time of exposure, increase shielding to protect against incident radiation, and increase distance from the radiation source. While some of these approaches may be employed for various scenarios to help manage radiation exposure for flight crew, many operational and engineering considerations remain in managing this risk. In aviation, mitigation is achieved primarily through administrative and operational controls, given the limited feasibility of engineering solutions.

Operational and Administrative Mitigations

As described in Chapter 4, aircraft altitude and latitude are two important determinants of radiation exposure. Time and distance are inherently linked with the nature of the work. In terms of distance from the radiation source, as airplanes increase altitude during flight, they get closer to the source of radiation (i.e., galactic and solar sources). In terms of time and distance, flight paths are carefully constructed to account for geodesic distance, wind and jet streams, air traffic and geopolitical factors, as well as operational efficiency. Route selection and frequency are the purview of network planners within the airline marketing department, while the flight dispatcher and pilot in command (PIC) can modify routes at the tactical level.

Safety Management System

In the United States, airlines and many other entities in the aviation industry (e.g., maintenance providers, airport operators, training establishments, and air traffic service providers) are required to have a functional safety management system (SMS) under the leadership of an accountable manager (often the airline's chief executive officer and sometimes the vice president of operations). Now a global standard, an SMS is a systematic approach to managing safety in aviation. Airlines that implement an SMS can identify and mitigate safety risks occurring during their day-to-day operations, ultimately improving safety performance. Within an SMS, hazards (i.e., phenomena with the potential to cause harm) are identified, often via confidential reports from frontline employees. These hazards are assessed based on their probability and severity, and the resultant risk is usually presented in a risk matrix. This approach enables the airline operator to focus on hazards presenting the greatest risk and then to apply mitigations.

Route Optimization

Optimizing operational flight plans is the primary responsibility of the airline flight dispatcher. Preflight planning typically includes route selection (both lateral and vertical), fuel use calculations, alternate airport planning, weight and balance considerations, and an assessment of meteorological conditions. Air traffic control constraints at departure and arrival airports as well as in route are further important considerations.

Route modifications to avoid expected hazardous weather, volcanic ash encounters, or known solar flare events, if considered, are typically made by flight dispatch.

PIC Authority

Federal aviation regulations give the PIC broad authority, which includes altering the flight path to avoid known hazards:

1. The PIC of an aircraft is directly responsible for, and is the final authority as to, the operation of that aircraft.
2. In an in-flight emergency requiring immediate action, the PIC may deviate from any rule to the extent required to meet that emergency.

While a PIC is expected to avoid obvious threats, such as deviating around convective weather or adjusting altitude to minimize turbulence, flight plan changes are usually made in coordination with licensed dispatchers at the airline and/or negotiated with air traffic control. Requesting a lower altitude or seeking a route with a lower latitude to minimize radiation exposure might be possible, but unavoidable constraints and tradeoffs remain. A lower altitude will probably increase fuel burn and may mean the aircraft arrives at its destination with less-than-required fuel reserves. Requesting a lower altitude or latitude may place the aircraft out of a favorable jet stream, increasing time in route and contributing to late arrival.

Particularly in the North Atlantic, congestion is common on the NAT Tracks, which are structured routes across the North Atlantic stretching from North America to Western Europe. These routes are designed to ensure the required lateral and longitudinal aircraft spacing in areas of little radar coverage, and while a pilot or dispatcher could deviate from an assigned track under certain conditions, in practice that is not so easily achieved. Therefore, choosing routes to minimize radiation exposure may be expensive or undesirable and would need to be considered along with other priorities, not all of which are apparent to the PIC, let alone within that person's control.

Flight Crew Scheduling Systems

Seniority within an airline is generally according to date of hire and usually does not attach to a flight crew should they change employers. Seniority is of paramount importance when flight crew bid or are scheduled for base assignments, vacations, and work schedules. Seniority also impacts the aircraft types a pilot can choose to fly and whether he or she can hold the left seat (captain) or right seat (first officer).

Nearly all major airlines use sophisticated computer programs to ensure that planned flights are adequately crewed with the required mix of qualified pilots and flight attendants. Members of the flight crew, usually monthly, request periodic work schedules through the preferential bidding system (PBS) using weighted preferences that they input into the computer program. The scheduling solution must be as efficient as possible while respecting flight crew preferences, honoring seniority, conforming to

applicable regulations and contractual agreements, and satisfying operational coverage requirements. While most major airlines use a PBS for assigning flight crew schedules, some airlines use manual scheduling systems. To encompass both approaches, this report uses the term “scheduling system” to include manual scheduling systems and PBSs.

The schedule for a particular flight crew, allocated in advance, may be changed during a given month because of operational requirements and employee choices. Adding and dropping trips is common, again respecting seniority and other constraints. Bidding for schedules or flights that minimize radiation exposure is currently possible but only crudely, such as by avoiding long-haul flights, preferring low-latitude routes, or bidding a low-time block (i.e., less time in the air in each month). More precise dose management would require integrating expected cosmic and solar radiation dose estimates into the scheduling system. A typical scheduling system allows myriad inputs and provides flight crews with considerable flexibility. Using validated, model-based estimates of radiation dose for flights in the scheduling system is possible today.

One source of filed contractual grievances by flight crew is “out-of-seniority” scheduling. Radiation exposure mitigations that do not align neatly with the traditional seniority system may need to be negotiated. For example, a junior flight attendant who is pregnant may need to be assigned to a low-latitude trip while a senior colleague may need to accept a polar flight with a short layover. Changes to the scheduling system and the factors that allow priority selection in flight schedules will introduce implementation challenges requiring engagement of airlines and flight crew labor organizations.

Engineering Mitigations

Shielding is a manufacturing and engineering consideration, and increasing shielding to block some radiation on airplanes needs to be weighed against other factors, such as aerodynamics. Although studies have shown that composite materials act as better shields against neutron radiation than aluminum or titanium, because of the mass of material required, shielding an airliner against cosmic radiation is generally considered impractical.

Flight data recorders (the so-called black boxes) record many parameters of in-flight data; newer aircraft may include records of more than 2,000 parameters, stored in solid state memory or, in some cases, downloaded in real time. Although the technology is available (e.g., the Concorde cockpit included a radiation monitor), radiation dose measurement, display, and recording devices are not yet installed on most commercial aircraft. Adding this type of radiation measurement device could facilitate collection of accurate near-real-time data that could inform other aspects of monitoring and reporting systems. An alternative and supplementary approach is to track radiation doses using the computational models described in earlier chapters of this report.

Communication and Education as Approaches to Mitigation

Outside the conventional radiation mitigation measures of time, distance, and shielding, administrative mitigation measures may be considered for use in U.S. air carriers, such as procedures to educate, train, and provide flexibilities to flight crew rather than changing physical conditions. Communication and education are core elements of a radiation safety program and are essential to enabling flight crew to make informed decisions.

CHALLENGES AND OPPORTUNITIES IN COMMUNICATING RADIATION RISK TO FLIGHT CREW

Risk communication is part of an effective radiation safety program. In the aviation context, the goal of risk communication is to provide information to flight crew on radiation risks to help them make decisions about their own acceptable risk exposure (Balog-Way et al. 2020). Thus, the goal is to increase domain-specific knowledge rather than influence risk perceptions or mitigation behaviors (Siegrist and Arvai 2020). Exposure is generally at safe levels, and no immediate mitigation actions are necessary.

Although estimated annual radiation exposure in aviation is below occupational dose limits, monitoring is warranted given the total cumulative exposure that workers could receive over their careers. As reported in Chapter 4, no immediate health effects exist, but the potential risk of long-term health effects from in-flight exposures remains. The health risks of low-dose radiation remain scientifically uncertain, with risk estimates either overestimating or underestimating risk, as noted in both the National Academies of Sciences, Engineering, and Medicine reports on low-dose radiation research (NASEM 2022) and space radiation and astronaut health (NASEM 2021) and the workshop proceedings on tracking radiation exposure from medical diagnostic procedures (National Research Council 2012).

Within the aviation environment, risk perceptions may influence the interpretation and effectiveness of risk communications. Risk communications are needed to address cumulative exposure (i.e., chronic exposure) as well as SEP events (i.e., acute exposures). This section highlights factors that influence radiation risk perceptions in aviation and ways to communicate potential doses to best support a flight crew's ability to make informed decisions regarding occupational exposure.

Although research exists on risk perceptions related to radiation (see Box 6-2), the committee found little literature focused on occupational exposure in aviation. Therefore, whether these exposures are perceived as voluntary is unclear. In general, many flight crew may not be aware of radiation risks. Risk perceptions vary across individuals and demographics. For example, women may be more concerned about radiation protection specifically due to the additional risks associated with pregnancy (Kitamura et al. 2026). In firefighting, risk perceptions increase for occupational exposure with a long delay of consequences and a high severity of consequences (Rodríguez-Garzón et al. 2021). Both of these factors, delay in and severity of effects, are relevant for radiation exposure in aviation. People may also underestimate the risks. For example, flight crews may have optimism bias and believe they are less likely to experience adverse

health outcomes from their occupational radiation exposure—especially if they believe that they can control their exposure (Shepperd et al. 2015). Although SEP events are rare and generally do not exceed dose limits with a single event, such events may still provide a large dose for someone who needs to minimize radiation exposure (e.g., a person who is pregnant or is receiving radiation treatment). Radiation exposure from SEP events is less likely to be perceived as voluntary and may be associated with higher-risk perceptions.

The current status quo, which requires flight crew to model their own radiation dose (see Box 6-1), is complex, and few flight crewmembers are likely to pursue that information creating another barrier to how flight crew may perceive radiation as a potential risk. Thus, effective risk communications would be relevant, easily accessible, and timely for decision-making. Flight crew need to be provided with individual estimates of their radiation doses over time and after SEP events. The communication design may differ for cumulative exposure and specific SEP events.

Multiple resources for best practices in risk communication are available (Fischhoff et al. 2011; NASEM 2021). Flight crew report wanting more information about radiation risks. For example, despite regulations in Europe requiring radiation risk communication for flight crew since 1996, flight crew in Belgium (largely pilots) still report receiving insufficient information about radiation hazards from their employer. Survey participants expressed concerns that economics were prioritized more than safety (Pepin

BOX 6-2

Lay Perceptions of Radiation Risk

People do not perceive all radiation as equally bad. For example, people perceive radiation from nuclear waste as much more dangerous than X-rays, despite expert evaluations of the risks being reversed. This is partly because people trust medical institutions to mitigate risks and perceive higher benefits from X-rays (Slovic 1996). X-rays are also considered a voluntary risk, while hazards like nuclear waste are considered involuntary exposure.

Another example is radon, a natural source of radiation that increases lung cancer risk. People tend to have limited knowledge of radon. While risk perceptions and knowledge are weakly associated with the likelihood of increased radon testing, this knowledge does not consistently lead to mitigation efforts, which are inconvenient and costly (Jones 2015). Rather, mitigation is more strongly associated with concerns about vulnerable residents (i.e., children) and social influence (Cori et al. 2022; Khan et al. 2021). For natural hazards such as weather, people who have experienced a hazard are more likely to take mitigation actions (Wachinger et al. 2013). Ultimately, no one-size-fits-all approach exists for radiation risk communication, which is highly dependent on the scenario (e.g., trust, perceived benefit, voluntariness) and individual approaches to risk.

et al. 2023). For weather-related hazards in particular, accidents are more related to misperceptions of the risk than to risk tolerance, suggesting that better training, education, and communication about risks are desirable (Hunter 2009).

Cumulative radiation dose can be communicated via quarterly (or at least annual) reports. Radiation dose is likely to be an unfamiliar measure that is difficult to translate to health risks. Confusion regarding ionizing versus nonionizing radiation and measurement units is likely, even if explanations are provided (Hurlbert et al. 2022). Existing tools use flight data to estimate dose and do not directly translate that into health risks. One strategy is to frame the dose using colored risk levels (e.g., lighter vs. darker shades) to communicate lower and higher risks (Zikmund-Fisher et al. 2008) or to communicate proximity to a limit. For example, NASA has used this type of communication for astronauts via a traffic light graphic (NASEM 2021). However, astronauts can be exposed to much higher doses of radiation over their careers, and no evidence demonstrates that this would be an effective strategy at the lower doses experienced by flight crew. For example, astronauts use colors like green and red to be consistent with other go/no-go decision-making tools. For flight crews, green and red may inappropriately imply good and bad health consequences rather than reflect the uncertainty about health outcomes from cumulative exposure.

Forecasting solar weather, especially SEP events, is difficult even in the presence of a large event on the Sun, because of high uncertainty related to the interactions with interplanetary and geomagnetic fields. As a result, the radiation doses are only known after an event. Following an SEP event, flight crew will need to be alerted to any radiation exposure as soon as possible to support trust. Trust in messengers is critical to maintain effective risk communication (Balog-Way et al. 2020). If risk communication is not provided by a trusted source, this can add an additional source of uncertainty and potentially fuel misinformation. Those individuals who seek to minimize their dose (e.g., those who are pregnant or are receiving radiation treatments) may choose to fly less after an SEP event to account for the larger dose received. In some cases, pilots may receive real-time information about a possible SEP event to inform decisions about changing the flight path (e.g., flying at a lower altitude to reduce radiation exposure).

Airlines can communicate general health risks from cumulative exposure via training and education. Communicating the uncertainty associated with translating dose to risk for adverse health outcomes is especially important given that the overall risk is relatively low and many confounding factors are present.

Best practices for communicating cancer risk use icon arrays to facilitate a part-to-whole comparison (Spiegelhalter 2017; Trevena et al. 2013; Zikmund-Fisher et al. 2008; Zipkin et al. 2014). For example, in Figure 6-1, an icon array shows that for people exposed to 100 mSv (i.e., 0.1 Sv) of low-dose radiation, 1 out of 100 people (indicated by the star) will develop cancer because of it. In comparison, 42 out of those 100 people (solid circles) will be diagnosed with cancer for reasons unrelated to radiation. While this analysis is not specific to aviation, this type of benchmark may support risk communication and could be revised to better account for occupational exposure risks (e.g., to reflect a typical flight crew career dose and incorporate uncertainty). Within an icon array, uncertainty is communicated via a gradient across icons (Raphael et al.

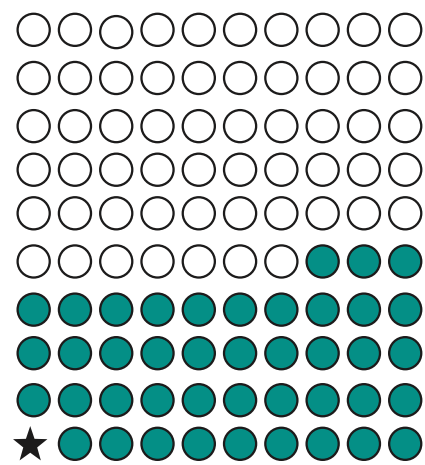


FIGURE 6-1 Example of an icon array to communicate population-level radiation exposure and cancer risk.

NOTE: In a lifetime, approximately 42 (solid circles) out of 100 people will be diagnosed with cancer, and approximately one cancer (star) per 100 people could result from a single exposure to 0.1 Sv of low linear energy transfer radiation above background.

SOURCE: Figure PS-4 in National Research Council (2006).

2020). In addition, numeric and/or verbal descriptions can be used to communicate important information during times of high uncertainty; however, attaching numerical interpretations (e.g., “2 out of 10”) to any verbal descriptors (e.g., “high risk”) used is highly recommended (Spiegelhalter 2017; van der Bles et al. 2019).

Newly hired pilots at U.S. airlines typically spend about 2 months in initial training, beginning with indoctrination under Federal Aviation Regulation 121.911, which covers company policies, operations, and SMSs. Similarly, flight attendants typically spend 6–8 weeks in initial training. This time spent in training provides a logical opportunity to introduce guidance on in-flight radiation exposure if adopted by the airline. Ongoing education about radiation exposure monitoring and mitigation can also occur through annual recurrent training, online modules, and requirements.

For primary flight crew, the general training would provide an overall understanding of the sources and risks of radiation exposure and contain the same material for both cabin and cockpit flight crew. This approach would establish the credibility of and trust in the employer who provides this training.

Regardless of the risk communication approach, conducting evaluations to measure the effectiveness of the messaging is critical. For example, providing full information on uncertainty can improve trust, but it can also make information overly complicated and reduce confidence (Balog-Way et al. 2020). In addition, risk communications may increase affective responses (e.g., anxiety) without changing behavior. Moreover, less research is available on effective risk communications for reproductive health than for

cancer. Evaluations support efforts to anticipate and address these challenges via an evidence-based process.

SYNTHESIS AND PATH FORWARD

The committee finds that radiation exposure in aviation warrants attention as an occupational hazard. Estimated annual occupational doses for flight crew generally fall well below recommended limits (see Chapter 4); however, cumulative exposures over a career warrant monitoring and tracking. Within this context, radiation exposure can be managed using established approaches that have been applied in other radiation-exposed worker populations.

Although uncertainties remain in quantifying health risks and characterizing the radiation environment, sufficient scientific understanding and technical capability exist to support practical risk management. Computational models, measurement campaigns, and space weather forecasting tools provide a foundation for estimating and managing exposure at aviation altitudes and ensuring those models can produce the best occupational dose estimates for flight crew.

The committee's review indicates that the primary gap in the United States is not a lack of scientific knowledge or technical capability but the absence of a systematic framework to apply these tools in an operational context. Flight crew currently lack consistent access to exposure information, formal mechanisms for dose tracking, and structured education to support informed decision-making. In contrast, other occupational settings rely on radiation safety programs that integrate hazard identification, exposure assessment and tracking, training, communication, and continuous evaluation.

The elements described in this chapter demonstrate that such a framework can be adapted to aviation. While engineering controls such as shielding are not practical for commercial aircraft, administrative and operational controls, including route planning, altitude selection when feasible, and crew scheduling, offer viable means to manage exposure. These approaches are consistent with the principle of ALARA and can be integrated into existing airline SMSs.

Given these findings, the committee concludes that implementation of a structured radiation safety program is a practical and appropriate approach to managing occupational radiation exposure in aviation. Accordingly, the committee recommends the following:

- Recommendation 6-1: The Federal Aviation Administration (FAA) should exert its regulatory authority and require U.S. commercial airlines to implement a radiation safety program for flight crewmembers that follows best practices for occupationally exposed workers. The FAA should create a set of requirements and implementation protocols for airlines to satisfy in their development of the required radiation safety program. The FAA should include the following elements in its set of requirements and implementation protocols:**
- **Methods for characterizing the radiation conditions in an aircraft (i.e., modeling, monitoring, and dosimetry).**

- **Evidence-based and expert-led training and education programs to inform flight crew about their radiation exposure and potential associated health risks. The training and education program should include specific content about radiation exposure during pregnancy and potential adverse consequences across a life course. This includes a declared pregnant worker process as is done in radiation safety programs for other occupationally exposed workers.**
- **Incorporating radiation exposure considerations into the scheduling systems for flight attendants and pilots. For this purpose, airlines and labor organizations should work together to incorporate solutions for individuals seeking to lower their radiation exposure (e.g., pregnant flight crew), respecting seniority in the scheduling system to the extent possible.**

Implementing a radiation safety program for flight crew aligns U.S. aviation practices with those used in other radiation-exposed occupations and with international aviation standards. Such a program provides flight crew with the tools and information needed to understand and manage their exposure, supports risk-informed operational decisions, and generates data to improve exposure assessment and risk characterization over time.

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7

The Way Forward

As reviewed in Chapter 2, the committee recommends that the Federal Aviation Administration (FAA) assert its authority over occupational safety and health of flight crew on aircraft in operation (Recommendation 2-1). With regard to in-flight cosmic ionizing radiation exposure, the FAA has provided advisory guidance but has neither required monitoring of doses nor promulgated enforced dose limits. Consequently, aircraft flight crew represent a substantial population with occupational radiation exposure, albeit naturally occurring, without a radiation safety program. Other occupational groups exposed to ionizing radiation, including medical radiation workers and nuclear industry personnel, operate within established radiation protection systems that have been associated with substantial reductions in occupational exposures over time (e.g., Villoing et al. 2021). Such programs include comprehensive monitoring for these worker populations (NCRP 2018; UNSCEAR 2022).

The Statement of Task (SoT) provided to this committee by the FAA addresses elements that could inform such a program for flight crew: understanding what is known about the health risks of in-flight radiation exposure and the potential for epidemiological investigations to advance that understanding; evaluating the computational tools available for estimating galactic cosmic radiation (GCR) and solar energetic particle event doses received by flight crew; addressing potential mitigation measures; and offering strategies for communicating about radiation exposure and associated risks to flight crew as a necessary element of mitigation. The SoT did not directly address the overarching issue of developing and implementing a radiation safety program for flight crew that would include a surveillance program. Ongoing collection of data on exposures and health outcomes via a surveillance or tracking program would create a platform for research and support mitigation measures as well as document their impact. Establishing a system for routine occupational radiation dose tracking would be a foundational first step toward such a comprehensive radiation safety program for flight crew.

Here, the committee offers comments on the need for a radiation safety program and critical steps for implementing such a program, including the assumption of authority by the FAA for doing so and then proceeding with a strategic and funded approach. The same general considerations around implementation are applicable to addressing the committee's specific recommendations related to the SoT.

As a starting point, the FAA and its stakeholder partners—the airline industry; cockpit crew, flight attendants, and their unions; and aircraft manufacturers—would need to engage in a decision-making process on moving forward with a program. An evidence-based characterization of risk would be essential to that process, centered on the acceptability of the risk of exposure to flight crew. This report provides relevant information in its review of the literature and the calculation of doses for various work profiles that would provide a foundation for this decision-making process. If a program were to be implemented successfully, the FAA would need to assume regulatory authority by implementing requirements for the Part 121 operators.¹ The International Commission on Radiological Protection and the National Council on Radiation Protection and Measurements provide guiding principles that could be leveraged by the FAA for radiation protection programs—notably, justification, limitation, and optimization (ICRP n.d.; NCRP 2018).

MOVING TOWARD A RADIATION SAFETY PROGRAM

Any process to move toward a radiation safety program would require substantial time to progress from decision-making to implementation. The committee's recommendations are actionable and following them would address the gaps that motivated the call for this study in the FAA Reauthorization Act. Here, the committee amplifies its recommendations in response to the SoT with comments on implementation.

Dose Estimation

As documented in Chapter 4, multiple computational models are available for estimating doses received by flight crew for specific flights. The committee reviewed the characteristics of these models without giving preference to a particular model and ultimately calls for the use of an ensemble approach, pending further evaluation. The committee calls for further verification and validation, an effort that should be led by the FAA per the committee's recommendations, a system should be established for monitoring and recording the doses received by individual flight crewmembers for all

¹ Part 121 operators are FAA-certified air carriers and for the purposes of this report include only commercial, civilian aviation (e.g., large U.S. airlines and regional air carriers). Military aircraft are not included in the definition of Part 121 operators. While cargo carriers are included in the definition of Part 121 operators, radiation from cargo is out of scope for this report. However, the committee acknowledges radiation as a potential related occupational risk for flight crew for cargo carriers. This report will use the terminology "U.S.-based commercial airlines" or "U.S. airlines" in reference to large U.S. airlines and regional air carriers as Part 121 operators.

of their flights with the goals of informing flight crew as to their accumulating dose, guiding mitigation, and supporting research (Recommendation 5-1).

One interim and readily accomplished step would be to simplify the multistep process for obtaining data on in-flight exposures, including by reducing the complexity of the user interface for CARI-7, so that flight crew could have a better understanding of the radiation doses received in their work. For the longer run, the burden of tracking doses would need to shift from individuals to the airline companies. Enhanced awareness of the doses received with various flight profiles (e.g., polar routes) is fundamental to risk communication and management of exposures by individuals.

Research

The committee's review of the epidemiologic literature highlights methodological limitations that could be addressed. Chapter 5 addresses these limitations and recommends the development of a centralized and standardized dose tracking system to support the generation of studies that incorporate accurate assessment of cosmic radiation exposure and collection of information on health outcomes and other relevant factors. The proposed dose tracking and registry would provide the foundations for research on the association between radiation exposure and the health of flight crew. Calls for such research raise questions as to how it would be funded and what entity would carry it out. These questions require answers if the committee's call for informative research on radiation risks for flight crew is to be addressed. If a new epidemiologic study were to be launched, results would not be forthcoming for some years. In the interim, more robust evidence on radiation risks could be obtained by pooled analyses of existing studies. For example, Pukkala and colleagues (2012) pooled cancer incidence data from cohort studies of flight crew in four Nordic countries: Finland, Iceland, Norway, and Sweden. By pooling the data from the relatively small individual cohorts, the sample sizes reached 8,507 female and 1,559 male airline cabin attendants. Exposure–response relationships were examined with estimated exposure to GCR, and statistically significant increases in risk were found for several cancer types.

A broader effort to combine existing data, using both meta-analytical and individual participant–level pooled designs, could be undertaken, using the committee's compilation of the literature as a starting point. Such combined analyses typically involve substantial effort in their arrangement, harmonization of datasets, analysis, and reporting. However, they provide a powerful approach for addressing key research questions and achieving the statistical power needed to determine health outcomes associated with flight crew exposure to cosmic radiation.

Risk Communication and Education

The report also addresses communication and education around risks of radiation, which together are fundamental to monitoring and any associated mitigation. Flight crew need foundational understanding of the nature of their exposures to cosmic radiation and of the implications of the doses that they have received. Education should

also cover how doses vary by routes flown. The science of risk communication is well developed generally and, more specifically, regarding the risks of radiation. While the committee did not examine the risk communication practices currently in place within U.S. airlines, it recommends communication about risks to all flight crew as well as targeted communication for female flight crewmembers who are pregnant. Moving forward, evidence-based communication strategies should be developed and implemented with stakeholder partners. This could be done incrementally as dose estimation tools and protocols are improved. The committee provides specific and readily implementable recommendations on providing initial and recurrent training that incorporates information on radiation exposure.

Managing Radiation Dose

Management of radiation dose is a key goal of a radiation safety program. Chapter 6 outlines the elements of such a program, with considerations for management of cosmic radiation exposure and potential mitigation measures. While mitigation would be accomplished most effectively within the framework of an established radiation safety program, several of the committee's recommendations could be implemented in a shorter time frame: specifically, modifying the scheduling systems for flights to provide greater opportunity for flight crew to manage their radiation dose, particularly for those who are pregnant. Education on how dose varies by flight routes would be needed to guide choices in the scheduling system.

TAKING ACTION

The committee concludes that progress requires a coordinated, phased approach led by the FAA, in collaboration with industry stakeholders, flight crew and their labor organizations, and federal partners. The recommendations in this report are actionable and can be implemented in sequence to build toward a comprehensive radiation safety framework.

Recommendation 7-1: The Federal Aviation Administration should take the lead in implementing a collaborative strategy to develop the requirements and the approach for U.S. airlines to implement radiation safety programs.

This recommendation establishes the basis for moving forward and sequencing the committee's recommendations; it also clarifies the role of the FAA in defining requirements that enable implementation by airlines and other stakeholders. The following recommendations are presented in a sequence, moving from immediate to longer-term implementation.

Sequenced Implementation of Recommendations

Immediate

Recommendation 2-1: The Federal Aviation Administration should exert its regulatory authority over ionizing radiation as an occupational exposure that requires oversight to ensure flight crewmember health and safety.

This action is foundational and enables implementation of all other recommendations.

Recommendation 2-2: The Federal Aviation Administration should improve the usability of the CARI model for estimating radiation dose by developing a user-friendly, web-based application to increase accessibility to dose estimation for flight crew.

This action is a feasible first step as well as an interim approach to enhance awareness and provide individual dose tracking while more comprehensive systems are developed. Tracking radiation dose should not be left up to individuals in the long-term.

Shorter-Term

To support the FAA's regulatory authority over radiation exposure, the following actions are recommended in the short-term.

Recommendation 6-1: The Federal Aviation Administration (FAA) should exert its regulatory authority and require U.S. commercial airlines to implement a radiation safety program for flight crewmembers that follows best practices for occupationally exposed workers. FAA should create a set of requirements and implementation protocols for airlines to satisfy in their development of the required radiation safety program. The FAA should include the following elements in the agency's set of requirements and implementation protocol:

- **Methods for characterizing radiation conditions in an aircraft (i.e., modeling, monitoring, and dosimetry).**
- **Evidence-based and expert-led training and education programs to inform flight crew about their radiation exposure and potential associated health risks. The training and education program should include specific content about radiation exposure during pregnancy and potential adverse consequences across a life course. This includes a declared pregnant worker process as is done in radiation safety programs for other occupationally exposed workers.**
- **Incorporating radiation exposure considerations into the scheduling systems for flight attendants and pilots. For this purpose, airlines and labor organizations should work together to incorporate solutions for individuals seeking to lower their radiation exposure (e.g., pregnant flight crew), respecting seniority in the scheduling system to the extent possible.**

Concurrently the FAA should collaborate with other agencies to improve radiation dose models and establish a centralized repository for tracking doses.

Recommendation 4-1: The Federal Aviation Administration, in conjunction with National Oceanic and Atmospheric Administration and National Aeronautics and Space Agency, should collaborate on sustained measurement campaigns to better characterize radiation environments at flight altitude and with dedicated resources to better validate models, especially for solar energetic particles.

Recommendation 5-1: The Federal Aviation Administration should work with appropriate agencies, such as the Centers for Disease Control and Prevention/ National Institute for Occupational Safety and Health, to establish a dose tracking system for flight crew. Such a system would enable U.S. airlines and individual flight crewmembers to monitor doses and to make decisions to manage them. The system would also facilitate epidemiologic research by providing standardized dose information for study participants. Periodic matches of the dose tracking data with health and mortality databases would support assessment of the population health of flight crew.

Longer-Term

While the actions described above should be undertaken promptly, the following recommendations address the longer-term and include efforts to improve computational models for estimating flight crewmember radiation doses and to strengthen the design of studies examining associations between occupational radiation exposure and health outcomes.

Recommendation 4-2: The Federal Aviation Administration, in collaboration with other organizations that develop aviation radiation exposure models, should systematically evaluate computational models under realistic operating conditions to better characterize their uncertainties and biases. This evaluation should establish a methodology for using an ensemble of models to assess variability and improve estimates of flight crew radiation exposure, particularly for transpolar routes and during solar energetic particle events.

Recommendation 5-2: In parallel with developing a dose-tracking system, a strategic research plan for future epidemiologic research on the association between occupational radiation exposure and health outcomes for flight crew should be elaborated by the Federal Aviation Administration and other federal agencies in collaboration with industry and flight crew partners.

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Appendix A

Biographical Sketches of the Committee and Project Staff

COMMITTEE

Jonathan M. Samet (*Chair*), a pulmonary physician and epidemiologist, is the past dean of the Colorado School of Public Health and a professor of epidemiology and of occupational and environmental health. Samet's research has focused on the health risks posed by the environment, including inhaled pollutants, radiation, and tobacco. He has served on numerous committees concerned with public health and the environment including the U.S. Environmental Protection Agency Science Advisory Board and the National Cancer Advisory Board. He is a member of the National Academy of Medicine and recipient of the David Rall Medal for his contributions. Samet received an A.B. in chemistry and physics from Harvard College, an M.S. in epidemiology from the Harvard T.H. Chan School of Public Health, and an M.D. from the University of Rochester School of Medicine and Dentistry. He previously served as chair of the National Academies of Sciences, Engineering, and Medicine Committee on Biological Effects of Ionizing Radiation VI and the Committee on Incorporating 21st Century Science in Risk-Based Evaluations; he also served as chair of the Board on Environmental Studies and Toxicology.

Amir A. Bahadori is a professor in the Alan Levin Department of Mechanical and Nuclear Engineering, serves as Nuclear Engineering Program director, and holds the Hal and Mary Siegle Professorship in Engineering at Kansas State University. He previously worked in the Space Radiation Analysis Group at the National Aeronautics and Space Administration's Lyndon B. Johnson Space Center. Bahadori has an extensive background in space radiation sources and transport, radiation dosimetry, radiation detection, radiation risk models, and radiation epidemiology. He is presently collaborating on the Million Person Study of radiation workers and atomic veterans. He is a member of the American Nuclear Society, the Health Physics Society, and the Radiation

Research Society. He serves on the National Council on Radiation Protection and Measurements and the Program Area Committee 6: Radiation Measurements and Dosimetry. In 2018, he was awarded the Zeldovich Medal for his work on space radiation detection, and in 2022, he was awarded the American Nuclear Society Presidential Citation for his work on the Society's position statement on low-level radiation exposure health effects. Bahadori received a B.S. in mechanical engineering with nuclear engineering option and a B.S. in mathematics from Kansas State University, an M.S. in nuclear engineering sciences from the University of Florida, and a Ph.D. in biomedical engineering from the University of Florida. Bahadori previously received research funding from Radiation Detection Technologies, Inc., a company that specializes in semiconductor-based radiation detection. He is also a listed inventor on a patent related to measurement of the in-flight neutron spectrum for radiation protection purposes.

Thomas A. Burke is professor emeritus at Johns Hopkins University Bloomberg School of Public Health and director emeritus of the Johns Hopkins Risk Sciences and Public Policy Institute. His research interests include environmental epidemiology and surveillance, population exposures to environmental pollutants, risk assessment and communication, and application of the risk sciences to public policy. Before joining the university faculty, he was deputy commissioner of health for the State of New Jersey and director of science and research for the New Jersey Department of Environmental Protection. From 2015 until 2017, Burke was the U.S. Environmental Protection Agency's science advisor and deputy assistant administrator for research and development. He is a fellow of the Society for Risk Analysis, an honorary member of the Society of Toxicology, and a lifetime national associate of the National Academies of Sciences, Engineering, and Medicine. Burke received a B.S. from St. Peter's University, an M.P.H. from the University of Texas, and a Ph.D. in epidemiology from the University of Pennsylvania. He previously served on the National Academies Division on Earth and Life Studies Committee and the Board on Environmental Studies and Toxicology, and he chaired the Committee on Improving Risk Analysis and the Committee on Human Biomonitoring for Environmental Chemicals.

Casey I. Canfield is an associate professor in engineering management and systems engineering at the Missouri University of Science and Technology. She quantifies the human part of complex systems to improve decision-making and policymaking in the context of energy, rural broadband, and health care. She leads multisector, cross-disciplinary, stakeholder-centered teams for problem-oriented research. Across domains, she conducts participatory research, collaborating with people who are ultimately impacted by technology. Canfield serves on the advisory board of the Missouri Science and Technology Policy Fellowship and the Missouri Energy Initiative. She was a Science and Technology Policy Fellow in the U.S. Department of Energy's Solar Energy Technologies Office where she was primarily involved in designing and managing programs that aim to increase innovation and reduce soft costs in the energy sector. Canfield received a B.S. in engineering systems from Olin College of Engineering and a Ph.D. in engineering and public policy from Carnegie Mellon University.

Sarah S. Cohen is director of public health research at DLH, LLC, a federal contractor. She is also an adjunct assistant research professor of medicine within the Department of Medicine at the Vanderbilt University School of Medicine. Previously, she spent 20 years in the commercial consulting space at EpidStat Institute, EpidStrategies, and the International Epidemiology Institute leading the design, conduct, and analysis of epidemiologic studies related to pharmacoepidemiology, nutrition, and health outcomes—including cancer, cardiovascular disease, and diabetes—as well as occupational cohort studies of aerospace workers, welders, and chemical manufacturers. Her expertise includes occupational exposures and health outcomes as well as behavioral and genetic determinants of cancer and metabolic-related conditions such as obesity, racial disparities in cancer, biomarkers of cancer and obesity, and cancer screening. She is a technical consultant to the National Council on Radiation Protection and Measurements with whom she has collaborated on multiple cohort studies examining health effects among radiation-exposed workers. Cohen received an M.S. in biostatistics and public health genetics from the University of Michigan and a Ph.D. in epidemiology from the University of North Carolina, Chapel Hill.

Mardi Crane-Godreau, former assistant professor at Geisel School of Medicine at Dartmouth (GMS), now devotes her attention to writing on long COVID and aging at Substack. As an associate editor at *Frontiers in Human Neuroscience* and *Frontiers in Public Health*, she recently saw completion of the publication of *Aerospace Health and Safety: Today and the Future, Volume II*, an editorial project from the Section on Environmental Health and Exposome of *Frontiers in Public Health*. Her research at GMS included a multiphase clinical trial studying the health of secondhand smoke-exposed airline flight attendants. This was focal to her interest after spending 18 years (~18,000 flight hours) as a Pan Am flight attendant. She is a current member of the Mitochondrial Medicine Society, the Pan Am Museum Foundation, and the National Association of Science Writers and a former member of World Wings International. Crane-Godreau's educational background includes a Ph.D. in physiology from GMS, a B.A. in biology and chemistry from Massachusetts College of Liberal Arts (MCLA), and a B.S. in education from the University of Vermont. Crane-Godreau was awarded an honorary doctor of science degree by MCLA in 2013. She also holds a non-degree credential in trauma therapy from the Somatic Experiencing Trauma Institute.

Lindsay S. Fenwick is an accomplished aviation professional with more than 21,000 flight hours spanning military, corporate, VIP, and major airline operations. His career began with the Royal New Zealand Air Force before transitioning to commercial aviation, where he served as a pilot for Northwest Airlines for 28 years. He held captain positions with international carriers including Bahrain Air, National Air Services (Saudi Arabia), and Qatar Amiri Flight. Captain Fenwick has extensive expertise in aviation safety management, serving as deputy manager for safety at Qatar Amiri Flight and holding leadership roles with the International Federation of Air Line Pilots' Associations and Air Line Pilots Association (ALPA), International. He is an experienced accident investigator, having been directly involved with three major National

Transportation Safety Board investigations and serving as course director/instructor for ALPA's accident investigation programs for more than a decade. Captain Fenwick continues his safety advocacy work with international aviation organizations. His comprehensive qualifications include certifications in safety management systems, fatigue risk management systems, aviation auditing, and emergency response management. Captain Fenwick is a graduate of the U.S. Air Force Academy with a B.S. in physics, and he holds an M.S. in aeronautical/astronautical engineering from Stanford University and an M.B.A. from the University of Minnesota.

Heidi A. Hanson is the group lead of biostatistics and biomedical informatics in the Computational Sciences and Engineering Division at Oak Ridge National Laboratory. She holds adjunct appointments in the Departments of Population Health Sciences and Surgery at the University of Utah and serves as a graduate advisor at the University of Tennessee Bredeesen Center for Interdisciplinary Research and Graduate Education. Hanson is the principal investigator of the U.S. Department of Energy–National Cancer Institute project Modeling Outcomes Using Surveillance Data and Scalable Artificial Intelligence for Cancer—which advances large-scale computing, predictive machine learning/deep learning models, and simulation methods for cancer research—as well as the biopreparedness project Electronic Health Records-Informed Lagrangian method for precision public Health. Her research spans machine learning and artificial intelligence, demography, statistics, and environmental and life-course epidemiology, including studies of environmental exposures such as radon and air pollution. She holds a B.S. in behavioral health sciences and an M.S. and a Ph.D. in sociology, along with a graduate certificate in demography, from the University of Utah.

Benjamin W. McGee is the assistant director for radiation safety and a radiation safety officer at the University of Maryland, College Park, within the Department of Environmental Safety, Sustainability and Risk. He brings nearly 20 years of experience in health physics and radiological safety across government, commercial spaceflight, and academic sectors. Previously, McGee served as a senior scientist with the U.S. Department of Energy's National Nuclear Security Administration Aerial Measuring System. He also worked as lead health physicist and radiological engineer for astronaut safety and dosimetry at both Bigelow Aerospace—whose module remains attached to Node 3 of the International Space Station—and Axiom Space, which has conducted four private astronaut missions to the International Space Station. Earlier in his career, he spent nearly a decade as a health physicist at the Nevada National Security Site, where he served as lead analyst for nuclear accident dosimetry and as a monitoring manager for the Federal Radiological Monitoring and Assessment Center's Consequence Management Response Team. McGee's research includes aviation-focused radiation dosimetry, and he served as proposer and principal investigator for a U.S. Department of Energy–funded study assessing cosmic radiation dose aboard both fixed-wing and rotary-wing aircraft. He is a member of the Health Physics Society, the National Registry of Radiation Protection Technologists, and the American Institute of Aeronautics and Astronautics, and he

is a national fellow of the Explorers Club. McGee holds a B.S. in geology from the University of Wyoming, where he specialized in infrared spectroscopy of planetary surfaces, and an M.S. in space studies from the University of North Dakota, where his research focused on space weathering and the effects of radiation on asteroid surfaces.

Christopher J. Mertens is a senior research physicist at the National Aeronautics and Space Administration (NASA) Langley Research Center, where he has been employed for 25 years. Mertens's areas of expertise include atmospheric and space ionizing radiation transport and dosimetry, and space environment modeling. He is the creator and primary developer of the Nowcast of Aerospace Ionizing Radiation for Aviation System model and was the principal investigator (PI) of the NASA Radiation Dosimetry Experiment and the NASA Space Weather Aviation Radiation flight campaigns. Mertens is the 2024 recipient of the NASA Exceptional Technology Achievement Medal and the 2022 recipient of the NASA Langley H. J. E. Reid Award for best scientific paper published in a peer-reviewed journal. He is the recipient of the Small Business Technology Council's 2016 Champion of Small Business Technology Commercialization Award, the 2012 and 2022 NASA Exceptional Scientific Achievement Medals, and many more professional awards. He has been the PI of numerous research and analysis projects over the past two decades and has authored more than 120 peer-reviewed scientific journal articles. Mertens earned a Ph.D. in physics from the Georgia Institute of Technology.

Christopher Scheibler is a chief flight surgeon in the United States Air Force and is board-certified in aerospace medicine and occupational and environmental medicine. He has served in clinical, executive, and command positions directing aerospace, occupational, and preventive medicine programs that support the health and safety of civilian and military populations across stateside, overseas, and deployed locations. Scheibler is an affiliated research scientist with the Harvard T.H. Chan School of Public Health and a staff collaborator on the Harvard Flight Attendant Health Study. He also serves as an assistant professor for the Uniformed Services University of the Health Sciences Department of Preventive Medicine and Biostatistics. His research focuses on potential health impacts from flight-related occupational exposures in the aerospace environment including radiation, circadian rhythm disruption, chemical and biological agents, noise and vibration, cardiopulmonary function changes, and flight-related mental stressors. Scheibler currently serves as an editor for *Frontiers in Public Health*, reviewing manuscripts covering topics dealing with aerospace health and safety. He previously worked as an advisory member with the Commercial Spaceflight Federation on the Committee to Create a Human Research Program for Spaceflight Participants in the Commercialization of Space. Scheibler holds a B.A. in mathematics from Baylor University, an M.D. from the Uniformed Services University of the Health Sciences, and an M.P.H. from the Harvard T.H. Chan School of Public Health.

PROJECT STAFF

Daniel J. Mulrow (*Study Director*) is a program officer in the Center for Health, People, and Places. At the National Academies of Sciences, Engineering, and Medicine (the National Academies), he is the primary staff officer for topics related to radiation health effects and has supported four consensus studies, including one as director. He serves as the National Academies program manager for the Radiation Effects Research Foundation, a U.S.-Japan cooperative research institute that investigates the health effects of nuclear bomb radiation for peaceful purposes. Additionally, he served as staff director of the Gilbert W. Beebe Symposium on artificial intelligence/machine learning applications in radiation therapy, diagnostics, and occupational radiation health and safety. Before the National Academies, Mulrow worked at the National Nuclear Security Administration for multiple years supporting efforts in stockpile stewardship and strategic partnerships and engagements. He received his Ph.D. in chemistry, jointly advised in radiation oncology, from Washington University in St. Louis. His research interests included initial studies in ultra-high dose rate (or FLASH) radiation therapy, and the development and characterization of dosimeters and radiation detectors.

Rebecca A. English is a senior program officer at the National Academies of Sciences, Engineering, and Medicine (the National Academies). She has directed, co-directed, and staffed several projects at the National Academies including, most recently, the Roundtable on Quality Care for People with Serious Illness (2024–present), Living with ALS (2024), the Forum on Temporomandibular Disorders (2023–2025), Realizing the Promise of Equity in the Organ Transplantation System (2022), Assessment of Strategies for Managing Cancer Risks Associated with Radiation Exposure During Crewed Space Missions (2021), and Necessity, Use, and Care of Laboratory Dogs at the U.S. Department of Veterans Affairs (2020). English supported the Forum on Drug Discovery, Development, and Translation at the National Academies in various capacities between 2009 and 2016, working on wide-ranging projects related to the U.S. clinical trials enterprise as well as multidrug-resistant tuberculosis throughout the world. Prior to joining the National Academies, she worked on health policy for Congressman Porter J. Goss (FL-14) and for the National Active and Retired Federal Employees Association. She holds an M.P.H. from the University of Michigan and a B.A. in political science from the University of Notre Dame.

Madeline L. Jensen is a research associate in the Center for Health, People, and Places' Earth Systems Resources Program Area. At the National Academies of Sciences, Engineering, and Medicine (the National Academies), she has assisted on several projects including an impacts assessment for offshore renewable energy on the West Coast (2024–2026), a research assessment for offshore critical minerals (ongoing), and the U.S. National Decade Committee for the United Nations' Ocean Decade (ongoing). Prior to coming to the National Academies, Jensen worked in fisheries research and as an offshore consultant participating in marine mammal and protected species visual and acoustic surveys. She holds an M.S. from Johns Hopkins University and a B.S. from the University of South Carolina.

Nicholas A. Murdock, is an associate program officer in the Center for Health, People, and Places. He has worked on consensus studies on veterans' mental and neurologic health as well as convening activities on infectious disease preparedness. He previously worked in HIV drug regulatory policy. He holds an M.P.H. in epidemiology and biostatistics from UC Berkeley's School of Public Health.

Lydia Teferra was a research associate in the Center for Health, People, and Places. She worked on several consensus studies during her 5 years at the National Academies of Sciences, Engineering, and Medicine (the National Academies). Teferra is also a former staff member on the National Academies Roundtable on Genomics and Precision Health and the Forum on Regenerative Medicine. Prior to her time at the National Academies, Teferra interned and volunteered for local nonprofit organizations addressing several public health issues. She graduated from Northwestern University in 2020 with a B.A. in psychology and global health. She hopes to pursue a master's in public health in the near future.

Appendix B

Public Meeting Agendas

**COMMITTEE ON ASSESSING RADIATION
EXPOSURE, HEALTH OUTCOMES, AND MITIGATION
STRATEGIES FOR FLIGHT CREWMEMBERS**

First Information-Gathering Session
September 3, 2025
Virtual

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| 1:00–1:05 | Welcome and Introductions
<i>Jonathan Samet</i> , Committee Chair, Colorado School of Public Health |
| 1:05–1:35 | National Academies Committee on Radiation Exposure Kickoff Discussion
<i>Anthony P. Tvaryanas</i> , Division Manager, Aviation Safety, Civil Aerospace Medical Institute
<i>Stacey Zinke</i> , Manager, Protection and Survival Research Laboratory (AAM-630), Civil Aerospace Medical Institute
<i>Hammad Baig</i> , Section Manager, Life Science Research, Civil Aerospace Medical Institute |
| 1:35–2:05 | CARI-7: Software for Calculating Cosmic Radiation Flight Doses
<i>Kyle Copeland</i> , Team Coordinator, Medical Research Team, Civil Aerospace Medical Institute |

2:05–2:35	Discussion with Committee Moderator: <i>Jonathan Samet</i> , Committee Chair, Colorado School of Public Health
2:35	Adjourn Open Session
Second Information-Gathering Session September 30, 2025 Virtual	
11:00–11:05	Welcome and Introductions <i>Jonathan Samet</i> , Committee Chair, Colorado School of Public Health
11:05–11:50	Space Weather and Airline Operations: A Forward-Looking Threat Analysis for the U.S. Airline Pilot Community <i>Rondeau Flynn</i> , Allied Pilots Association
11:50–12:05	Radiation Exposure During Pregnancy: Protections, Please. <i>Judith Anderson</i> , Association of Flight Attendants-CWA
12:05–12:20	Remarks from the Association of Professional Flight Attendants <i>Lori Vitto Glattly</i> , Association of Professional Flight Attendants
12:20–12:40	Ionizing Radiation and Flight Crewmembers: Literature Review from the Aerospace Medical Association Journal <i>Diego Garcia</i> , Aerospace Medical Association
12:40–1:00	Break
1:00–1:05	Welcome Back and Explanation of Session <i>Jonathan Samet</i> , Committee Chair, Colorado School of Public Health
1:05–1:50	Additional Community Member Comments • <i>Zac Dohnal</i>, Occupational Health and Safety In-Flight Services and Flight Operations, Air Canada • <i>Francis Heil</i>, Safety, Airlines for America • <i>Renaud Fenster</i>, Transport Workers Union (TWU) Local 579 • <i>Michael Massoni</i>, TWU Local 556—The Union of Southwest Airlines Flight Attendants • <i>Marissa Mianzo</i>, Southwest Airlines

- *Todd Moore*, Air Line Pilots Association, International
- *Alex Schroeder*, American Airlines
- *Brent Weisner*, Southwest Airlines Pilots Association

1:50–2:00 Public Comment via Slido

2:00 Adjourn Open Session

Third Information-Gathering Session
December 3, 2025
Virtual

1:00–1:10 Welcome and Introductions
Jonathan Samet, Committee Chair, Colorado School of Public Health

1:10–1:40 Operational Science
Michael McCall, President and Chief Executive Officer, PCAire

1:40–2:10 ARMAS Radiation Monitoring System
W. Kent Tobiska, President and Chief Scientist, Space Environment Technologies

2:10–2:40 Radiation Monitoring in the Commercial Aviation Environment
Eric Benton, Professor, Oklahoma State University

2:40–2:50 Break

2:50–3:20 The Art of Developing Practical Dosimetry—Stochastic Energy Deposition and Airline Considerations
Les Braby, Research Professor, Texas A&M University

3:20–3:50 Forecasting Radiation Exposure on a Decadal Scale (1–22 years)
Katherine Monson and *Scott McIntosh*, Founders, Hale SWx

3:50–4:00 Public Comment

4:00 Adjourn Open Session
Jonathan Samet, Committee Chair, Colorado School of Public Health
Daniel Mulrow, Study Director, National Academies

Fourth Information-Gathering Session
January 14, 2026
Virtual

- 12:00–12:05 Welcome and Introductions
Jonathan Samet, Committee Chair, Colorado School of Public Health
- 12:05–12:35 Presentation on Design of Reproductive Health Epi Design
David Savitz, Professor Emeritus of Epidemiology, Brown University School of Public Health
- 12:35 Adjourn Open Session
Jonathan Samet, Committee Chair, Colorado School of Public Health
Daniel Mulrow, Study Director, National Academies

Appendix C

Summary of Presentations

PRESENTATIONS: SECOND INFORMATION-GATHERING SESSION

Rondeau Flynn, Allied Pilots Association (APA), described cosmic ionizing radiation exposure in aviation with a particular focus on the role of space weather in shaping radiation levels at flight altitudes. Flynn explained that radiation exposure experienced by flight crew is not constant; it varies based on conditions in near-Earth space, including solar activity and geomagnetic conditions.

Flynn emphasized the need to strengthen aircrew awareness and improve the operational integration of radiation risk information across the pilot community. Although the Federal Aviation Administration's (FAA's) guidance on in-flight radiation exposure has long been available, he noted that understanding and practical application of this information remain inconsistent. Radiation exposure was described as a recognized occupational hazard that is not always fully appreciated, particularly in relation to solar particle events (SPEs), cumulative career exposure, and maternity considerations.

A substantial portion of the presentation outlined APA's efforts to address these gaps. APA has developed structured aeromedical and space weather education initiatives aimed at translating radiation science into operationally relevant guidance for line pilots. These efforts include pilot-focused programming through APA's occupational health channels, collaboration with subject matter experts, and targeted outreach to improve understanding of exposure variability and regulatory limits. The focus is on providing clear, applicable information that supports real-time operational awareness.

Workforce-specific considerations were addressed, including the growing number of women in the airline profession and the importance of maternity awareness. Flynn underscored the need for pilots to understand FAA-recommended dose limits for the conceptus and appropriate exposure management following pregnancy notification.

Flynn cited national survey findings indicating that aviation end users prioritize improved education, information dissemination, and policy development related to

space weather and crew health. While the industry recognizes operational disruptions associated with severe space weather, he noted the need for stronger data collection, predictive modeling, and routine integration of radiation exposure considerations into operational planning.

Overall, the presentation positioned radiation education as integral to workforce resilience. APA's efforts center on improving awareness, strengthening decision-support capabilities, and ensuring pilots are equipped to manage occupational radiation exposure within established regulatory limits.

Judith Anderson, Air Safety, Health & Security Department of the Association of Flight Attendants-CWA, presented the flight attendant perspective on occupational radiation exposure, with particular emphasis on pregnancy protections. Her remarks centered on the view that although airline crew are recognized as radiation-exposed workers, regulatory protections and required education for cabin crew remain limited in the United States.

Anderson framed radiation exposure during pregnancy as a precautionary workplace health issue. She provided a brief overview of fetal sensitivity during early development and referenced federal public health guidance indicating that in utero radiation exposure can be associated with developmental effects and increased lifetime cancer risk. Rather than focusing on detailed dose modeling, she emphasized uncertainty in measuring absolute risk at aviation exposure levels and argued that this uncertainty supports application of the “as low as reasonably achievable” principle and a precautionary approach.

A central concern was the disconnect between scientific recognition of exposure and regulatory requirements. Citing the National Council on Radiation Protection and Measurements Report No. 160, which identified airline crew as among the highest exposed occupational groups in the United States, Anderson noted that the FAA does not require airlines to provide mandatory radiation education, conduct individual exposure monitoring, or implement specific pregnancy protections for flight attendants. She characterized crew awareness as low and stated that pregnancy-related risks are nonzero but not routinely tracked.

SPEs were highlighted as periods of potentially elevated exposure, particularly on high-latitude and high-altitude routes. Anderson emphasized that these events are often short in duration and that timely notification and scheduling flexibility could meaningfully reduce exposure for pregnant crew.

She also placed radiation within a broader occupational context, noting that cabin crew face additional stressors—including circadian disruption, long duty days, physical demands, and chemical exposures—that may affect pregnancy outcomes. Overall, the presentation called for practical protections, including mandatory education and opt-out provisions during significant solar events, arguing that crew health safeguards should not be deferred pending further study.

Lori Vitto Glattly, government affairs representative, Association of Professional Flight Attendants (APFA), spoke from the perspective of a line flight attendant and emphasized the gap between subject matter expertise and frontline awareness within the cabin crew workforce. She concurred with other panelists that occupational radiation

exposure is not meaningfully addressed in routine flight attendant training or communications. In her view, most flight attendants do not receive baseline education on radiation exposure, cumulative dose, or potential health implications associated with long-term flying. The current state of knowledge on radiation exposure among flight attendants is extremely limited; they lack access to clear information and education about radiation.

According to Vitto Glattly, the most meaningful initiatives in this space have come from unions, academic researchers, or international carriers. The outreach of the APA led the APFA to become aware of the Space Weather Prediction Center's solar storm notification system; the challenge is in developing effective education strategies and providing flight attendants with the knowledge to minimize exposure risk in the absence of regulatory or policy-based protections. Vitto Glattly highlighted the confusion and frustration among flight attendants as to why radiation risk is not openly communicated, why flight crew are not provided access to monitoring data in a digestible format, why flight attendants are treated differently from other workers with comparable exposures, and why U.S. airlines are behind compared to the European Union's standard for notification and risk mitigation.

Vitto Glattly noted that the APFA advocates for radiation exposure monitoring to be required for all flight crews; long-term health studies specific to flight attendants and radiation to be funded; and communication, education, and protections to be standardized so that aircrews have the same rights as other occupationally exposed U.S. workers.

Diego Garcia, Aerospace Medical Association, shared that discussions about radiation exposure among aircrew have become cyclical and repetitive, largely because the same foundational problems remain unresolved. He noted that conversations repeatedly return to the lack of data, lack of regulation, and lack of education surrounding occupational radiation exposure in aviation. Garcia suggested that responsibility for this educational gap lies in part with the professional and scientific community itself. He stressed that stakeholders—including aircrew, operators, regulators, and health professionals—have not been adequately educated about radiation risks, monitoring, or mitigation strategies, despite decades of awareness that the issue exists. In Garcia's view, insufficient education has hindered progress even more than regulatory inertia.

Garcia also conveyed concern that radiation exposure is frequently treated as an abstract or theoretical risk rather than as a practical occupational health issue. He indicated that without better education and engagement, aircrew may lack both awareness and agency in discussions about their own health, reinforcing a cycle in which meaningful action is continually deferred.

Community Discussion

Following the individual presentations, the committee invited participants to respond to a common set of guiding questions addressing current knowledge of occupational radiation exposure among flight crewmembers, key concerns raised within their communities, ongoing efforts related to risk communication and mitigation, and additional resources or information for the committee's consideration. The discussion reflected a range of perspectives across pilots, flight attendants, medical professionals, and industry representatives, with several consistent themes emerging.

Labor representatives, particularly from flight attendant organizations, broadly agreed that awareness of occupational radiation exposure remains limited at the line-employee level. Participants emphasized that most crewmembers do not receive structured education during initial or recurrent training regarding radiation exposure, cumulative dose, or potential health implications. As a result, radiation is often not perceived as an active occupational hazard, and concerns about pregnancy, cancer risk, or SPEs are not widely understood within the workforce. Questions raised by stakeholders frequently centered on long-term cancer risk, pregnancy outcomes, SPE management, cumulative lifetime dose, and the availability of individual exposure tracking.

Regarding risk communication and mitigation, participants described uneven practices across airlines and regions. While tools and models exist, these resources are not consistently integrated into crew education or operational decision-making by Part 121 operators. Comparisons were drawn to European regulatory frameworks, where dose tracking and formalized requirements are more established. Several speakers noted that despite decades of discussion, systematic individual monitoring and standardized notification protocols remain limited domestically.

Participants also emphasized the need for improved data collection and coordination among stakeholders, including airlines, unions, regulators, insurers, and manufacturers. They expressed interest in enhanced dosimetry, epidemiologic research, and clearer communication of what is known, and not known, about health risks. Across perspectives, education emerged as a central theme: stakeholders conveyed a desire for accessible evidence-based information that empowers crewmembers to understand occupational exposure and participate meaningfully in decisions affecting their health.

Overall, the community discussion underscored a shared recognition that radiation exposure is an occupational reality in aviation, accompanied by ongoing debate about the adequacy of current communication, monitoring, and mitigation strategies.

PRESENTATIONS: THIRD AND FOURTH INFORMATION-GATHERING SESSIONS

Eric Benton, professor, Oklahoma State University, discussed the scientific and operational challenges of detecting and quantifying radiation in aviation environments. He emphasized that progress in this area is constrained by the limited willingness of U.S. commercial airlines to support onboard radiation measurements, which has significantly shaped the design and deployment of measurement strategies. Benton described the atmospheric ionizing radiation environment at flight altitudes as highly stochastic, resulting from extensive air showers initiated by galactic cosmic ray protons interacting with the upper atmosphere and producing electromagnetic, hadronic, and muonic components. While photons, electrons, and muons dominate particle fluxes, neutrons are particularly important for biological dose despite their lower abundance and pose distinct measurement challenges.

To address these challenges, Benton developed the Atmospheric Ionizing Radiation Tissue Equivalent Dosimeter (AirTED) detector system, which combines complementary detector technologies to characterize different components of the radiation field.

The system integrates a silicon PIN photodiode, which is sensitive to minimum-ionizing charged particles and photons, with a tissue-equivalent proportional counter, which is required to detect highly ionizing radiation and neutrons. Benton emphasized that no single detector technology can adequately measure all relevant radiation components, making hybrid systems necessary for biologically meaningful dose assessment.

In response to limited aircraft access, Benton described an alternative measurement approach using lightweight, low-cost solar balloons capable of reaching commercial flight altitudes without regulatory barriers. These balloon-based measurements were validated against the FAA CARI-7 model and demonstrated the feasibility of targeted, rapid-response measurements during geomagnetic disturbances. Benton concluded that improved access to aviation platforms, expanded hybrid detector deployments, and coordinated measurement campaigns are needed to reduce uncertainties in radiation exposure assessment for commercial flight operations.

Les Braby, research professor, Texas A&M University, discussed biological mechanisms associated with exposure to ionizing radiation. He described how radiation interacts with biological tissue through energy deposition along particle tracks, producing ionization events that can result in molecular and cellular damage—including damage to DNA. He explained that biological effects depend on factors such as radiation type, energy, and the spatial distribution of energy deposition.

Braby described distinctions between different radiation types, including differences between low-linear energy transfer and high-linear energy transfer radiation, and explained that these differences influence biological response. He discussed cellular repair processes and variability in biological response to radiation exposure, noting that biological outcomes depend on dose and dose rate.

Braby also described how experimental studies, epidemiological evidence, and modeling approaches are used together in radiation protection science to evaluate potential biological effects.

Kent Tobiska, president and chief scientist, Space Environment Technologies, presented on the Automated Radiation Measurements for Aerospace Safety (ARMAS) system, which employs solid-state silicon semiconductor detectors to measure in situ ionizing radiation in aviation environments. The ARMAS detectors provide continuous high-time-resolution measurements of dose and dose rate from charged particles and secondary photons, including X-rays and gamma rays produced in the atmosphere.

Tobiska noted that ARMAS's ability to make continuous high-time-resolution measurements is important for characterizing commercially relevant radiation exposure, as it allows variability associated with latitude, altitude, and geomagnetic activity to be directly observed rather than inferred. This capability supports improved understanding of how radiation conditions change during routine operations and space weather disturbances, which is necessary for assessing occupational exposure in commercial aviation.

Tobiska noted important limitations, including ARMAS's limited sensitivity to neutrons, which are a significant contributor to total dose at aviation altitudes. As a result, total dose estimates rely on calibration and modeling to account for unmeasured components of the radiation field. He concluded that ARMAS measurements provide valuable empirical evidence of secondary radiation processes affecting commercial

aviation and underscored the need for complementary neutron-sensitive instruments and expanded measurement campaigns to improve characterization of occupational radiation exposure.

Mike McCall, president and chief executive officer, PCAire, described the development and operational application of the company's proprietary code for estimating cosmic radiation exposure in aviation. Developed between 1997 and 2000 and commercialized in 2004, PCAire's code was intentionally designed as an operational dosimetry tool rather than a research platform. The code is empirically derived, based on extensive in-flight measurements using tissue-equivalent proportional counters flown on aircraft operated by Air Canada and the Royal Canadian Air Force. These measurements were correlated with detailed cockpit flight data to construct a three-dimensional atmospheric dose-rate model incorporating solar modulation, geomagnetic cutoff rigidity, and geographic position.

McCall emphasized that accurate dose estimation in operational settings depends critically on the use of detailed actual flight path data, including waypoints, altitudes, and ascent and descent profiles, rather than simplified city-pair or great-circle assumptions. He noted that simplified routing assumptions and manual data entry can introduce substantial errors that exceed uncertainties associated with validated radiation models. McCall underscored that automated data ingestion, validation, and error-checking processes, ideally integrated with professional flight-planning systems, are essential components of reliable aviation radiation monitoring programs.

Katherine Monson, co-founder of Hale Space Weather Consulting (Hale SWx), presented on commercial radiation exposure forecasting for aviation and the role of space weather information in operational decision-making. Monson described Hale SWx's work in translating space weather observations and models into radiation exposure forecasts relevant to flight operations, particularly during SPEs and geomagnetic disturbances.

Monson emphasized that forecasting radiation exposure in aviation environments differs fundamentally from post-flight dose estimation. Forecasts must be produced in advance, often with incomplete information, and must balance scientific uncertainty with operational usefulness. She noted that while galactic cosmic radiation produces a relatively steady background that can be modeled with reasonable confidence, episodic events such as SPEs introduce large uncertainties in both timing and magnitude. These uncertainties are compounded by limited in situ measurements at flight altitudes during extreme events.

Consistent with other speakers, Monson highlighted that radiation exposure varies strongly with altitude, latitude, and geomagnetic conditions, and that operational mitigation strategies depend on timely, credible forecasts rather than precise dose calculations. She emphasized that effective use of radiation forecasts requires close coordination with airline dispatch and flight-planning systems as well as clear communication of uncertainty to decision-makers.

Monson concluded that improved forecasting will depend on better integration of space weather observations, radiation models, and limited measurement data, as well as clearer guidance on how forecast information should be used operationally to manage radiation risk in commercial aviation.

David Savitz, Brown University School of Public Health, highlighted key methodological challenges in studying reproductive health outcomes related to environmental and occupational exposures, including ionizing radiation. Reproductive outcomes differ from many other epidemiologic endpoints because they are relatively common, involve contributions from multiple individuals (i.e., mother, father, and fetus), and are highly sensitive to the timing of exposure.

Critical windows of vulnerability may be very brief, making it difficult to determine whether exposures occur at biologically relevant times. Measurement challenges are also significant, particularly for early pregnancy losses that occur before clinical recognition.

Savitz described the evidence on ionizing radiation and reproductive outcomes as limited and heterogeneous, drawing from occupational, medical, and environmental contexts. Some studies report small increases in risks such as miscarriage, stillbirth, or reduced birthweight, but findings are inconsistent.

He reviewed key reproductive endpoints. Fertility reflects multiple biological processes, and infertility (i.e., failure to conceive after 1 year) does not identify specific causes. Time to pregnancy is more sensitive but difficult to measure, especially for unplanned pregnancies. Pregnancy complications (e.g., hypertensive disorders, gestational diabetes) are more reliably captured in clinical data. Pregnancy loss is common but often underreported. Birthweight and gestational age are well measured, although small changes may have uncertain clinical significance. Structural birth defects and neurodevelopmental outcomes are important but influenced by timing and diagnostic practices.

Savitz emphasized that rigorous study design, accurate exposure assessment, and careful attention to timing are essential for reliable conclusions.

Appendix D

Written Requests to Stakeholders

National Academies of Sciences, Engineering, and Medicine Section 322 Committee Questions and Federal Aviation Administration Responses

This list of questions was sent to the Federal Aviation Administration (FAA), and responses were presented to the committee during the information-gathering session on September 3, 2025.

1. Part 121 operators include cargo carriers, should the committee consider radiation exposure due to radiological cargo?

The SOT specifies that the study focuses on crew members of Part 121 operators, which includes both passenger and cargo carriers. However, the scope is aerospace environmental radiation, not radiation from cargo. Radiological cargo exposure is regulated separately under hazardous materials and NRC oversight; it should be noted as out of scope for this study but acknowledged as a related occupational risk.

2. Could you better define “operating in the aerospace environment” – roughly what altitudes should the committee consider?

The study’s scope covers flight crews on Part 121 operations. Practically, this means commercial aviation altitudes (generally 30,000–41,000 feet, with extensions to high-altitude long-range operations such as transpolar routes). The committee may explicitly define this as the troposphere and lower stratosphere where crew routinely operate.

3. Should the committee consider suborbital altitudes?

The SOT is tightly scoped to airline Part 121 operations, not commercial space or suborbital flight. Suborbital operations involve different exposure regimes and regulatory frameworks (e.g., FAA/AST rather than FAA/AVS). Thus, suborbital altitudes should not be included in this study.

4. **What is meant by understanding plausible worst-case radiation exposure scenarios? Should the committee consider Solar Energetic Particle Events (including Coronal Mass Ejections)? Should the committee consider scenarios where flight crew may be exposed to other events, such as radiation from Earth based nuclear accidents or acts of war?**

The SOT directs the committee to identify harmful radiation sources at aviation altitudes and select bounding flight paths for plausible worst-case exposures. This explicitly includes SEP events and CMEs (recognized as major contributors to episodic exposure). Scenarios involving terrestrial nuclear accidents or acts of war fall outside the study scope, since the SOT centers on natural cosmic radiation hazards, not human caused ones.

5. **Should the CARI model be one of the methodologies that the committee uses to perform a cumulative radiation exposure assessment?**

Yes. The SOT requires the use of at least two computational methodologies. The CARI model (developed by FAA's CAMI) is a widely accepted standard tool and should be one of them. A second methodology (e.g., NAIRAS, SIEVERT, or other validated space weather models) should also be applied for cross-comparison.

6. **Should the impact of radiation induced electron failure or single event upsets of electronics be considered?**

The SOW specifies that the committee assesses radiation exposure to crew members and related health risks. While SEUs are a recognized radiation effect in avionics, they fall outside the crew health risk mandate. Therefore, SEUs should be considered out of scope, but could be briefly acknowledged in the report as a related technical issue.

QUESTIONS POSED TO AIRLINE ASSOCIATIONS

Note that the aggregated and summarized response provided by Airlines for America is provided in Chapter 2.

- Do you have a formal radiation protection policy for flight crew? If so, what does it cover?
- Are radiation exposure considerations included in your occupational health program?
- How do you handle crew concerns or questions about radiation exposure?
- Do you currently monitor and track radiation doses for your flight crew?
- Who in your organization is responsible for radiation safety and dose monitoring?
- If you monitor, how do you maintain dose records, and for how long?
- What training do you provide to crew about radiation exposure and associated risks? Is this one-time training (such as during airline indoctrination) or ongoing, such as in annual recurrent training or periodic bulletin?
- Do you dynamically adjust routes and altitudes in response to short-term events such as high radiation events (i.e., coronal mass ejections, etc.)?

- If yes, how does radiation exposure factor into your route planning (especially polar routes), if at all?
- If your airline tracks radiation exposure, what software model does your airline use to calculate radiation exposure for a particular flight?
- If your airline tracks radiation exposure, do you outsource the use of this model and the associated record-keeping?
- If your airline tracks radiation exposure, do crew members have access to their individual dose records?

QUESTIONS POSED TO AIRCRAFT MANUFACTURERS

Note that the aggregated and summarized response is provided Chapter 2.

- Is radiation protection considered in aircraft design and manufacturing? If yes, what is considered?
- Is radiation detection/monitoring considered in design? If yes, what types of methods are considered?
- Is space weather tracking and monitoring considered in designs? If yes, how is this incorporated?
- Are there any other considerations regarding radiation detection, monitoring, or protection (e.g., electronic radiation hardness) that your company incorporates into design and manufacturing?

Appendix E

Literature Review: Methods, Approach, and Results

LITERATURE SEARCH STRATEGY

Three literature searches were performed in PubMed and Scopus to identify medical and scientific literature. The first literature search was conducted on October 16, 2025, and retrieved systematic reviews on in-flight radiation exposure and health outcomes. The second search was conducted on November 4, 2025, and retrieved studies on in-flight radiation exposure and reproductive outcomes. The third search was conducted on December 2, 2025, and retrieved studies on in-flight radiation exposure and cancer outcomes.

Search 1:

PubMed

(Aircraft[Mesh] or Aviation[Mesh] or “Aerospace Medicine”[Mesh] or Pilots[Mesh] or aircraft*[tw] or aviation[tw] or “aerospace medicine”[tw] or airline*[tw] or aircrew*[tw] or “flight attendant”*[tw]) AND (“Occupational Exposure”[Mesh] or “Occupational Diseases”[Mesh] or “Risk Factors”[Mesh] or “Risk Assessment”[Mesh] or “Risk”[Mesh] or “Cosmic Radiation”[Mesh] or “Radiation Dosage”[Mesh] or “Radiation, Ionizing”[Mesh] or “occupational exposure”*[tw] or “occupational disease”*[tw] or “risk factor”*[tw] or “risk assessment”*[tw] or “cosmic radiation”[tw] or “radiation dosage”*[tw] or “ionizing radiation”[tw]) AND (“Systematic Review” [Publication Type] or “Meta-Analysis” [Publication Type] or “systematic review”[ti] or “meta analysis”[ti] or “meta-analysis”[ti])

Language: English

Results: 73

Scopus

TITLE-ABS-KEY(("aerospace medicine" or airline* or aircrew* or "flight attendant*" or "airline pilot*") AND ("occupational exposure*" or "occupational disease*" or "risk factor*" or "risk assessment*" or "cosmic radiation" or "radiation dosage*" or "ionizing radiation")) AND TITLE("systematic review" or "meta analysis" or meta-analysis or review)

Language: English

Results: 84

Search 2:

PubMed

(Aircraft[Mesh] or Aviation[Mesh] or "Aerospace Medicine"[Mesh] or Pilots[Mesh] or aircraft*[tw] or aviation[tw] or "aerospace medicine"[tw] or airline*[tw] or aircrew*[tw] or "flight attendant*[tw]) AND ("Occupational Exposure"[Mesh] or "Occupational Diseases"[Mesh] or "Risk Factors"[Mesh] or "Risk Assessment"[Mesh] or "Risk"[Mesh] or "Cosmic Radiation"[Mesh] or "Radiation Dosage"[Mesh] or "Radiation, Ionizing"[Mesh] or "occupational exposure*[tw] or "occupational disease*[tw] or "risk factor*[tw] or "risk assessment*[tw] or "cosmic radiation"[tw] or "radiation dosage*[tw] or "ionizing radiation"[tw]) AND ((("Pregnancy"[Mesh] NOT "Pregnancy, Animal"[MESH]) OR antenatal[tw] OR antepartum[tw] OR ante-partum[tw] OR birth*[tw] OR caesarean [tw] OR cesarean[tw] OR "c section*[tw] OR "c-section*[tw] OR "Delivery, Obstetric"[Mesh] OR episiotom*[tw] OR gestat*[tw] OR gravidity[tw] OR labor[tw] OR labour[tw] OR matern*[tw] OR miscarriage*[tw] OR perinatal[tw] OR perineotomy[tw] OR placenta*[tw] OR "Placenta"[Mesh] OR "Obstetrics"[Mesh] OR "Obstetricians"[Mesh] OR "Congenital Abnormalities"[Mesh] OR pregnan*[tw] OR "Pregnancy Trimesters"[Mesh] OR "Pregnant People"[Mesh] OR prenatal[tw] OR pre-natal[tw] OR pre-term*[tw] OR preterm*[tw] OR parturient[tw] OR parturition[tw] OR "spontaneous abortion"[tw] OR stillbirth*[tw] OR stillborn[tw] OR trimester[tw] OR "congenital abnormalit*[tw] OR "birth defect*[tw] OR "congenital defect*[tw] OR deformit*[tw] OR "fetal anomal*[tw] OR "fetal malformation*[tw])

Language: English

Results: 206

Scopus

TITLE-ABS-KEY(("aerospace medicine" or airline* or aircrew* or "flight attendant*" or "airline pilot*") AND ("occupational exposure*" or "occupational disease*" or "risk factor*" or "risk assessment*" or "cosmic radiation" or "radiation dosage*" or "ionizing radiation")) AND (pregnan* OR antenatal OR antepartum OR ante-partum OR birth* OR caesarean OR cesarean OR "c section*" OR "c-section*" OR episiotom* OR gestat* OR gravidity OR labor OR labour OR matern* OR miscarriage* OR perinatal OR perineotomy OR placenta* OR obstetrics OR obstetrician* OR prenatal OR pre-natal OR pre-term* OR preterm* OR parturient OR parturition OR "spontaneous abortion" OR stillbirth* OR stillborn OR trimester OR "congenital abnormalit*" OR

“birth defect*” OR “congenital defect*” OR deformit* OR “fetal anomal*” OR “fetal malformation*”)

Language: English

Results: 110

Search 3:

PubMed

(Aircraft[Mesh] or Aviation[Mesh] or “Aerospace Medicine”[Mesh] or Pilots[Mesh] or “Flight crew*”[tiab] OR “Flight attendant*”[tiab] OR “Air crew”[tiab] OR Airline*[tiab] OR Airplane*[tiab] OR “Cabin crew*”[tiab] OR “Cabin attendant*”[tiab] OR Aviat*[tiab]) AND (“Melanoma”[Mesh] OR “Skin Neoplasms”[Mesh] OR “Breast Neoplasms”[Mesh] OR “Prostatic Neoplasms”[Mesh] OR “Lymphoma”[Mesh] OR “Leukemia”[Mesh] OR “Thyroid Neoplasms”[Mesh] OR “Sarcoma, Kaposi”[Mesh] OR “Brain Neoplasms”[Mesh] OR “Central Nervous System Neoplasms”[Mesh] OR “Neoplasms”[Mesh] OR Melanoma[tiab] OR “Skin cancer*”[tiab] OR “Skin neoplasia”[tiab] OR “skin neoplasm*”[tiab] OR “basal cell carcinoma*”[tiab] OR “squamous cell carcinoma*”[tiab] OR “breast neoplasm*”[tiab] OR “breast tumor*”[tiab] OR “breast cancer*”[tiab] OR “mammary cancer*”[tiab] OR “breast carcinoma*”[tiab] OR “prostatic neoplasm*”[tiab] OR “prostate neoplasm*”[tiab] OR “prostate cancer*”[tiab] OR “prostate neoplasm*”[tiab] OR lymphoma*[tiab] or leukemia*[tiab] or leucocythaemia*[tiab] OR leucocythemia*[tiab] OR “thyroid cancer*”[tiab] OR “thyroid neoplasm*”[tiab] OR “thyroid carcinoma*”[tiab] OR “kaposi sarcoma”[tiab] OR “brain neoplasm*”[tiab] OR “brain tumor*”[tiab] OR “brain cancer*”[tiab] OR “intracranial neoplasm*”[tiab] OR “brain metastase*”[tiab] OR “central nervous system neoplasm*”[tiab] OR “central nervous system cancer*”[tiab] OR “CNS neoplasm*”[tiab] OR neoplasm*[tiab] OR cancer*[tiab] OR tumor*[tiab])

Date: 2015–Present

Language: English

Results: 345

Scopus

TITLE-ABS-KEY((“Flight crew*” OR “Flight attendant*” OR “Air crew” OR Airline* OR Airplane* OR “Cabin crew*” OR “Cabin attendant*” OR Aviat*) AND (Melanoma OR “Skin cancer*” OR “Skin neoplasia” OR “skin neoplasm*” OR “basal cell carcinoma*” OR “squamous cell carcinoma*” OR “breast neoplasm*” OR “breast tumor*” OR “breast cancer*” OR “mammary cancer*” OR “breast carcinoma*” OR “prostatic neoplasm*” OR “prostate neoplasm*” OR “prostate cancer*” OR “prostate neoplasm*” OR lymphoma* or leukemia* or leucocythaemia* OR leucocythemia* OR “thyroid cancer*” OR “thyroid neoplasm*” OR “thyroid carcinoma*” OR “kaposi sarcoma” OR “brain neoplasm*” OR “brain tumor*” OR “brain cancer*” OR “intracranial neoplasm*” OR “brain metastase*” OR “central nervous system neoplasm*” OR “central nervous system cancer*” OR “CNS neoplasm*” OR neoplasm* OR cancer* OR tumor*)) AND PUBYEAR AFT 2014

Language: English

Results: 348

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagrams for the literature search on cancer outcomes and reproductive health outcomes are shown in Figures E-1 and E-2, respectively. PRISMA is an evidence-based set of guidelines developed and maintained by an international group of researchers, methodologists, and journal editors (the PRISMA Group) to improve the transparency, completeness, and quality of reporting in systematic reviews and meta-analyses.

CANCER EVIDENCE TABLES AND FOREST PLOTS

A forest plot is a graphical display used to summarize results from multiple studies, showing individual study effects, confidence intervals, and the overall combined effect in one image. Each study is a horizontal line, with the colored shape representing the study estimate and the ends of the horizontal line representing the confidence interval.

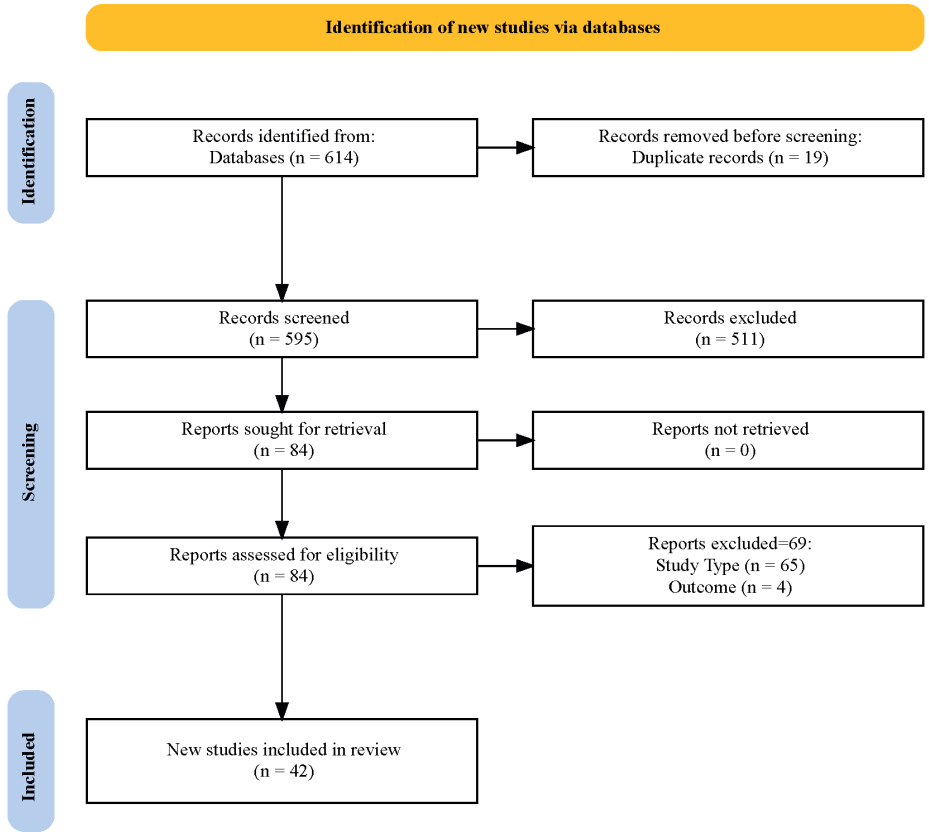


FIGURE E-1 Cancer outcomes PRISMA diagram.
SOURCE: Generated via PRISMA diagram tool; Haddaway and colleagues (2022).

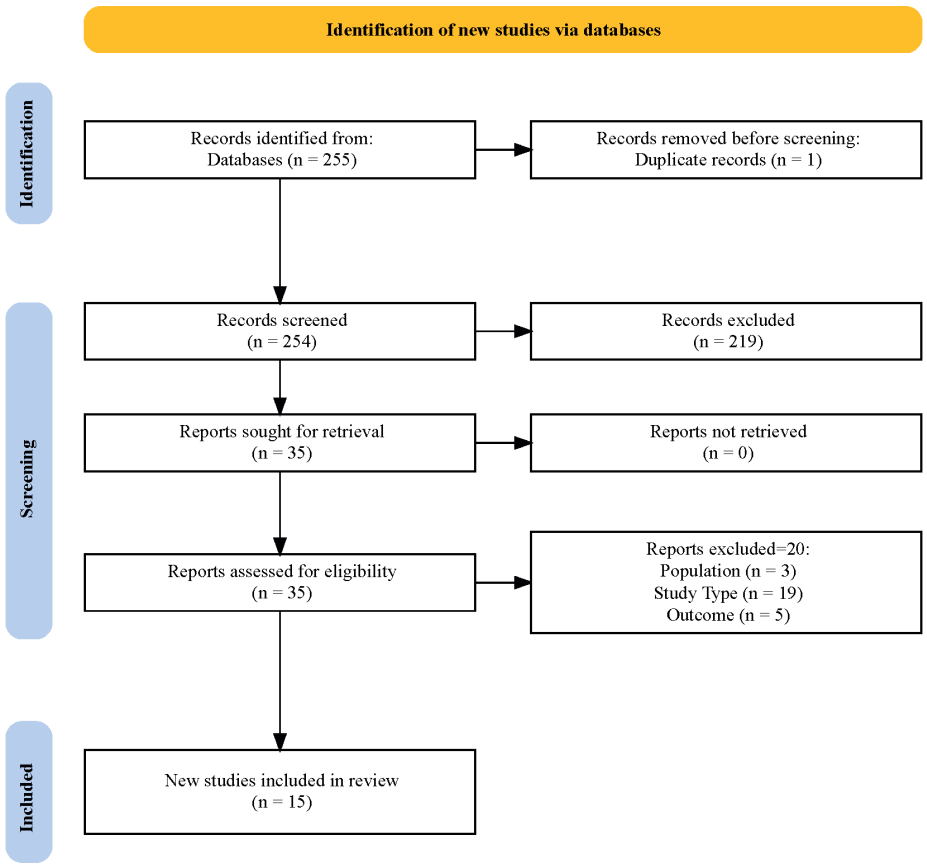


FIGURE E-2 Reproductive outcomes PRISMA diagram.
SOURCE: Generated via PRISMA diagram tool; Haddaway and colleagues (2022).

Each forest plot has a specific symbol/color key indicating aircrew status and cancer subtype, where applicable. The vertical dashed line is the line of no effect, represented here by the number 1. Estimates to the left of the horizontal line indicate a lower risk of the aircrew developing the cancer when compared to the control/comparison group. Estimates to the right of the horizontal line indicate a higher risk. Estimate types included in the forest plots are abbreviated in Box E-1.

BOX E-1**Key Terms for Types of Estimates Used in Forest Plots**

OR: Odds Ratio—The strength and direction of the association between a particular exposure and outcome.

PMR: Proportional Mortality Ratio—The proportion of deaths from a specific cause within a population of interest to the proportion of deaths from that same cause in an unexposed or control population.

SIR: Standardized Incidence Ratio—Compares the number of new cases occurring over a specified period to the expected number. It reflects the risk of developing the disease.

SMR: Standardized Mortality Ratio—The ratio of observed to expected number of deaths in a specific population.

SPR: Standardized Prevalence Ratio—Compares the total number of existing cases (both new and preexisting) in a population to the expected number. It reflects the overall burden of disease at a point or period in time.

RR (i): Relative Risk (incidence)—The ratio of the probability of cancer incidence occurring in an exposed group to the probability of it occurring in an unexposed group.

RR (m): Relative Risk (mortality)—The ratio of the probability of death in an exposed group to the probability of death in an unexposed or control group.

Four forest plots are provided for each cancer type, excluding breast and prostate cancer. The top left plot indicates male flight crew estimates in primary studies (i.e., original, firsthand data collection), and the top right plot indicates female flight crew estimates. The bottom plots indicate estimates from meta-analyses (i.e., studies that combine or pool multiple primary studies to produce one overall effect estimate). Some of the forest plots contain a horizontal dashed line. This line is the line of separation between studies of incidence (i.e., cancer cases) and studies of mortality (i.e., deaths from cancer).

The provided forest plots are updated from Scheibler and colleagues (2022) and include new studies identified from the literature review (see Figures E-3 through E-12). Information on the new studies can be found in evidence tables (see Tables E-1 through E-8).

TABLE E-1 Studies Identified Reporting on Malignant Melanoma Among Flight Crew

Author (year)	Study Design	Population	Outcome	Exposure	Select Results	Key Limitations
Webber et al. (2022)	Retrospective Cohort	U.S. Air Force fighter aviators (N=34,976)	Melanoma skin cancer from medical records (cancer registries and medical surveillance systems)	Did they work as fighter aviators? (Y/N)	Male fighter aviators compared to general population SIR 1.25 (95% CI 1.13, 1.38); SMR 1.64 (95% CI 1.32, 2.03)	Lack of data on possible confounders; chose not to adjust the alpha level for multiple comparisons
Pedersen and Hansen (2023)	Nested Case-Control	Danish male aircraft workers diagnosed with melanoma skin cancer (N=199) versus male cancer-free controls (N=1,126)	Self-reported melanoma skin cancer	Did they work on an aircraft? (Y/N)	Compared to controls/other occupations OR 2.30 (95% CI 1.06, 4.97). Pilots with work history >10 years OR 1.07 (95% CI 1.01, 1.14)	Lack of data on possible confounders; possible selection bias and recall bias
Park et al. (2024)	Retrospective Cohort	Korean air transportation industry workers (male N=21,558; female N=12,547)	Melanoma skin cancer from medical records (health insurance database)	Did they work in air transportation? (Y/N)	Compared to the general population SIR 0.57 (95% CI 0.12, 1.67)	Limited in available data. Population is described as air transportation industry workers with no distinction for flight crew or pilot status.
Vágerö et al. (1990)	Retrospective Cohort	Malignant melanoma cases (N=9,835)	Cutaneous melanoma, ocular melanoma, non-ocular melanoma, non-cutaneous melanoma from medical records (cancer registries)	Did they work as pilots? (Y/N)	Observed compared to expected cases by occupation IR 273 (95% CI 118, 583)	Comparisons for a large number of occupations; limited N for pilot occupation

Perez-Gomez et al. (2004)	Retrospective Cohort	Swedish cohort of male cutaneous melanoma cases (N=6,187) with sub-cohort of aircraft workers (N=6)	Cutaneous melanoma from medical records (cancer registries)	Did they work as aircrew? (Y/N)	Compared to the full cohort RR 1.83 (95% CI 0.82, 4.11); Long-term employed pilot sub-cohort RR 1.94 (95% CI 0.72, 5.26)	Limited sub-cohort population
Nicholas et al. (2001)	Cross-sectional	Active and retired commercial airline pilots (N=6,533)	Self-reported	Did they work as pilots? (Y/N)	Compared to SEER rates SIR 3.47 (95% CI 2.85, 4.23)	Comparison between record-based controls and self-report by pilots; comparing the healthy worker group with the general population

NOTE: CI = confidence interval; IR = incidence ratio; OR = odds ratio; RR = relative risk; SEER = Surveillance, Epidemiology, and End Results program; SIR = standardized incidence ratio; SMR = standardized mortality ratio.

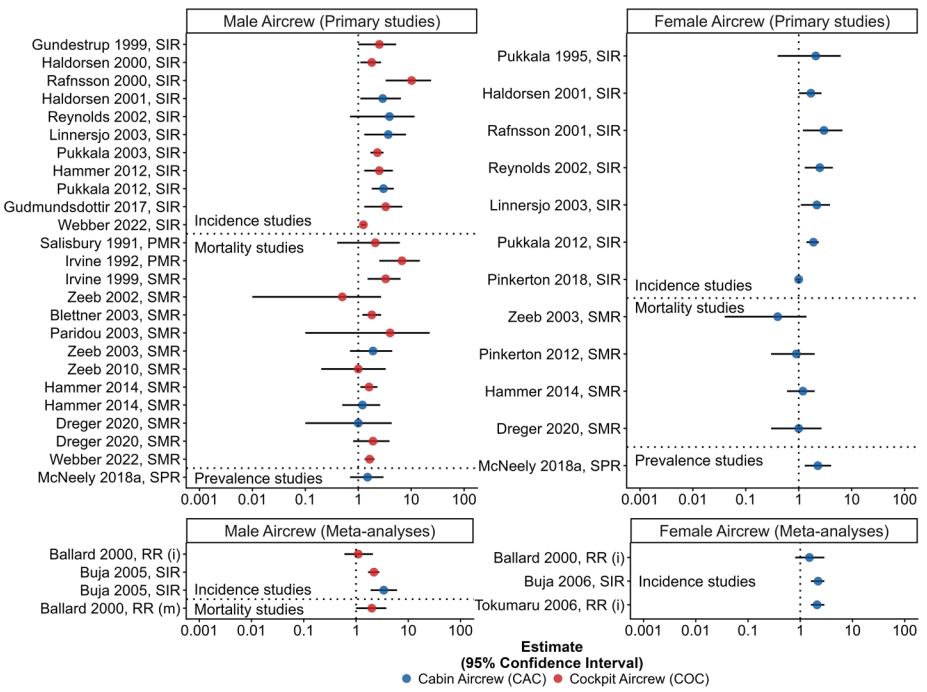


FIGURE E-3 Forest plot showing the summarized results between flight crew radiation exposure and malignant melanoma.

TABLE E-2 Studies Identified Reporting on Nonmelanoma Skin Cancer Among Flight Crew

Author (year)	Study Design	Population	Outcome	Exposure	Select Results	Key Limitations
Lee et al. (2016)	Prospective Cohort	Active component U.S. servicemembers diagnosed with nonmelanoma skin cancer during 10-year surveillance period (N=6,670)	Unspecified malignant neoplasms of the skin and carcinoma in situ of skin from medical records (health care records)	Did they work as pilots or aircrew? (Y/N)	Compared to combat service-member reference group, fixed wing pilots RR 6.0. Aircrew RR 3.2.	Uncertainty in incidence capture due to lack of established methods of recording in administrative data. Lack of confidence intervals.
Park et al. (2024)	Retrospective Cohort	Korean air transportation industry workers (male N=21,558; female N=12,547)	Nonmelanoma skin cancer from medical records (health insurance database)	Did they work in air transportation? (Y/N)	Compared to the general population SIR 1.19 (95% CI 0.71, 1.85)	Limited in available data. Population is described as air transportation industry workers with no distinction for flight crew or pilot status.
Nicholas et al. (2001)	Cross-sectional	Active and retired commercial airline pilots (N=6,533)	Self-reported nonmelanoma skin cancer	Did they work as pilots? (Y/N)	Compared to SEER rates 592 per 100,000	Comparison between record-based controls and self-report by pilots; comparing the healthy worker group with the general population

NOTE: CI = confidence interval; RR = relative risk; SEER = Surveillance, Epidemiology, and End Results program; SIR = standardized incidence ratio.

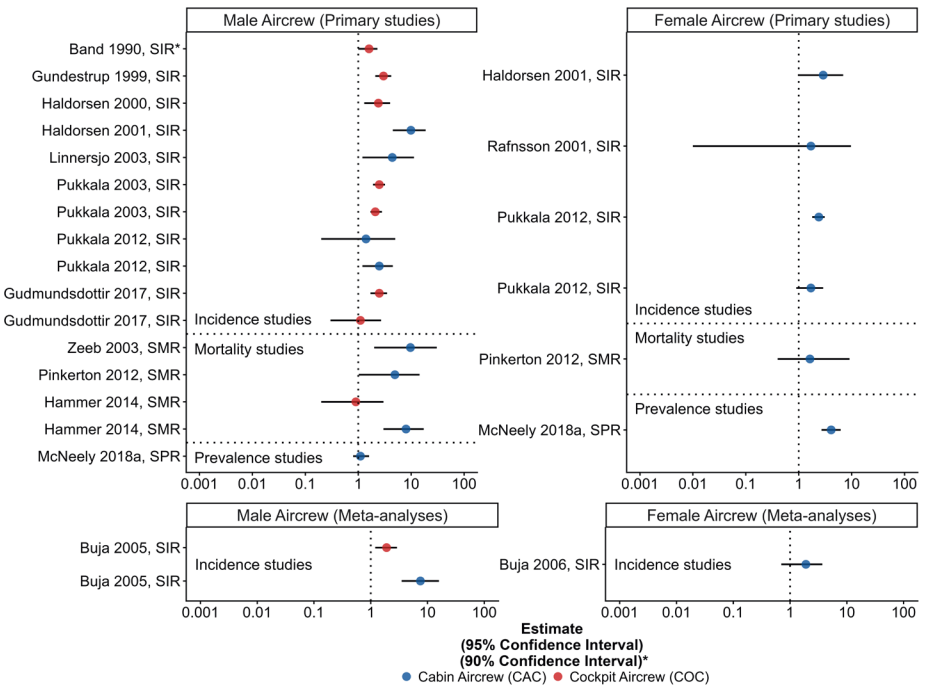


FIGURE E-4 Forest plot showing the summarized results between flight crew radiation exposure and nonmalignant melanoma.

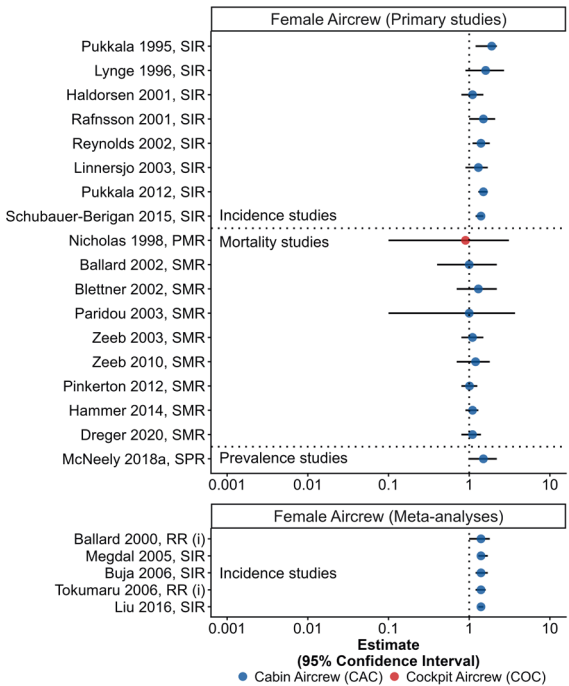


FIGURE E-5 Forest plot showing the summarized results between flight crew radiation exposure and breast cancer.

TABLE E-3 Studies Identified Reporting on Prostate Cancer Among Flight Crew

Author (year)	Study Design	Population	Outcome	Exposure	Select Results	Key Limitations
Webber et al. (2022)	Retrospective Cohort	U.S. Air Force fighter aviators (N=34,976)	Prostate cancer from medical records (cancer registries and medical surveillance systems)	Did they work as fighter aviators? (Y/N)	Compared to general population SIR 1.19 (95% CI 1.14, 1.25); SMR 1.23 (95% CI 1.06, 1.41). Compared to other officers' incidence OR 1.23 (95% CI 1.17, 1.30)	Lack of data on possible confounders; chose not to adjust the alpha level for multiple comparisons
Park et al. (2024)	Retrospective Cohort	Korean air transportation industry workers (male N=21,558; female N=12,547)	Male genital cancer including prostate from medical records (health insurance database)	Did they work as pilots or aircrew? (Y/N)	Compared to general population SIR 0.93 (95% CI 0.80, 1.08)	Limited in available data. Population is described as air transportation industry workers with no distinction for flight crew or pilot status.
Nicholas et al. (2001)	Cross-sectional	Active and retired commercial airline pilots (N=6,533)	Self-reported prostate cancer	Did they work as pilots? (Y/N)	Compared to SEER rates SIR 0.70 (95% CI 0.59, 0.84)	Comparison between record-based controls and self-report by pilots; comparing the healthy worker group with the general population

NOTE: CI = confidence interval; OR = odds ratio; SEER = Surveillance, Epidemiology, and End Results program; SIR = standardized incidence ratio; SMR = standardized mortality ratio.

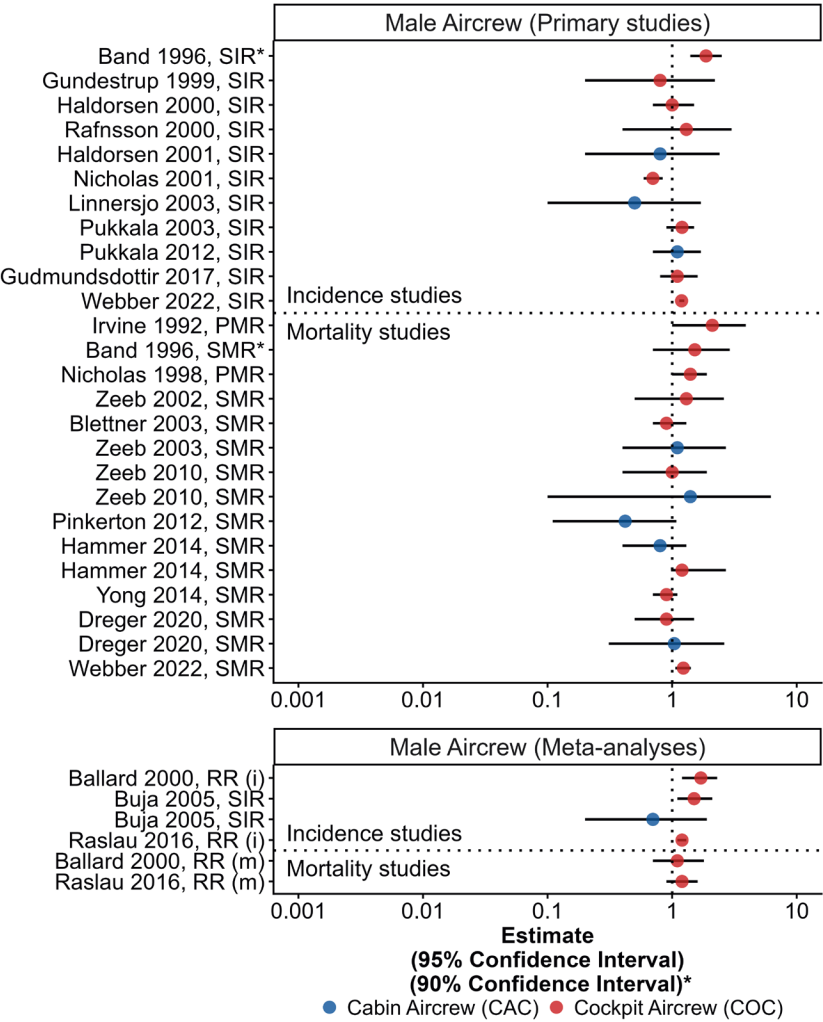


FIGURE E-6 Forest plot showing the summarized results between flight crew radiation exposure and prostate cancer.

TABLE E-4 Studies Identified Reporting on Brain/Central Nervous System Cancer Among Flight Crew

Author (year)	Study Design	Population	Outcome	Exposure	Select Results	Key Limitations
Webber et al. (2022)	Retrospective Cohort	U.S. Air Force fighter aviators (N=34,976)	Brain/CNS cancer from medical records (cancer registries and medical surveillance systems)	Did they work as fighter aviators? (Y/N)	Compared to the general population SIR 1.06 (95% CI 0.87, 1.29); SMR 1.13 (95% CI 0.91, 1.38)	Lack of data on possible confounders; chose not to adjust the alpha level for multiple comparisons
Park et al. (2024)	Retrospective Cohort	Korean air transportation industry workers (male N=21,558; female N=12,547)	Brain/CNS cancer from medical records (health insurance database)	Did they work in air transportation? (Y/N)	Compared to the general population SIR 0.88 (95% CI 0.53, 1.38)	Limited in available data. Population is described as air transportation industry workers with no distinction for flight crew or pilot status.
Nicholas et al. (2001)	Cross-sectional	Active and retired commercial airline pilots (N=6,533)	Self-reported brain/CNS cancer	Did they work as pilots? (Y/N)	Compared to SEER rates SIR 0.22 (95% CI 0.06, 0.76)	Comparison between record-based controls and self-report by pilots; comparing the healthy worker group with the general population

NOTE: CI = confidence interval; CNS = central nervous system; SEER = Surveillance, Epidemiology, and End Results program; SIR = standardized incidence ratio; SMR = standardized mortality ratio.

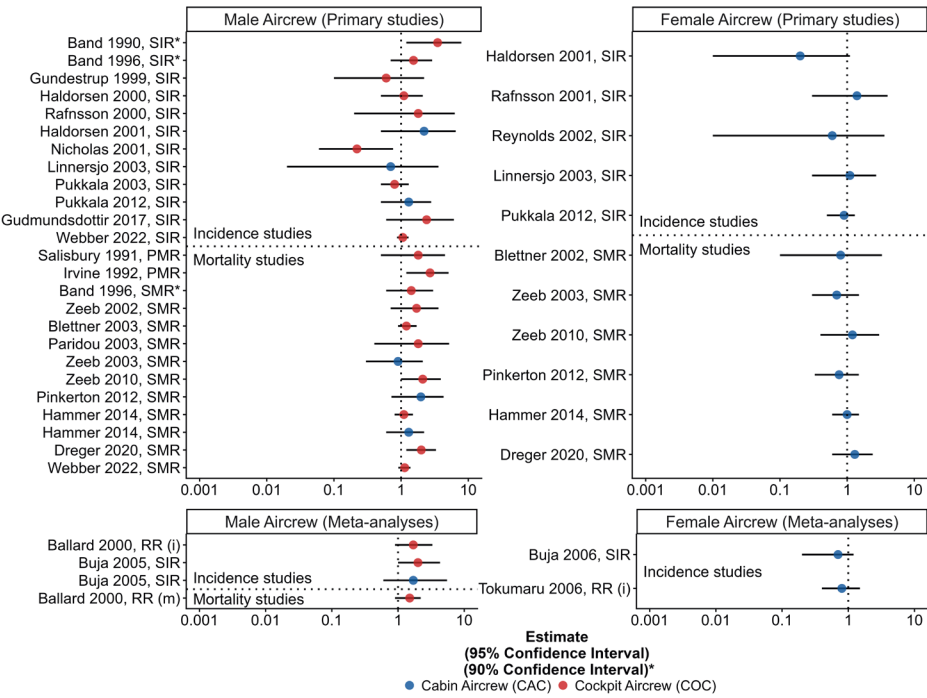


FIGURE E-7 Forest plot showing the summarized results between flight crew radiation exposure and brain/central nervous system cancer.

TABLE E-5 Studies Identified Reporting on Thyroid Cancer Among Flight Crew

Author (year)	Study Design	Population	Outcome	Exposure	Select Results	Key Limitations
Webber et al. (2022)	Retrospective Cohort	U.S. Air Force fighter aviators (N=34,976)	Thyroid cancer from medical records (cancer registries and medical surveillance systems)	Did they work as fighter aviators? (Y/N)	Compared to the general population SIR 0.71 (95% CI 0.56, 0.90); SMR 1.83 (95% CI 0.91, 3.27)	Lack of data on possible confounders; chose not to adjust the alpha level for multiple comparisons
Park et al. (2024)	Retrospective Cohort	Korean air transportation industry workers (male N=21,558; female N=12,547)	Thyroid cancer from medical records (health insurance database)	Did they work in air transportation? (Y/N)	Compared to the general population SIR 1.19 (95% CI 1.04, 1.36)	Limited in available data. Population is described as air transportation industry workers with no distinction for flight crew or pilot status.
Nicholas et al. (2001)	Cross-sectional	Active and retired commercial airline pilots (N=6,533)	Self-reported thyroid cancer	Did they work as pilots? (Y/N)	Compared to SEER rates SIR 1.08 (95% CI 0.40, 2.89)	Comparison between record-based controls and self-report by pilots; comparing the healthy worker group with the general population

NOTE: CI = confidence interval; SEER = Surveillance, Epidemiology, and End Results program; SIR = standardized incidence ratio; SMR = standardized mortality ratio.

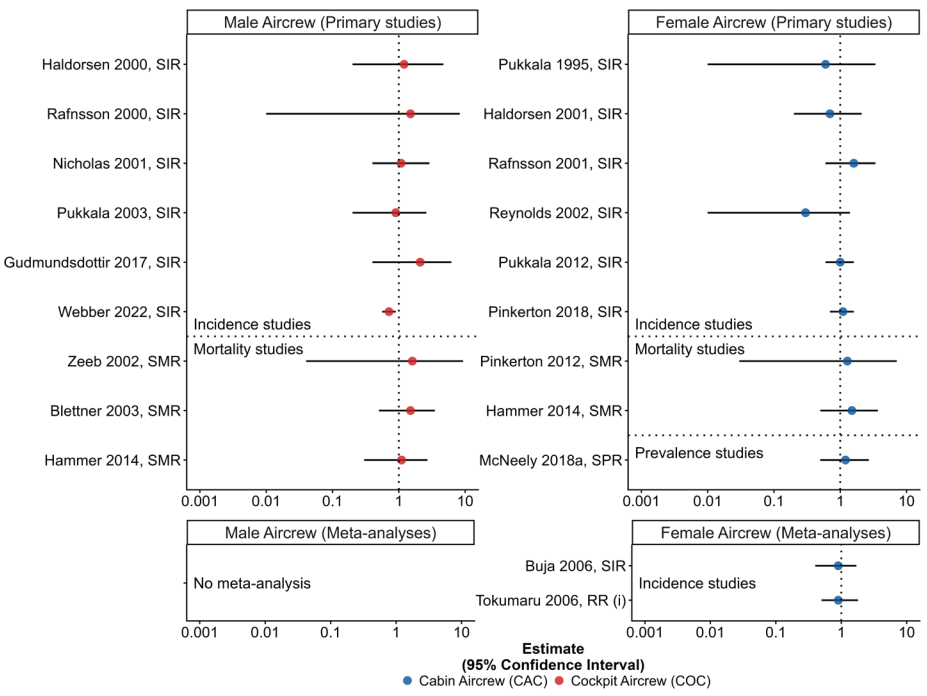


FIGURE E-8 Forest plot showing the summarized results between flight crew radiation exposure and thyroid cancer.

TABLE E-6 Studies Identified Reporting on Lymphomas Among Flight Crew

Author (year)	Study Design	Population	Outcome	Exposure	Select Results	Key Limitations
Webber et al. (2022)	Retrospective Cohort	U.S. Air Force fighter aviators (N=34,976)	Non-Hodgkin lymphoma from medical records (cancer registries and medical surveillance systems)	Did they work as fighter aviators? (Y/N)	Male fighter aviators when compared to general population SIR 1.13 (95% CI 1.01, 1.27); SMR 1.32 (95% CI 1.09, 1.58)	Lack of data on possible confounders; chose not to adjust the alpha level for multiple comparisons
Park et al. (2024)	Retrospective Cohort	Korean air transportation industry workers (male N=21,558; female N=12,547)	Hodgkin and non-Hodgkin lymphoma from medical records (health insurance database)	Did they work in air transportation? (Y/N)	For Hodgkin lymphoma compared to general population SIR 2.79 (95% CI 0.76, 7.13). Non-Hodgkin lymphoma compared to general population SIR 1.48 (95% CI 1.00, 2.10)	Limited in available data. Population is described as air transportation industry workers with no distinction for flight crew or pilot status.
Nicholas et al. (2001)	Cross-sectional	Active and retired commercial airline pilots (N=6,533)	Self-reported lymphoma	Did they work as pilots? (Y/N)	Compared to SEER rates SIR 0.39 (95% CI 0.22, 0.70)	Comparison between record-based controls and self-report by pilots; comparing the healthy worker group with the general population

NOTE: CI = confidence interval; SEER = Surveillance, Epidemiology, and End Results program; SIR = standardized incidence ratio; SMR = standardized mortality ratio.

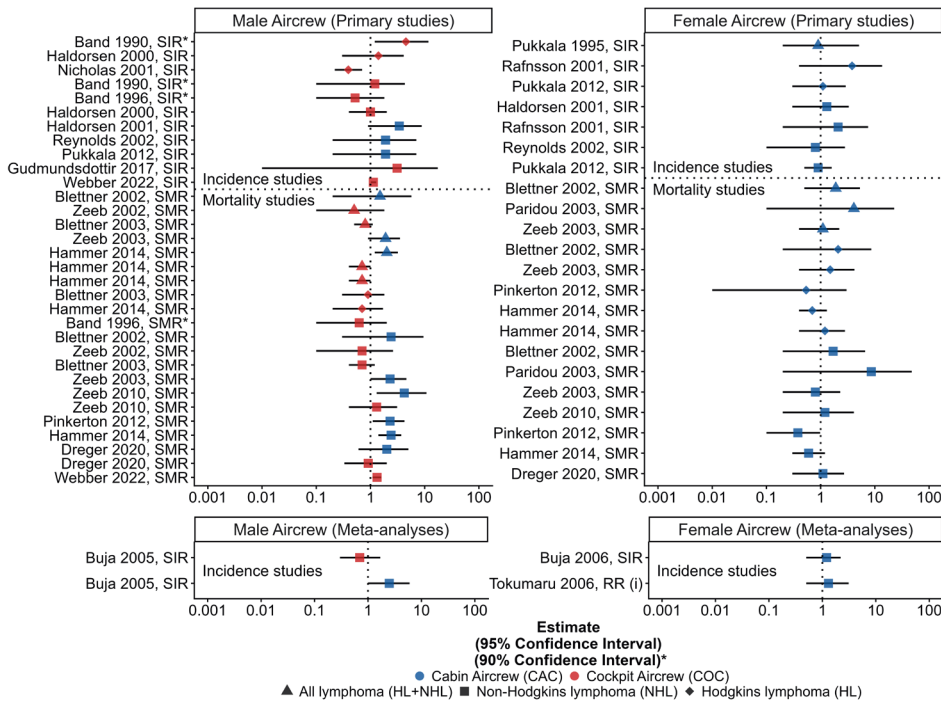


FIGURE E-9 Forest plot showing the summarized results between flight crew radiation exposure and lymphoma.

TABLE E-7 Studies Identified Reporting on Leukemias and Lymphomas Among Flight Crew

Author (year)	Study Design	Population	Outcome	Exposure	Select Results	Key Limitations
Park et al. (2023)	Case-control	Newly diagnosed AML patients with flight crew work history (N=3) among a larger AML patient cohort (N=304) versus control group (N=1,170)	AML from medical records (medical interview)	Did they work as aircrew? (Y/N)	Compared to paired controls OR 6.00 (95% CI 1.00, 35.91)	Possible recall bias; limited power; large number of comparisons; patient recruitment from only one hospital
Park et al. (2024)	Retrospective Cohort	Korean air transportation industry workers (male N=21,558; female N=12,547)	Lymphoid, myeloid, and unspecified leukemia from medical records (health insurance database)	Did they work in air transportation? (Y/N)	For lymphoid aircrew compared to general population SIR 1.33 (95% CI 0.27, 3.87). Myeloid in male aircrew compared to general population SIR 0.90 (95% CI 0.36, 1.86). Unspecified in males compared to general population SIR 1.80 (95% CI 0.37, 5.27)	Limited in available data. Population is described as air transportation industry workers with no distinction for flight crew or pilot status.
Nicholas et al. (2001)	Cross-sectional	Active and retired commercial airline pilots (N=6,533)	Self-reported leukemia	Did they work as pilots? (Y/N)	Compared to SEER rates SIR 0.25 (95% CI 0.11, 0.56)	Comparison between record-based controls and self-report by pilots; comparing the healthy worker group with the general population

NOTE: AML = acute myeloid leukemia; CI = confidence interval; OR = odds ratio; SEER = Surveillance, Epidemiology, and End Results program; SIR = standardized incidence ratio.

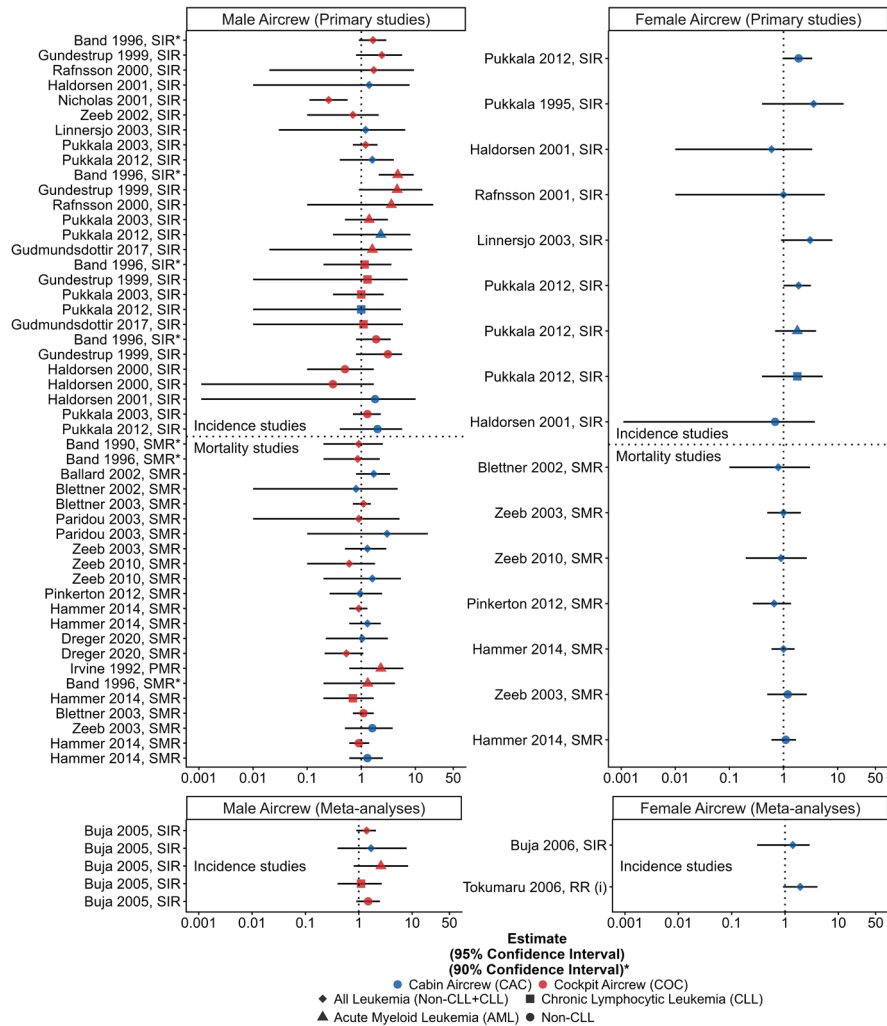


FIGURE E-10 Forest plot showing the summarized results between flight crew radiation exposure and leukemia.

TABLE E-8 Studies Identified Reporting on Genital Cancer Among Flight Crew

Author (year)	Study Design	Population	Outcome	Exposure	Select Results	Key Limitations
Webber et al. (2022)	Retrospective Cohort	U.S. Air Force fighter aviators (N=34,976)	Testis cancer from medical records (cancer registries and medical surveillance systems)	Did they work as fighter aviators? (Y/N)	Compared to other officers SMR 1.58 (95% CI 0.46, 5.49)	Lack of data on possible confounders; chose not to adjust the alpha level for multiple comparisons
Denic-Roberts et al. (2023)	Nested Case-Control	U.S. Air Force pilots and trainees (N=46); Control group (N=530)	Testicular germ cell tumors from medical records (cancer registries)	Did they work as aircrew? (Y/N)	Compared to other active-duty U.S. Air Force occupations OR 1.78 (95% CI 1.06, 3.01)	Lack of data on possible confounders; multiple comparisons across multiple occupations
Park et al. (2024)	Retrospective Cohort	Korean air transportation industry workers (male N=21,558; female N=12,547)	Female breast and genital cancer from medical records (health insurance database)	Did they work in air transportation? (Y/N)	Compared to the general population SIR 0.71 (95% CI 0.2, 3.95)	Limited in available data. Population is described as air transportation industry workers with no distinction for aircrew or pilot status.

NOTE: CI = confidence interval; OR = odds ratio; SIR = standardized incidence ratio; SMR = standardized mortality ratio.

REPRODUCTIVE HEALTH EVIDENCE TABLES

TABLE E-9 Studies Identified Reporting on Spontaneous Abortion (SA) Among Flight Crew

Author (year)	Study Design (country)	Population	Outcome	Exposure	Select Results	Key Limitations
Aspholm et al. (1999)	Retrospective Cohort (Finland)	Female flight attendants (N=613)	SA from medical record	Work during first trimester (Y/N)	OR 1.3 (95% CI 0.9, 1.8)	Indirect exposure measure
Cone et al. (1998)	Retrospective Cohort (United States)	Female flight attendants with at least one pregnancy during 2-year study period (N=418)	Self-reported SA	Work during first trimester (Y/N)	OR 1.91 (95% CI 0.78, 4.66)	Low survey response rate; indirect exposure measure; self-reported outcome
Daniell et al. (1990)	Retrospective Cohort (United States)	Female flight attendants (N=514); control women (N=475)	SA from birth certificates	Work during pregnancy (Y/N)	Compared to employed controls: RR 1.3 (95% CI 0.9, 1.9)	Indirect exposure measure; selection bias due to use of birth certificates
dos Santos Silva et al. (2009)	Cross-sectional (United Kingdom)	Female flight crew (N=325); female air traffic control officers (N=316)	Self-reported SA	Flight crew vs. air traffic control officer	OR 1.02 (95% CI 0.58, 1.77)	Indirect exposure measure; self-reported outcome
Grajewski et al. (2015)	Retrospective Cohort (United States)	Female flight attendants (N=2,273)	Self-reported SA, confirmed by medical record for ~43%	Cumulative absorbed dose (mGy), estimated from CARL-6P	Miscarriage at weeks 9–13 for dose 0.1+ mGy v. <0.1: OR 1.7 (95% CI 0.95, 3.2)	Computationally estimated exposure; outcome not validated for >50% of self-reports
Heidecker et al. (2017)	Cross-sectional (United States)	Female flight attendants before airline smoking ban enacted (N=145)	Self-reported SA	Flight attendant vs. general population comparator	Increased rate of miscarriage (26% vs. 17.1%)	Convenience sample; indirect exposure measure; self-reported outcome
Lauria et al. (2006)	Cross-sectional (Italy)	Female flight attendants with at least one pregnancy (N=780)	Self-reported SA	Work during pregnancy (Y/N)	No difference in proportion of SA for in-service vs. not (12.6% vs. 11.4%)	Indirect exposure measure; self-reported outcome

McNeely et al. (2018b)	Cross-sectional (United States)	Female flight attendants (N=4,368)	Self-reported SA	Five-year tenure as flight attendant prior to age 45 vs. not	OR 1.33 (95% CI 1.20, 1.46)	Indirect exposure measure; self-reported outcome
Stark et al. (2024a)	Retrospective Cohort (United States)	Female military aviation officers with at least one pregnancy (N=25,929)	SA from Military Health System database	Mother was aviation officer vs. nonaviation officer	RR 1.00 (95% CI 0.89, 1.12)	Indirect exposure measure
Yang et al. (2013)	Cross-sectional (China)	Female flight attendants (N=206) and ground service workers (N=269) who gave birth	Self-reported SA	Flight attendants vs. ground service workers	History of SA 6.8% vs. 2.97%, p-value=0.049	Indirect exposure measure; self-reported outcome

NOTES: Results are reported for the most adjusted statistical model. CI = confidence interval; OR = odds ratio; RR = relative risk; SA = spontaneous abortion.

TABLE E-10 Studies Identified Reporting on Birth Outcomes Among Flight Crew

Author (year)	Study Design (country)	Population	Outcome	Exposure	Select Results	Key Limitations
Irgens et al. (2003)	Retrospective Cohort (Norway)	Births among female FA (N=3,346); births among male pilots (N=2,356)	Low BW, preterm birth from national birth register	Hours in air (above/below median) and dose (above/below median) estimated from CARL-6P, in year preceding birth and ever	Low BW: OR 0.88 (95% CI 0.72, 1.08) for male pilots and OR 0.83 (95% CI 0.69, 0.998) for female FA. Preterm birth: OR 0.85 (95% CI 0.70, 1.03) for male pilots and OR 0.95 (95% CI 0.81, 1.12) for female FA. ^a	Computationally derived exposure; exposure dichotomized; too few births among female pilots or male FA to study
Cone et al. (1998)	Retrospective Cohort (United States)	Female FA with at least one pregnancy during 2-year study period (N=418)	Self-reported low BW	Work during first trimester (Y/N)	3% of births were low BW and 1% were very low BW, similar or less than general population rates	Indirect exposure measure; self-reported outcome; crude statistical comparison
Daniell et al. (1990)	Retrospective Cohort (United States)	Female FA (N=514); control women (N=475)	Low BW, preterm birth from birth certificates	Work during pregnancy (Y/N)	Compared to employed controls: Low BW RR 1.7 (95% CI 0.7, 4.5); preterm birth RR 1.3 (95% CI 0.8, 2.1)	Indirect exposure measure; selection bias due to use of birth certificates
McNeely et al. (2018b)	Cross-sectional (United States)	Female FA (N=4,368)	Self-reported preterm birth	Five-year tenure as FA prior to age 45 vs. not	OR 1.43 (95% CI 1.17, 1.74)	Indirect exposure measure; self-reported outcome
Stark et al. (2024a)	Retrospective Cohort (United States)	Female military aviation officers with at least one pregnancy (N=25,929)	Preterm birth from Military Health System database	Mother was aviation officer vs. nonaviation officer	RR 0.86 (95% CI 0.68, 1.08)	Indirect exposure measure

Stark et al. (2024b)	Retrospective Cohort (United States)	Births among female fixed-wing aviation officers (N=1,144) and nonaviation officers (N=25,889)	Low BW, premature birth from Military Health System database	Mother was aviation officer vs. nonaviation officer	Low BW RR 0.78 (95% CI 0.56, 1.10); preterm birth RR 0.81 (95% CI 0.63, 1.04)	Indirect exposure measure
Yang et al. (2013)	Cross-sectional (China)	Female FA (N=206) and ground service workers (N=269) who gave birth	Self-reported low BW	FA vs. ground service workers	Low BW 0.97% vs. 4.09%, p=0.039	Indirect exposure measure; self-reported outcome

^a Results shown for exposure in year preceding births; similar results observed for “ever” exposure.
NOTE: BW = birthweight; CI = confidence interval; FA = flight attendants; OR = odds ratio; RR = relative risk.

TABLE E-11 Studies Identified Reporting on Birth Defects Among Flight Crew

Author (year)	Study Design (country)	Population	Outcome	Exposure	Select Results	Key Limitations
Irgens et al. (2003)	Retrospective Cohort (Norway)	Births among female FA (N=3,346); births among male pilots (N=2,356)	Birth defects from national birth register	Hours in air (above/below median) and dose (above/below median) estimated from CARL-6P, in year preceding birth and ever	OR 0.85 (95% CI 0.65, 1.11) for male pilots and OR 1.03 (95% CI 0.82, 1.28) for female FA. ^a	Computationally derived exposure; exposure dichotomized; too few births among female pilots or male FA to study
dos Santos Silva et al. (2009)	Cross-sectional (United Kingdom)	Female flight crew (N=325); female air traffic control officers (N=316); male flight crew (N=9,880); male air traffic control officers (N=1,802)	Self-reported child born with congenital abnormalities	Flight crew vs. air traffic control officer	Females: OR 3.94 (95% CI 0.79, 19.5) Males: OR 1.06 (95% CI 0.79, 1.41)	Indirect exposure measure; self-reported outcome
McNeely et al. (2018b)	Cross-sectional (United States)	Female FA (N=4,368)	Self-reported fetal abnormality	Five-year tenure as FA prior to age 45 vs. not	OR 1.64 (95% CI 1.23, 2.18)	Indirect exposure measure; self-reported outcome
Royall et al. (2025)	Retrospective Cohort (United States)	Births among female fixed-wing aviation officers (N=1,144) and nonaviation officers (N=25,889)	Congenital malformations from Military Health System database	Aviation or flight crew occupation at time of birth vs. not	HR 0.96 (95% CI 0.88, 1.04)	Indirect exposure measure
Yang et al. (2013)	Cross-sectional (China)	Female FA (N=206) and ground service workers (N=269) who gave birth	Self-reported birth defect	FA vs. ground service workers	Birth defect 0.49% vs. 0.39%, p-value=0.85	Indirect exposure measure; self-reported outcome; crude statistical comparison

^a Results shown for exposure in year preceding births; similar results observed for “ever” exposure.
NOTE: CI = confidence interval; FA = flight attendants; HR = hazard ratio; OR = odds ratio.

TABLE E-12 Studies Identified Reporting on Sex Ratio Among Flight Crew

Author (year)	Study Design (country)	Population	Outcome	Exposure	Select Results	Key Limitations
Baczk et al. (2009)	Cross-sectional (United States)	Fixed-wing naval aviation officers' children (N=560)	Self-reported infant sex	Flying a fixed-wing aircraft	Sex ratio = 0.499 or 1 male for every 1,002 females	Indirect exposure measure; self-reported outcome; crude statistical comparison
Cone et al. (1998)	Retrospective Cohort (United States)	Female FA with at least one pregnancy during 2-year study period (N=418)	Self-reported infant sex	Work as FA during first trimester	Sex ratio male: female = 0.89:1	Indirect exposure measure; self-reported outcome; crude statistical comparison
Daniell et al. (1990)	Retrospective Cohort (United States)	Female FA (N=514); control women (N=475)	Infant sex from birth certificates	Work during pregnancy (Y/N)	50% male among FA vs. 53% male among controls RR 0.9 (95% CI 0.8, 1.1)	Indirect exposure measure; selection bias due to use of birth certificates
Lauria et al. (2006)	Cross-sectional (Italy)	Female FA with at least one pregnancy (N=780)	Self-reported infant sex	Work during pregnancy (Y/N)	51.0% male for in-service FA vs. 50% male for not in-service FA	Indirect exposure measure; self-reported outcome; crude statistical comparison
Yang et al. (2013)	Cross-sectional (China)	Female FA (N=206) and ground service workers (N=269) who gave birth	Self-reported infant sex	FA vs. ground service workers	52.91% male for FA vs. 50.93% male for ground crew, p=0.699	Indirect exposure measure; self-reported outcome; crude statistical comparison

NOTE: CI = confidence interval; FA = flight attendants; RR = relative risk.

TABLE E-13 Studies Identified Reporting on Infertility Among Flight Crew

Author (year)	Study Design (country)	Population	Outcome	Exposure	Select Results	Key Limitations
dos Santos Silva et al. (2009)	Cross-sectional (United Kingdom)	Female flight crew (N=325); female air traffic control officers (N=316); male flight crew (N=9,880); male air traffic control officers (N=1,802)	Self-reported difficulty conceiving	Flight crew vs. air traffic control officer	Females: OR 1.21 (95% CI 0.53, 2.77). Males: OR 1.08 (95% CI 0.88, 1.32)	Indirect exposure measure; self-reported outcome
Lauria et al. (2006)	Cross-sectional (Italy)	Female flight attendants with at least one pregnancy (N=780)	Self-reported fertility problems	Years of activity as a flight attendant (≤ 6 , 7–10, 11–15, >15)	OR (95% CI) for 7–10, 11–15, and >15 years were 1.2 (0.6, 2.4), 1.3 (0.8, 2.1), and 1.4 (0.8, 2.3)	Indirect exposure measure; self-reported outcome
McNeely et al. (2018b)	Cross-sectional (United States)	Female flight attendants (N=4,368)	Self-reported infertility	Five-year tenure as flight attendant prior to age 45 vs. not	OR 1.45 (95% CI 1.29, 1.64)	Indirect exposure measure; self-reported outcome
Yang et al. (2013)	Cross-sectional (China)	Female flight attendants (N=563) and ground service workers (N=612)	Fertility rate among respondents	Flight attendants vs. ground service workers	Fertility rate 39.59% in flight attendants vs. 43.95% in ground service workers, $p < 0.05$	Indirect exposure measure; self-reported outcome; crude statistical comparison

NOTE: CI = confidence interval; OR = odds ratio.

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Appendix F

Information and Methodologies for Computational Models

TABLE F-1 Commercial Flight Paths and Space Weather Conditions for Cosmic Radiation Exposure Model Evaluation

City-Pair	Flight Level	Flight Duration (h)	SC24 Min (Departure Datetime)	SC24 Max (Departure Datetime)	SEP E1A (Departure Datetime)	SEP E1B (Departure Datetime)	SEP E2 (Departure Datetime)
HKG–JFK	400	15.4	12/15/2008	04/15/2014	10/28/2003	10/29/2003	01/19/2005
			01:00 UT	01:00 UT	17:34 UT	13:34 UT	23:52 UT
LHR–LAX	400	11.1	12/15/2008	04/15/2014	10/28/2003	10/29/2003	01/20/2005
			15:00 UT	15:00 UT	18:42 UT	18:04 UT	01:33 UT
JFK–LHR	400	6.4	12/15/2008	04/15/2014	10/28/2003	10/29/2003	01/20/2005
			03:00 UT	03:00 UT	21:03 UT	17:23 UT	03:54 UT
LAX–JFK	350	5.5	12/15/2008	04/15/2014	10/28/2003	10/29/2003	01/20/2005
			18:00 UT	18:00 UT	21:30 UT	17:46 UT	04:21 UT
DFW–MIA	300	2.6	12/15/2008	04/15/2014	10/28/2003	10/29/2003	01/20/2005
			18:00 UT	18:00 UT	22:57 UT	20:57 UT	05:48 UT

SOURCE: Data derived from FlightPaths, <https://www.flightpaths.com/flight-paths-north-pole>.
NOTE: Route identifiers (e.g., HKG–JFK, LHR–LAX) represent origin–destination airport pairs using IATA airport codes. “UT” denotes Coordinated Universal Time.

TABLE F-2 Ascent Time from Ground to Cruise Flight Level and Decent from Cruise Altitude to Ground

Flight Level	Ascent Time	Decent Time
300	15 min	15 min
350	15 min	15 min
400	15 min	20 min

TABLE F-3 Geographic Latitudes and Longitudes of Airport City-Pairs

Airport (IATA Code)	Latitude (degrees)	Longitude (degrees)
LHR	51.48N	359.54E
HKG	22.31N	113.91E
LAX	33.94N	241.59E
JFK	40.64N	286.22E
DFW	32.90N	262.96E
MIA	25.79N	279.71E

AVIDOSE PROCEDURE

1. Navigate to <https://swe.ssa.esa.int/avidos-federated> using a web browser.
2. Log in to the website.
3. Select the PUBLIC option on the lower left-hand corner of the page.
4. Specify the departure date and time in Coordinated Universal Time (UTC).
5. Select the departure airport by filtering on International Civil Aviation Organization (ICAO) code, International Air Transport Association (IATA) code, country, or airport name.
6. Select the arrival airport by filtering on ICAO code, IATA code, country, or airport name.
7. Click the “Calculate” button.
8. Examine the Effective Dose value displayed to the right of the FLIGHT PLANNER entries.

CARI-7A PROCEDURE

For Galactic Cosmic Radiation Analyses

1. Create a *.BIG file for the flight path of interest (e.g., LHR2LAX.BIG) in the main CARI-7A directory. For each specific flight date/time of interest, this file includes the following:
 - a) Descriptive title (e.g., SC24 MIN).
 - b) Flight start date (YYYY/MM/DD)/time(UTC) (e.g., 2008/12/15, 1500).

- c) Origin airport ICAO code (e.g., EGLL).
 - d) Destination airport ICAO code (e.g., KLAX).
 - e) Number of cruising altitudes (1 for all).
 - f) Time, in minutes, for ascent (e.g., 15).
 - g) Cruising altitude, in feet, and time at cruising altitude, in minutes (e.g., 40000 631).
 - h) Time, in minutes, for descent (e.g. 20).
 - i) Delimiter line (----- for all).
2. Execute the CARI-7A program in the main CARI-7A directory.
 3. Select option <2> Galactic radiation received on flights.
 4. Select option <1> Flight path(s) nearly geodesic...
 5. Select option for *.BIG file to run (e.g., LHR2LAX.BIG).
 6. Under SELECT RADIATION, select option <0> TOTAL.
 7. Under SELECT COSMIC RAY MODEL, select option <4> GCR: ISO LIS MODULATED WITH CARI-6 HP.
 8. Under SELECT DOSE TYPE, select option <2> ICRP PUB 103 EFFECTIVE DOSE.
 9. For USE SUPERPOSITION APPROXIMATION, enter N.
 10. For USE DATES FROM FLIGHT DATA FILE, enter Y.
 11. Wait for analysis to complete (can take on the order of a few minutes).
 12. Within the main CARI-7A directory, locate *.OUT file corresponding to the *.BIG file executed using CARI-7A (e.g., LHR2LAX.OUT).
 13. Obtain results for each specific date/time of interest from the *.OUT file.

For Solar Energetic Particle Analyses

1. Obtain time-averaged proton flux spectra in energy units of GeV and flux units of $m^{-2} sr^{-1} s^{-1} GeV^{-1}$ from desired source (e.g., NAIRAS).
2. Use log-log interpolation to interpolate proton flux spectra onto the CARI-7A energy grid obtained from the MY_MODEL.OUT file in the ~/GCR_MODELS folder of the CARI-7A main directory.
3. Create new MY_MODEL.OUT file containing the proton flux spectra on the CARI-7A energy grid for the flight path and flight date/time of interest. NOTE: Take care to use the same format for each line as the original MY_MODEL.OUT file. This will include data entries for ions heavier than protons. Do not enter zero for zero flux but rather use a very small number like 1.000E-33.
4. Create *.BIG file for the flight path and flight date/time of interest (e.g., LHR-2LAXA.BIG) in the main CARI-7A directory. The file includes a single entry in the format described for the GCR analyses.
5. Execute the CARI-7A program in the main CARI-7A directory.
6. Select option <2> Galactic radiation received on flights.
7. Select option <1> Flight path(s) nearly geodesic...
8. Select option for *.BIG file to run (e.g., LHR2LAXA.BIG).
9. Under SELECT RADIATION, select option <0> TOTAL.

10. Under SELECT COSMIC RAY MODEL, select option <7> USER SELECTED: GCR_MODELS\MY_MODEL.OUT.
11. Under SELECT DOSE TYPE, select option <2> ICRP PUB 103 EFFECTIVE DOSE.
12. For USE SUPERPOSITION APPROXIMATION, enter N.
13. For USE DATES FROM FLIGHT DATA FILE, enter Y.
14. Wait for analysis to complete (can take on the order of a few minutes).
15. Within the main CARI-7A directory, locate *.OUT file corresponding to the *.BIG file executed using CARI-7A (e.g., LHR2LAXA.OUT).
16. Obtain results for the flight path and flight date/time of interest from the *.OUT file.

NAIRAS PROCEDURE

- Flight Trajectories: Five airport city-pairs and five space weather conditions (see Table F-1).
- Created flight trajectory files for the 25 cases (above) using codes that are part of the NAIRAS model. The city-pair flight trajectories were great circle routes with trajectory points at 1-minute time intervals. The other characteristics of the flight trajectories are given in Tables F –2 from NAIRAS_Results_NAS_v2.docx.
- All 25 flight trajectories were run from the NAIRAS run-on-request service (RoR) at the Community Coordinated Modeling Center (CCMC).
- Click the Run-on-Request tab at NAIRAS 3.0 | CCMC.
- There are four pages in the RoR submission process for each flight trajectory:
 - Page 1: Select “Dosimetric quantities at each trajectory point” and “Time-integrated dosimetric quantities” under the “Dosimetric Quantities” heading. Note: NAIRAS version 3 effective dose quantities are based on ICRP Publication 60 weighting factors.
 - Page 2: Upload the flight trajectory file. Select “Best Available” for “B-Field Model.” For the datetime periods of the 25 flight trajectories, this selection will include the IGRF model for Earth’s internal magnetic field and the TS05 magnetospheric magnetic field model. Select “Protons Only” for “SEP Model.” This selection is chosen for consistency with other models which don’t include SEP heavy-ion contributions. “Code friendly” was selected for “Output Format.”
 - Page 3: This page is a summary of the run options selected. Click “Confirm” if the input is correct and “Back” to revise input selections.
 - Page 4: This is a run submission confirmation page which also includes a unique Run Registration Number to search the CCMC RoR data tree for the model output results (CCMC: Runs on Request System | CCMC). In addition, an email is sent when the run is complete which also provides a link to the output results.

- Note: The default setting is to calculate the selected output quantities at 0, 4, and 50 g/cm² aluminum shielding thickness. The NAIRAS results reported in this document are at zero shielding thickness. At commercial aviation altitudes, the overhead thickness of the atmosphere (~ 200 –300 g/cm²) is nearly two orders of magnitude greater than the thickness of the aircraft structure (~4 g/cm²). Thus, the differences in computed effective dose rates with and without aircraft shielding is less than the uncertainty of dosimeter measurements at commercial aircraft altitudes. The CARI-7 User’s Guide also notes that the “industry standard” is to report computed doses at zero vehicle thickness.
- The NAIRAS results in this report are publicly accessible at CCMC: CCMC: Runs on Request System | CCMC, Below are the Run Registration Numbers for the 25 flight trajectories:
 - SC24MIN HKG –JFK: Chris_Mertens_121525_IT_1
 - SC24MIN LHR –LAX: Chris_Mertens_111725_IT_2
 - SC24MIN JFK –LHR: Chris_Mertens_111825_IT_1
 - SC24MIN LAX –JFK: Chris_Mertens_111725_IT_4
 - SC24MIN DFW –MIA: Chris_Mertens_111725_IT_5
 - SC24MAX HKG –JFK: Chris_Mertens_111725_IT_6
 - SC24MAX LHR –LAX: Chris_Mertens_111725_IT_7
 - SC24MAX JFK –LHR: Chris_Mertens_111725_IT_8
 - SC24MAX LAX –JFK: Chris_Mertens_111725_IT_9
 - SC24MAX DFW –MIA: Chris_Mertens_111825_IT_2
 - E1A HKG –JFK: Chris_Mertens_111825_IT_3
 - E1A LHR –LAX: Chris_Mertens_111825_IT_4
 - E1A JFK –LHR: Chris_Mertens_111825_IT_5
 - E1A LAX –JFK: Chris_Mertens_111825_IT_6
 - E1A DFW –MIA: Chris_Mertens_111825_IT_7
 - E1B HKG –JFK: Chris_Mertens_112025_IT_1
 - E1B LHR –LAX: Chris_Mertens_112025_IT_2
 - E1B JFK –LHR: Chris_Mertens_112025_IT_3
 - E1B LAX –JFK: Chris_Mertens_112025_IT_4
 - E1B DFW –MIA: Chris_Mertens_112025_IT_5
 - E2 HKG –JFK: Chris_Mertens_112525_IT_1
 - E2 LHR –LAX: Chris_Mertens_112525_IT_2
 - E2 JFK –LHR: Chris_Mertens_112525_IT_3
 - E2 LAX –JFK: Chris_Mertens_112525_IT_4
 - E2 DFW –MIA: Chris_Mertens_112525_IT_5

SIEVERT PROCEDURE

1. Navigate to <https://www.sievert-system.org> using a web browser.
2. Select English version of website by clicking on UK flag in lower right-hand corner.
3. Click the “Calculate the dose received” button near the website header.

4. Select the departure country, including U.S. state if applicable (e.g., UNITED KINGDOM).
5. Select the departure city (e.g., LONDON).
6. Specify the departure date in local time of the departure city. NOTE: It is unclear whether this includes daylight savings time.
7. Specify the departure time in local time of the departure city. NOTE: It is unclear whether this includes daylight savings time.
8. Select the arrival country, including U.S. state if applicable (e.g., UNITED STATES CALIFORNIA).
9. Select the arrival city (e.g., LOS ANGELES).
10. Specify the arrival date in local time of the departure city. NOTE: It is unclear whether this includes daylight savings time.
11. Specify the arrival time in local time of the departure city. NOTE: It is unclear whether this includes daylight savings time.
12. For the “Type of aircraft” dropdown menu, select “Subsonique.”
13. Click the “Calculate” button.
14. In the “Dose received” pop-up window, examine the “Dose received during the flight” value. Use the “Flying time” value to cross-check that the appropriate times were entered for departure and arrival.

Appendix G

Information and Methodologies for Cancer Risk Calculations

EXAMPLES OF SURVEILLANCE

In occupational settings, the integration of exposure surveillance and health outcomes research has proven effective in protecting workers' health, creating a continual feedback loop that enables the identification of hazardous conditions and the assessment of how exposures affect health outcomes (see Table G-1).

TECHNICAL DOCUMENTATION: SIMULATION-BASED POWER CALCULATION FOR CANCER RISK FROM COSMIC RADIATION EXPOSURE IN FLIGHT CREW

Original Code Date: January 19, 2026; Documentation Generated: March 2026

Overview and Purpose

This R script implements Monte Carlo simulation-based power calculations for detecting elevated cancer incidence risk associated with low-dose cosmic radiation exposure in commercial flight crew. The simulation framework is designed to inform sample-size requirements for epidemiologic cohort studies of occupational radiation exposure. Several key assumptions were made when designing the synthetic dataset. The committee's intention is not to assert that this is the only way to conduct an epidemiologic study but rather to provide a conceptual framework for assessing the feasibility of future research. All parameters and assumptions made in these power calculations are adjustable, and the committee recommends conducting more rigorous simulations before making a decision about the value of an epidemiologic study.

TABLE G-1 Examples of Established Surveillance Programs in the United States

Program	Entity	Year	Purpose	Participation	Key Findings
CWHSP (Hall et al. 2019)	NIOSH	1970	Monitors respiratory disease in miners using imaging and physiological data; supports trend analysis.	Nationwide (55 years; ended 2025)	Identified resurgence of CWP and PMF; informed exposure limits and reductions.
ABLES (NIOSH n.d.)	CDC	1987	Tracks elevated BLLs in working adults; supports exposure and health outcomes research.	Up to 41 states	Helped establish BLL thresholds; contributed to major reductions in lead exposure.
EPINet (AOEC n.d.)	ISC/AOEC	1992	Monitors needlestick and body fluid exposures in health care workers.	Voluntary	Identified differences by staff group and region.
SENSOR (Baker 1989)	NIOSH/EPA	1987	Tracks occupational illness/injury; includes pesticide exposure surveillance.	13 states (CDC 2024b)	Distinguished new-onset versus work-aggravated asthma.

NOTE: ABLES = Adult Blood Lead Epidemiology and Surveillance; AOEC = Association of Occupational and Environmental Clinics; BLL = blood lead level; CDC = Centers for Disease Control and Prevention; CWHSP = Coal Workers’ Health Surveillance Program; CWP = coal workers’ pneumoconiosis; EPA = U.S. Environmental Protection Agency; EPINet = Exposure Prevention Information Network; ISC = International Safety Center; NIOSH = National Institute for Occupational Safety and Health; PMF = progressive massive fibrosis; SENSOR = Sentinel Event Notification System for Occupational Risks.

Key Assumptions

Key Assumption 1

In each simulation, flight crew were randomly sorted into haul class/flight route types (e.g., short-haul, medium-haul, long-haul, and polar). Annual exposure to ionizing radiation was then estimated by randomly selecting a value from the typical effective dose range for that route type, using flight-specific dose estimates calculated at the solar minimum from Chapter 4. The flight route data came from the U.S. Department of Transportation’s Bureau of Transportation Statistics (BTS) T-100 Segment data. Figure G-1 shows the total number of flights per year by flight route type. The number of flights per year for each crewmember was determined by flight route type, and this number was used to calculate yearly statistics for each flight route category (see Table G-2).

Key Assumption 2

Occupational, demographic, health, lifestyle, and employment characteristics were collected from several sources including the Bureau of Labor Statistics, Population Reference Bureau, the Federal Aviation Administration’s Civil Airmen Statistics, and published literature. Because no single source exists of definitive information at the

TABLE G-2 Flight Route Category

Category	Avg mSv per Year	GSD	Flights per Year
Short-haul	3.17	1.02	600
Medium-haul	6.52	1.01	260
Long-haul	8.24	1.02	112
Polar	9.22	1.01	75

NOTE: GSD = geometric standard deviation; mSv = millisievert.

individual level, this ecological approach assumes that marginal summaries approximate the joint distribution of individual-level variables. Consequently, this approach may not preserve correlations among exposures, confounders, and time.

Key Assumption 3

The synthetic dataset was created assuming that galactic cosmic radiation exposure follows the same pattern as the Life Span Study (LSS) excess relative risk (ERR) estimates. Table G-3 shows the ERR per Gray values that were used in the simulations. Two sets of simulations were conducted, first using the ERR point estimate to assign risk of cancer and then using the upper 95% confidence interval value from the same paper (Brenner et al. 2025). Because required sample sizes generally decrease as the effect size increases, the upper bound of the 95% confidence interval yields a lower bound on the needed sample size. Brenner and colleagues (2025) studied varying confounders for each cancer site, and various lag periods were considered. The leukemia ERRs are from Hsu and colleagues (2013). Paired with the point estimate, this defines a planning range for the target. Additionally, LSS reports negative ERRs for melanoma; however, because it is prominent in the literature, a value of 0.5 was selected for the power calculations. This number is arbitrary and should be treated as such.

TABLE G-3 ERR per Gray by Cancer Site and Sex

Cancer Site	Female ERR	Male ERR
All Solid	0.64	0.2
Breast	1.04	—
Prostate	—	0.54
Lung	1.2	0.42
Colon	0.5	0.77
Bladder	2.2	0.64
Brain/CNS	0.77	2.46
Leukemia	0.7	1.06
Melanoma	0.5	0.5

NOTE: CNS = central nervous system.
SOURCE: Brenner and colleagues (2025); Hsu and colleagues (2013).

Methodological Approach

The simulation incorporates several methodologically rigorous features:

- Attained age as the timescale for Cox regression analysis, consistent with best practices in radiation epidemiology
- Time-varying dose accumulation with cancer-type-specific exposure lag periods
- Lognormal dose distributions ensuring physiologically plausible positive values
- Berkson and classical measurement error models for dose uncertainty
- Healthy worker effect (HWE) modeling through selection bias and frailty convergence
- Cancer-specific confounding adjustment (smoking for lung/bladder; reproductive factors for breast)

Data Sources and Parameter Derivation*BTS Data***Flight Routes**

The BTS publishes the T-100 Domestic Segment data on a monthly basis (BTS 2024b). These data include information describing the passenger and freight volumes between different airports, carrier name, origin and destination airport ID, and flight date. Data are available from 1990 to the present and can be downloaded through the BTS website. The BTS T-100 data have two files: Domestic Market and Segment data. The database includes data obtained from a 100 percent census of BTS Form 41 schedule submissions by large air carriers. Market data include enplanement data, and segment data include arrivals, departures, freight, and mail. All data from 1995 to 2025 were downloaded. In addition to these two files, BTS provides monthly public and searchable data on U.S. airline on-time performance for 17 major U.S. carriers. These data, which are part of the Department of Transportation's Office of Aviation Consumer Protection, are available for download from the TranStats website (BTS n.d.). While the data have detailed information about flight times, they do not include information about international flights. The monthly data from 1995 to 2025 have been downloaded, but given the lack of international information, they were not used for the rest of this report.

T-100 Segment data cover domestic and international flights, including foreign carriers. The data are monthly by route (origin/destination), carrier, aircraft type, and service class. Multiple types of data are incorporated, including Cargo Service. Class F, 'Scheduled Passenger/Cargo Service F' data were used for this analysis. Carriers not included in the Domestic Market and Segment data with 'DEPARTURES_PERFORMED' = 0 were also removed. The resulting dataset included 9,170,509 segment entries from 1995 through 2025.

BTS data do not contain the point-location of each airport. This information was obtained from OpenFlights (2024), which contains information about more than

67,000 routes between 3,321 airports and 548 airlines. Latitude and longitude for each origin and destination in the BTS data were joined using the International Air Transport Association (IATA) codes. Polar routes were classified as any flight path that crossed a latitude of 75 degrees. Short-, medium-, and long-haul routes were classified by overall distance; short-haul $\leq 1,999$ km, medium-haul = 2,000–5,000 km, and long-haul $\geq 5,001$ km. Polar flights were classified using the `pyproj.geod.npts` function in Python. This function calculates a specified number of equally spaced latitude and longitude points along a geodesic path between the origin and destination. The committee used 64 as the input for the number of points plus the origin and destination. The absolute latitude values of all 66 points were collected, and the route was flagged as polar if the maximum absolute latitude met or exceeded 75. Figure G-1 shows the departures by haul class. The known increase in polar flights after 2000 is visible. The grey sections highlighted in 2020 and 2021 are COVID-19-related reductions in the number of flights. The number of polar flights in 2022 and beyond is known to be lower because of restrictions in Russian air space related to the war in Ukraine. Note that Segment data include every departure between two points and what is on the aircraft between those two points—including diversions, stops, and emergency landings. Market data are flight number-driven or “enplanement data.”

Flight Time

The variable ‘AIR_TIME’ in the T-100 Segment data is the sum of all minutes flown on that combination during the entire month. ‘DEPARTURES_PERFORMED’ is the total number of departures performed for that combination. The average time per flight in minutes can be obtained by $AVG_AIR_TIME = AIR_TIME / DEP_PERFORMED$. Assuming the 1,000-hour, or 60,000-minute, flight time cap for pilots in a given year, the average number of flights per haul class is as follows: short-haul = 714, medium-haul = 260, long-haul = 112, and polar = 75. Average air time was calculated from the BTS T-100 Segment fields as described previously. Average air time was calculated as follows: $AIR_TIME / DEPARTURES_PERFORMED$.

Here AIR_TIME is the monthly aggregate of minutes flown, and DEPARTURES_PERFORMED is the total number of revenue departures for that carrier–route–month combination.

Employment Data

BTS also collects information on the number of flight personnel by carrier and carrier operation region (BTS 2024a) and reports that information in the T_F41_Schedule_P10 tables. Single-year information was downloaded at 5-year intervals and utilized to estimate the number of flight crew by occupation type and carrier. A summary of the number of pilots and copilots by year and airline for the airlines with the most flight crew over this period of time can be found in Figure G-2.

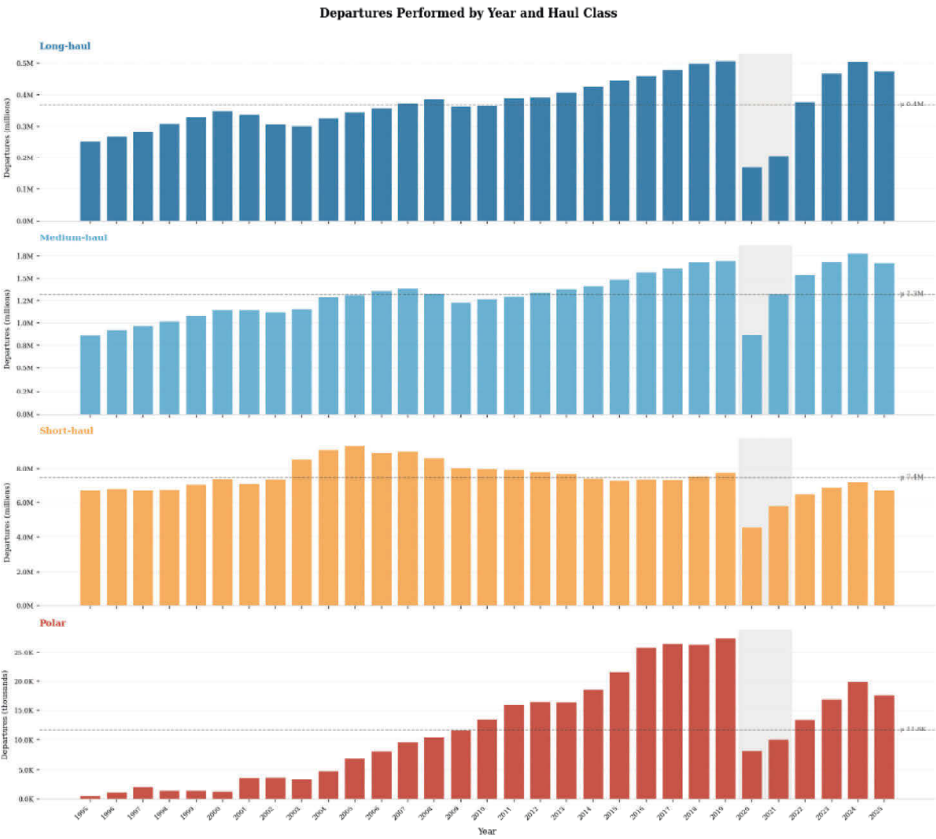


FIGURE G-1 Total number of recorded departures by year and haul class.
SOURCE: BTS T-100 Segment Data. (BTS 2024b).

Occupation Distributions and Career Length

BTS data do not contain detailed information about flight attendants. This information was pulled from multiple sources including the Standard Occupational Classification system (SICCODE n.d.) and Population Reference Bureau (PRB 2018). Age ranges for pilots were based on the annual U.S. Civil Airmen Statistics (FAA 2025, Table 12).

ERR Estimates

Cancer-specific ERR per Gray values were derived from the LSS of Japanese atomic bomb survivors. Primary sources include the following:

- Summary of radiation effects on incidence of solid cancers in the LSS of atomic bomb survivors: 1958–2009 (Brenner et al. 2025); see Table G-3 for updated solid cancer risk estimates.

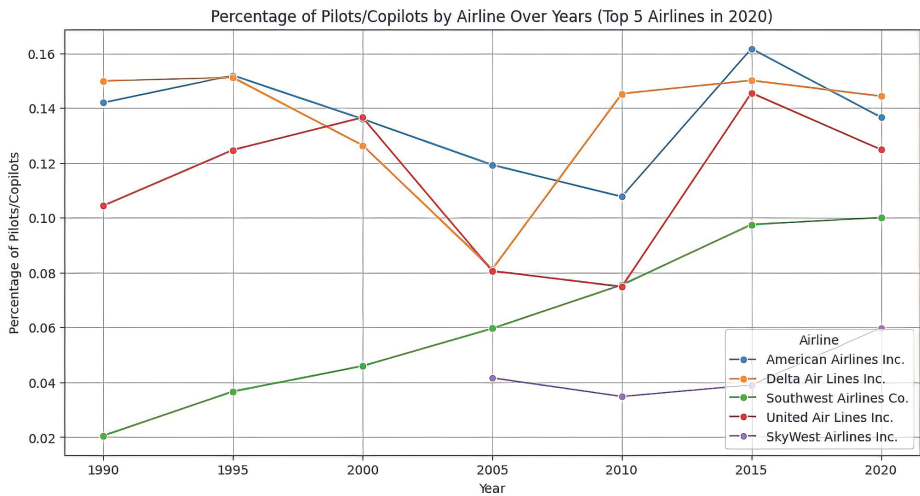


FIGURE G-2 Total number of pilots and copilots by airline and year for single-year snapshots at 5-year intervals between 1990 and 2020.
SOURCE: (BTS 2024a).

- Solid cancer incidence in atomic bomb survivors: 1958–1998 (Preston et al. 2007).

Baseline Cancer Incidence Rates

Age-specific baseline cancer incidence rates were obtained from the Surveillance, Epidemiology, and End Results (SEER) program for 2010. Rates were specified as piecewise constant hazards across four age bands: 20–39, 40–64, 65–74, and 75+ years. The SEER Explorer tool provides rates per 100,000 person-years by cancer site, sex, and age group (NCI 2026).

Conversion from period rates to instantaneous hazards uses the transformation

$$h = \frac{-\log(1 - \min(r \times \Delta t, 0.99))}{\Delta t},$$

where r is the rate per person-year and Δt is the interval length. This accounts for the nonlinear relationship between cumulative incidence and hazard rates over multiyear intervals.

Cosmic Radiation Exposure Parameters

Exposure Distribution for Simulations

To generate the exposure distributions for the simulations, an exposure per minute was calculated. This was done by taking the average exposure values per haul type and

dividing by the average flight time. Exposure values by haul class were extracted from the Chapter 4 calculations for flights during the solar minimum as follows:

- Short-haul: 8.58 μSv
- Medium-haul: 31.05 μSv
- Long-haul: 89.89 μSv (LHR–LAX) and 50.638 μSv (JFK–LAX¹)
- Polar: 113 μSv

Exposure Rate by Haul Class

A haul class–specific exposure rate r_c (μSv per minute) was assigned to each segment based on its haul class c :

$$r_c = \begin{cases} 0.123951 & c = polar \\ \left(\frac{0.1411478 + 0.13266}{2} \right) = 0.136907 & c = long - haul \\ 0.108559 & c = medium - haul \\ 0.062871 & c = short - haul \end{cases}$$

Estimated Exposure per Segment

Estimated exposure (μSv) for each segment is then

$$E = \bar{t} \times r_c.$$

This yields a flight-duration-weighted exposure estimate that varies both by haul class and by the actual average flying time recorded in the T-100 Segment data, capturing differences in route length within each haul class (see Figure G-3). Dose per segment was calculated and used to estimate the mean and standard deviation of exposure for each haul class. This information was then used for the simulations and is summarized in the list below. Values used in simulations are summarized in Table G-4.

Dose for Simulation

See Figures G-3 and G-4 below.

- Short-haul: 600 flights per year (total short-haul/60,000 = 714; adjusted to 600). Average per flight exposure: 0.00528 mSv, standard deviation 0.0026 mSv.
- Medium-haul: 260 flights per year. Average per flight exposure: 0.025071 mSv, standard deviation 0.0058 mSv.
- Long-haul: 112 flights per year. Average per flight exposure: 0.0735 mSv, standard deviation 0.0157 mSv.
- Polar: 75 flights per year. Average per flight exposure: 0.123 mSv, standard deviation 0.0128 mSv.

¹ IATA airport codes for London Heathrow Airport (LHR), Los Angeles International Airport (LAX), and John F. Kennedy International Airport (JFK).

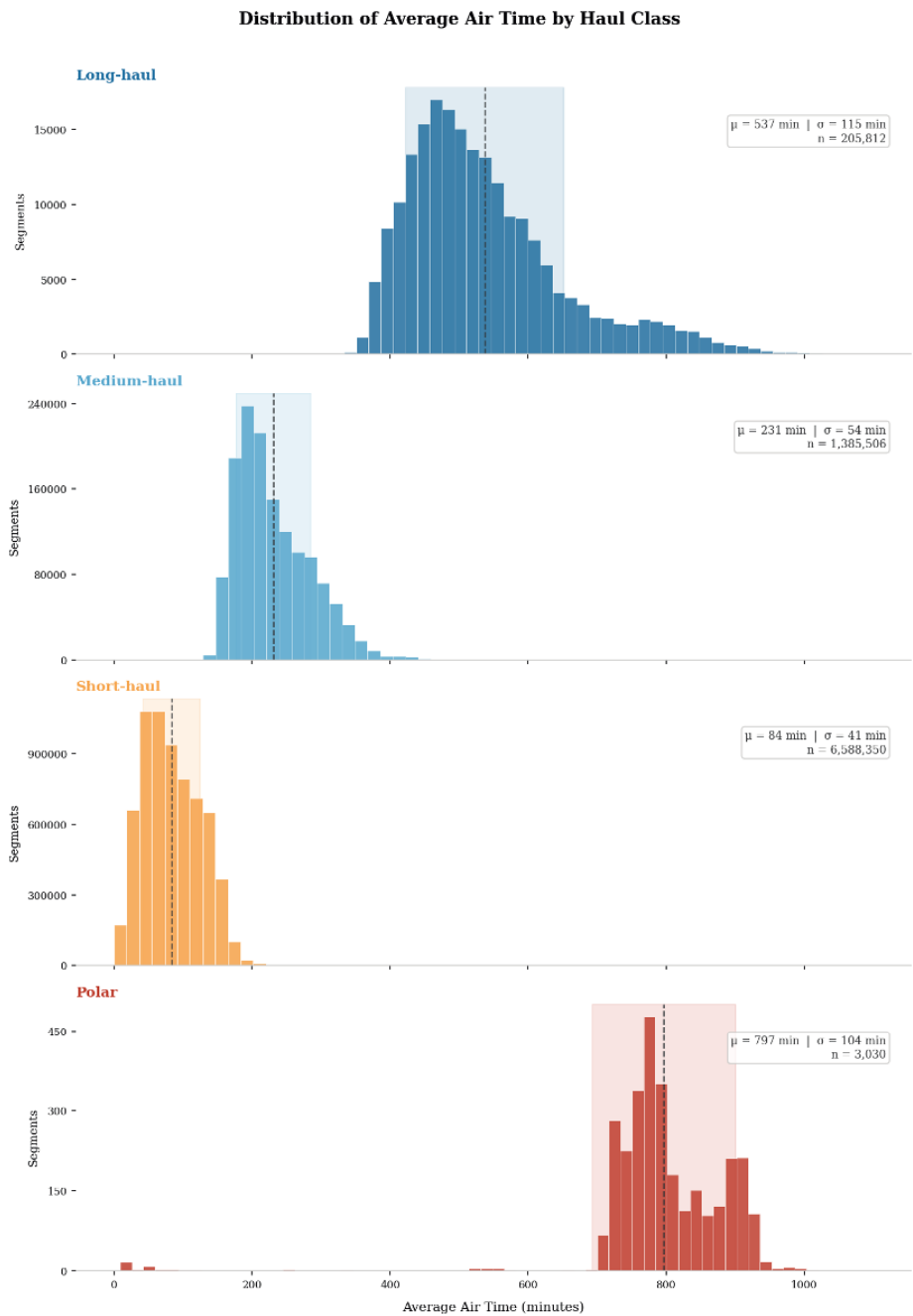


FIGURE G-3 Distribution of air time by haul class.
SOURCE: T-100 Segment data (BTS 2024b).

TABLE G-4 Values Used in Simulations for Per-year Exposure Distributions

Haul Class	Mean (mSv)	GSD
Short-haul	3.168	1.02
Medium-haul	6.52	1.01
Long-haul	8.24	1.02
Polar	9.22	1.01

NOTE: GSD = geometric standard deviation; mSv = millisievert.

In the simulations, annual radiation dose was generated as a time-varying exposure, with a base dose drawn from a lognormal distribution using the route-specific parameters above. To account for uncertainty, two types of error were incorporated:

- Berkson error (random error): geometric standard deviation (GSD) = 1.15, applied as a multiplier to the group dose.
- Classical error (measurement inaccuracy): GSD = 1.20. Dose accumulates over the duration of active employment.

Geographic Coordinate Augmentation

Airport latitude and longitude were sourced from the OpenFlights airports.csv file, which contains 14 columns including IATA, latitude, longitude, altitude, and country. Two copies of the airport’s DataFrame were created:

1. Airports2—The IATA column was renamed to ORIGIN, and latitude/longitude were renamed to o_lat and o_lon. This copy was left-joined to routes on the ORIGIN key.
2. airports_dest—The IATA column was renamed to DEST, and latitude/longitude were renamed to d_lat and d_lon. This copy was left-joined to the result on the DEST key.

After both joins, rows for which any of the four coordinate columns was missing or nonnumeric were dropped, ensuring all subsequent geometric computations receive valid floating-point inputs.

Lognormal Approximation and GSD

Although the yearly total is a sum of individual flight doses, the lognormal distribution is a natural and conventional model for occupational radiation exposure. The sum of independent, identically distributed positive random variables can be approximated as lognormal when the per-flight coefficient of variation (CV) is not negligible. The CV of the yearly total was first computed as follows:

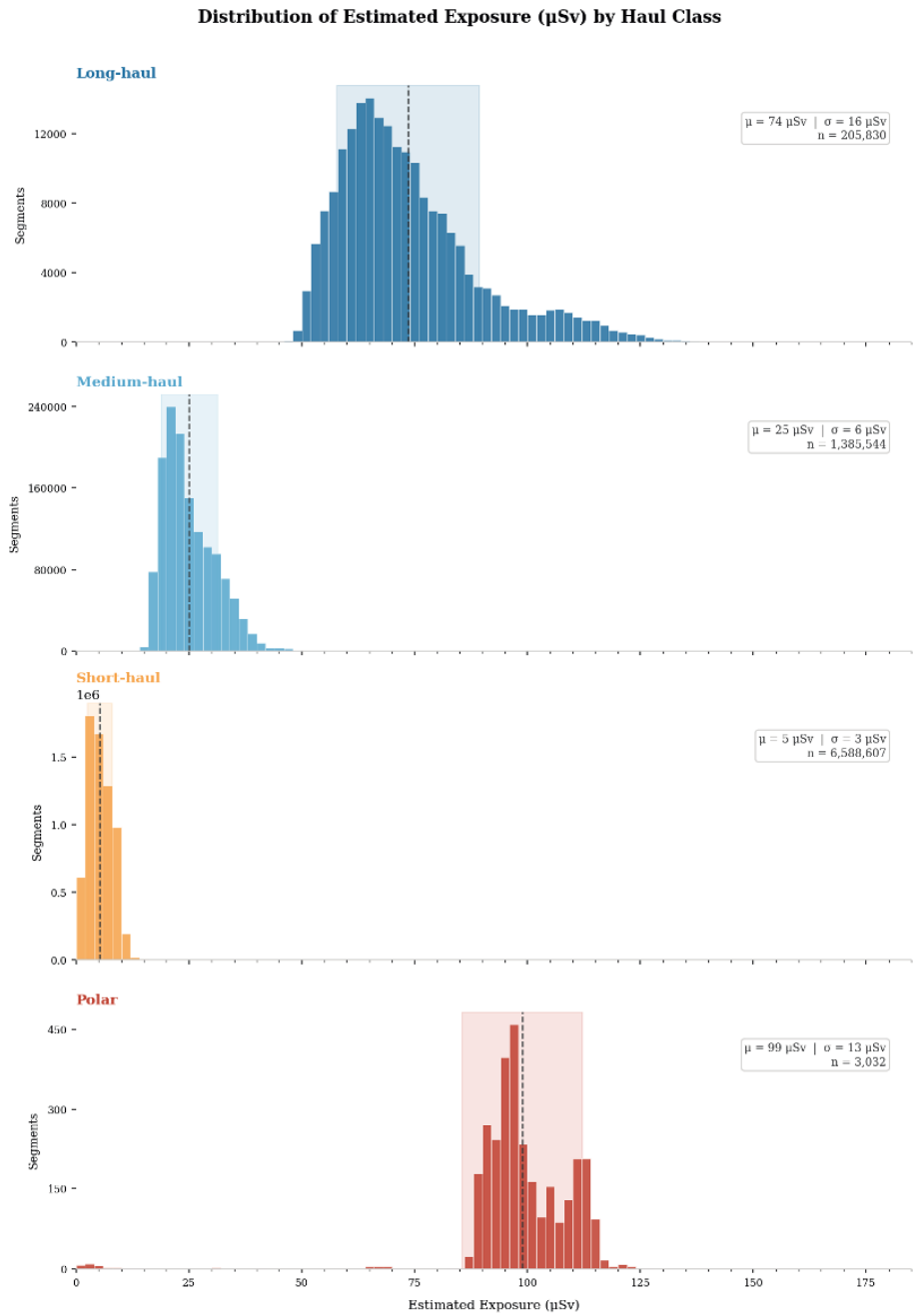


FIGURE G-4 Distribution of exposure estimate by haul class.
SOURCE: T-100 Segment data (BTS 2024b).

$$CV_{yr} = \frac{\sigma_{yr}}{\mu_{yr}}$$

The lognormal shape parameter σ_{ln} (the standard deviation of the log-transformed variable) was then derived from the CV via the moment-matching identity:

$$\sigma_{ln} = \sqrt{\ln(1 + CV_{yr}^2)}$$

The GSD was obtained by exponentiating σ_{ln} :

$$GSD = e^{\sigma_{ln}}$$

A GSD close to 1.0 indicates a near-symmetric distribution with low relative variability, while larger values indicate greater spread on a multiplicative scale. Because the yearly total was formed by summing many independent flights, CV_{yr} was substantially smaller than the per-flight CV, and the resulting GSD values were correspondingly modest.

Simulation Methodology

Cohort Generation

Each simulated flight crewmember was generated with the following characteristics and demographics.

Occupation and Demographics

- Approximate sex distribution: Flight attendants 80% female, pilots 10% female (U.S. Census Bureau 2023).
- Age at hire: Triangular distribution was used as an approximate because complete data are not readily available. The continuous probability distribution is defined by a minimum, maximum, and mode, and probabilities are calculated by finding the area under the triangular probability density function. Flight attendants: min = 18, mode = 23, max = 40; pilots: min = 20, mode = 25, max = 40 (FAA 2025).

Employment Duration

U.S. flight crew can work until age 65. Career length for flight crew generally has high turnover at entry-level positions and sustained, stable employment for individuals who do not leave during the first 5 years. Therefore, employment duration was modeled using a mixture model reflecting the bimodal distribution observed in aviation employment (Grajewski et al. 2016; McNeely et al. 2018):

- 50% probability of short career: Gamma($\alpha = 2$, $\beta = 0.67$), mean ≈ 3 years
- 50% probability of long career: Gamma($\alpha = 5$, $\beta = 0.23$), mean ≈ 22 years

This captures both early attrition and full-career workers. Duration was bounded between 0.5 and 45 years.

Health and Lifestyle Factors

The committee notes that the modeled estimates may understate potential impacts. Parameter values drawn from the literature were selected conservatively with respect to adverse health outcomes, and certain inputs were rounded to reflect this approach.

- Smoking: The study by McNeely and colleagues (2018) was used for flight attendants and pilots (Current = 8%, Former = 31%, Never = 61%).² These rates are lower than the general population.
- Smoking relative risks (RR): Current smoker RR = 15.0, former smoker RR = 5.0 for lung cancer (CDC 2024a),³ and current and former smokers RR = 2.0 for bladder cancer (NCCDPHP 2014).
- Circadian disruption: 100% flight attendants exposed, 85% pilots exposed (Grajewski et al. 2016; Samuelsson et al. 2018; Wen et al. 2023).⁴
- Nulliparity: 28% of female flight attendants, RR = 1.44 for breast cancer (McNeely et al. 2018).⁵

Dose Accumulation Model

Annual radiation dose is generated as a time-varying exposure with the following components:

1. Base dose from lognormal distribution: The base dose values were assigned based on the route type assigned to the flight crew, which matched the distribution of route types during this period of time period 1:

$$X \sim \text{Lognormal}(\log(\text{mean}), \log(\text{GSD})),$$

where the base dose is selected from a lognormally distributed random variable with route-specific mean (mSv) and spread (GSD).

2. Berkson error (group-level assignment): Berkson error is random error, or misclassification, in measurement. This error type causes little or no bias in measurement but can reduce the power of a study. Therefore, it was included

² These values are derived from McNeely and colleagues (2018) by summing values for both sexes and taking the percentage of the total population. Never smokers is the difference of % (100 – current% – former %).

³ The Centers for Disease Control and Prevention report that cigarette smoking is associated with a 15- to 30-fold increase in lung cancer risk and mortality relative to nonsmoking; an RR of 15 is assumed here, indicating that risk among the exposed population is 15 times that of the unexposed population.

⁴ These values are derived from the cited publications to provide conservative parameters for the committee's analysis.

⁵ THESE VALUES ARE DERIVED FROM MCNEELY AND COLLEAGUES (2018) BY DIVIDING THE TOTAL NULLIPAROUS BY THE TOTAL PARITY NUMBERS OF LIFETIME JOB TENURE.

in the simulations to provide a conservative estimate of power (Ackerman et al. 2024; Armstrong 1998; Heidi et al. 2004):

$$D_{group} = X \times \varepsilon_B, \quad \varepsilon_B \sim \text{Lognormal}\left(0, \log(1.15)\right),$$

where X is the base dose for each route-type and ε_B is the noise-term drawn from a lognormal distribution with mean = 0 (no systematic bias) and spread = $\log(1.15)$. This means that the exposure value for each route type stays within $\pm 32\%$ of the base dose most of the time.

3. Classical error (observation): Classical error occurs when measurements vary around the true value and result in attenuation of the true signal. This type of error normally arises from instrument inaccuracy (Ackerman et al. 2024; Armstrong 1998; Heidi et al. 2004) and biases the dose-response toward 0. It was included in the simulations to account for known measurement imprecision:

$$D_{obs} = D_{true} \times \varepsilon_C, \quad \varepsilon_C \sim \text{Lognormal}\left(0, \log(1.20)\right),$$

where D_{obs} is the observed dose per person-year, and it deviates from the true underlying dose, D_{true} , by a multiplicative random error term ε_C , and ε_C is drawn from a lognormal distribution with mean = 0 and spread = $\log(1.20)$.

4. Year-to-year variation: The dose will vary over time due to solar cycles, meteorological variability, and other factors:

$$D_{year} = D_{group} \times \varepsilon_V, \quad \varepsilon_V \sim \text{Lognormal}\left(0, \log(1.25)\right),$$

where D_{year} is the dose for a specific year, D_{group} is the base dose input from the prior equations, and ε_V is the random year-to-year variability term that is drawn from a lognormal distribution with mean = 0 and spread = $\log(1.25)$. Future simulations should consider other ways to incorporate the 11-year solar minimum and maximum cycles that modulate exposure.

Dose accumulates only during active employment. For cancer risk modeling, lagged cumulative dose was calculated by summing doses received more than L years prior to each time point, where L is cancer-type-specific (2 years for leukemia, 5 years for brain/central nervous system cancers, and 10 years for solid tumors).

HWE Modeling

HWE is modeled through individual-level frailty rather than blanket rate multipliers. This accounts for the fact that the HWE varies by age/time since hire and other individual-level factors. Frailty has a multiplicative effect on the baseline hazard function (Balan and Putter 2020). Individuals with a frailty >1 are less healthy, while individuals with a frailty <1 are more healthy. Frailty was set to 0.8 on average, with a lower bound of 0.4 and a standard deviation of 0.15. The committee chose these values for its calculations to represent a likely HWE for flight crew:

- Entry frailty: At hire, individuals receive a frailty value from $N(0.80, 0.15)$, truncated at 0.4 minimum. Frailty < 1.0 indicates lower baseline risk than the general population.
- Frailty convergence: Over time, frailty drifts toward 1.0 (general population level) at 2% per year, representing attenuation of the HWE with age and time since hire:

$$frailty_{t+1} = frailty_t + (1 - frailty_t) \times 0.02$$

Outcome Simulation and Event Generation

Hazard Model

Cancer incidence was simulated using an ERR multiplicative model. The total hazard at any time point is

$$h(t) = h_0(\text{age}) \times frailty(t) \times \left[1 + ERR \times D_{lagged}(t) \right] \times HR_{smoking} \times HR_{circadian} \times HR_{nulliparity},$$

where $h_0(\text{age})$ is the age-specific baseline hazard from SEER rates, $D_{lagged}(t)$ is cumulative lagged dose, and the HR terms are cancer-specific confounder adjustments applied when relevant.

Event Generation Process

Follow-up was simulated in 1-year intervals from age at hire until the earliest of cancer diagnosis, loss to follow-up (LTFU), death, or study end (age 85 or 50 years of calendar follow-up). At each interval, the following are needed:

1. Calculate interval-specific hazard using the model above.
2. Convert to probability: $P(\text{event}) = 1 - \exp(-h \times \Delta t)$.
3. Draw Bernoulli trial to determine if event occurs.
4. If event occurs, draw exact time within interval from exponential distribution.
5. Consider that registry sensitivity (95%) determines event detection—undetected events are treated as censored. This value is realistic if the identifiers can be obtained as part of study enrollment. It is most realistic for mortality studies.

Loss to Follow-up

LTFU was modeled as a competing risk with rates of 0.5 percent per year during active employment and 0.8 percent per year post-employment. These relatively low rates assume good follow-up through the linkages of personally identifiable information using Research Data Center linkages. This can be varied to assess the effect on the power calculations.

Statistical Analysis

Data Structure

The simulation generates person-year level data with one record per year of follow-up. This long-format structure captures time-varying dose accumulation. For computational efficiency, data were collapsed to 2-year intervals prior to model fitting using the `data.table` package, preserving cumulative exposure totals and taking the maximum lagged dose within each interval.

Cox Proportional Hazards Model

Each simulated cohort was analyzed using Cox regression with attained age as the timescale (age at interval start and end as `Surv()` endpoints). Models were fit without storing the design matrix (X), the response object (Y), or the model frame in the output object (`X = FALSE`, `Y = FALSE`, `model = FALSE`). This was done to reduce memory usage and the file size of the object, as the long files are very large and can cause memory issues. The primary exposure is lagged cumulative dose in Gray. Model specification varies by cancer type:

- Breast cancer: `dose_gy + circadian_exposed + nulliparous`
- Lung/bladder cancer: `dose_gy + factor(smoking)`
- Other cancers: `dose_gy` (unadjusted)

Power Calculation

Statistical power is estimated as the proportion of simulated cohorts achieving $p < 0.10$ for the dose coefficient (Wald test). For each cancer/sex combination and sample size, multiple simulations were conducted in parallel.

Computational Implementation

Parallelization

The simulation leveraged parallel processing via the `parallel` package using `mclapply`. Worker count was determined from SLURM environment variables (`SLURM_CPUS_PER_TASK` or `SLURM_NTASKS`) when running on high-performance computing clusters, falling back to `detectCores()-1` for local execution. Maximum cores were capped at 64.

Reproducibility

Each worker received a unique random seed via the `mc.set.seed` mechanism. Setting `mc.set.seed = TRUE` (the default) ensures that the random number streams across

workers are independent and that results are reproducible across runs given the same base seed.

Dependencies

The following R packages are required:

- survival: Cox proportional hazards modeling
- parallel: multicore process forking via mclapply
- dplyr: data manipulation (bind_rows)
- data.table: efficient data collapsing

Output Files

The script generates three output files:

1. simulation_power_results_revised.RData: complete R workspace with all result objects
2. simulation_power_summary_revised.csv: summary table of power by cancer type and sample size
3. required_sample_sizes_revised.csv: estimated N for 80% power by cancer site

Reproducibility and Replication

Random Seed Control

The base seed was set to 1568 (set.seed(base_seed)). Within parallel simulations, each iteration uses base_seed + iteration_number, ensuring reproducible results across runs while avoiding correlation between parallel workers.

Replication Steps

To replicate this analysis, the following steps are needed:

1. Install required packages: survival, parallel, dplyr, and data.table.
2. Ensure consistent R version (developed under R 4.5.1).
3. Set working directory to desired output location.
4. Run script via Rscript script_name.R (command line) or source() in R.
5. For SLURM, submit with appropriate –cpus-per-task allocation.

Modifying Simulation Parameters

Key parameters were defined in named lists at the beginning of the script (exposure_params, employment_params, health_params, hwe_params, followup_params)

and can be modified to conduct sensitivity analyses. The cancer_params_all data frame contains ERR values and can be updated with alternative risk estimates.

Limitations and Assumptions

Finally, this is a series of assumptions used for the calculations and the associated limitations acknowledged by the committee:

- ERR values from the LSS may not directly transfer to chronic low-dose exposures; dose-rate effectiveness factors are not explicitly modeled.
- Competing mortality is not currently modeled. This was considered but deemed too complicated for the purposes of the report.
- Route-type dose distributions are approximations based on available dosimetry literature.
- Year-to-year dose variation GSD (1.25) is assumed without direct empirical validation.
- The HWE model assumes frailty convergence without accounting for survivor bias selection.
- Model assumes proportional hazards; time-varying effect modification by age or dose is not examined.

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