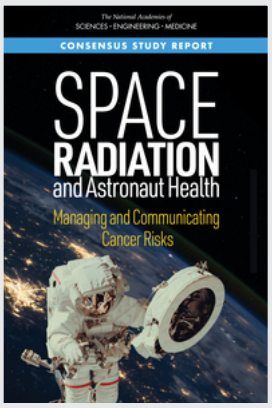

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SPACE RADIATION
and Astronaut Health
Managing and Communicating Cancer Risks

Committee on Assessment of Strategies for Managing Cancer Risks Associated with Radiation Exposure During Crewed Space Missions

Board on Health Sciences Policy

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Health and Medicine Division

Nuclear and Radiation Studies Board

Division on Earth and Life Studies

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COMMITTEE ON ASSESMENT OF STRATEGIES FOR MANAGING CANCER RISKS ASSOCIATED WITH RADIATION EXPOSURE DURING CREWED SPACE MISSIONS

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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:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions

or recommendations of this report, nor did they see the final draft before its release. The review of this report was overseen by **ELI Y. ADASHI,** Brown University, and **JOE W. GRAY,** Oregon Health & Science University. 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.

Preface

Understanding and mitigating the health effects of exposure to space radiation has challenged scientists and engineers for decades. While science has advanced our knowledge of the effects of radiation on the human body on land and in space, uncertainties remain regarding how best to assess, manage, and communicate radiation risks to those affected.

The present study—focused on space radiation and astronaut health—occurs at a time when plans are being developed for long-duration spaceflight missions beyond low Earth orbit to the Moon and Mars. These missions, particularly to Mars, could introduce health risks and challenges unlike others experienced by previous astronauts and their space agencies. Our study committee took on the task of providing advice to NASA on the space radiation health standard with enthusiasm and a sense of significance, as the implementation of the standard will have a measurable impact on astronaut health, opportunity for spaceflights, and overall mission viability.

The committee worked to develop this report in an objective manner based on the options and suggested approaches for updating the space radiation standard provided by the National Aeronautics and Space Administration (NASA), available scientific evidence, and individual committee member expertise and knowledge. During this process we were specifically attendant to the considerable importance of the uncertainties and developing knowledge around radiation and cancer risks, as well as the uniquely complex and challenging mission of NASA. As astronaut Ellison Onizuka's words are memorialized on the last page of every U.S. passport, "Every generation has the obligation to free men's minds for a look at new worlds … to look out from a higher plateau than the last generation."

NASA has many tools and resources for continued evaluation and reconsideration of health standards. It is the committee's hope that this report provides an incremental step forward for NASA and its astronauts in the planning of space travel farther afield.

Hedvig "Hedi" Hricak, *Chair*
R. Julian Preston, *Vice Chair*
Committee on Assessment of Strategies for Managing Cancer Risks Associated with Radiation Exposure During Crewed Space Missions

Acknowledgments

The committee thanks the National Aeronautics and Space Administration (NASA) for sponsoring this study and engaging with the committee in public meetings and providing thoughtful, timely responses to the committee's questions and requests for information throughout the study process. We are appreciative of NASA's willingness to engage with external experts on a complex issue such as space radiation as the safety and success of space travel is of national interest. We especially thank NASA staff—David Francisco and Edward Semones—for providing a technical review of portions of this report describing NASA programs and processes. The committee is also grateful to members of the International Commission on Radiological Protection Task Group 115 on Risk and Dose Assessment for Radiological Protection of Astronauts—particularly presenters Marco Durante and Werner Rühm—for sharing information with the committee during the April 2021 public webinar on international space radiation dose limits. The speakers provided valuable information and perspectives on the complex work of considering standards for spaceflight across international agencies.

It was our great privilege to work with such dedicated committee members, each of whom thoroughly engaged in the study, generously shared their expertise, and contributed significant time and effort to this endeavor. This was a complex task, and the committee members truly stepped up to meet the challenge. Their reasoned and thoughtful discussions made this report possible.

We were all fortunate to work with a diligent and outstanding team of National Academies of Sciences, Engineering, and Medicine staff, and

we deeply thank Rebecca English, Leah Cairns, Ourania Kosti, Claire Giammaria, Ruth Cooper, and Kendall Logan, led by Andrew Pope and Sharyl Nass, senior board directors in the Health and Medicine Division. We also sincerely thank Michael Zierler for his thoughtful writing and editing work, Rebecca Morgan of the National Academies Research Center staff for her assistance with fact-checking the report, and Michael Berrios for thoughtful Japanese-English translation.

Contents

Acronyms and Abbreviations

ALARA	as low as is reasonably achievable
ARS	acute radiation syndrome
DDREF	dose and dose-rate effectiveness factor
DREF	dose-rate effect
EAR	excess absolute risk
ERR	excess relative risk
ESA	European Space Agency
GCR	galactic cosmic rays
HMTA	Health and Medical Technical Authority
HZE	high-energy (particles)
ICRP	International Commission on Radiological Protection
ISS	International Space Station
JAXA	Japanese Space Agency
LD_{50}	lethal dose to 50 percent of the human population
LDEF	low dose effect
LEO	low Earth orbit
LET	linear energy transfer
LSS	Life Span Study

mGy	milligray
mSv	millisievert
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection and Measurements
NSCR	NASA Space Cancer Risk
OSHA	Occupational Safety and Health Administration
PMD	permissible mission duration
RADS	radiation-attributed decrease of survival
RBE	relative biological effectiveness
REIC	risk of exposure-induced cancer
REID	risk of exposure-induced death
RSA	Russian Space Agency
SPE	solar particle event
SPEL	space permissible exposure limit

Summary[1]

The National Aeronautics and Space Administration (NASA) works to realize the benefits of space exploration and these benefits accrue to society through technological and scientific advances, as well as national and international pride and collaboration. Astronauts are in a unique class of employees, as they work for an agency whose mission is exploration. This implies both a high level of risk and uncertainty as astronauts explore space, as well as NASA's duty to care for their safety during a mission and throughout an astronaut's lifetime. NASA has long recognized that crewed space missions carry a range of unique hazards and challenges, including health-related risks. As NASA prepares for space exploration missions that extend to greater distances into our solar system and for longer durations, including missions to the Moon and Mars, these challenges are amplified.

Assessing, managing, and communicating radiation risks for space exploration is challenging because of incomplete knowledge of the complicated radiation environment in space, limited data on the cellular damage mechanisms resulting from radiation, absence of direct observations resulting from epidemiological studies, individual characteristics affecting susceptibility, and complex concepts associated with radiation risk ascertainment.

Beyond the protection of Earth's magnetic field, astronauts are exposed to a complex radiation environment composed of galactic cosmic rays (GCR) and solar particle events (SPEs). When humans are exposed to ionizing radiation, in general terms, the risk of cancer increases with increasing dose of

[1] This Summary does not include references. Citations for the discussion presented in the Summary appear in the subsequent report chapters.

radiation. Cancer risk projections have largely been based on the epidemiology data from the Life Span Study (LSS) of the Japanese atomic bomb survivors. There remain a number of uncertainties associated with the development of risk estimates from epidemiological studies, including the LSS data.

The NASA space radiation health standard sets a permissible limit for spaceflight radiation exposure, which functions to prevent in-flight risks that would jeopardize mission success and to limit chronic risks to acceptable levels based on legal, ethical or moral, and financial considerations. NASA notes that the standard is a quantifiable limit of exposure to a component of the environment during spaceflight over a given length of time, as in lifetime radiation exposure.

This report reviews and assesses NASA's processes for long-term risk assessment and management for currently anticipated crewed missions with respect to radiation-induced cancer risk and specifically considers NASA's proposed updates to the space radiation standard (see Box S-1).

To accomplish the task for this NASA-sponsored study, the National Academies of Sciences, Engineering, and Medicine (the National Academies) empaneled a committee of 18 members with expertise in the areas of radiation and cancer biology; biostatistics and mathematical modeling; risk communication, management, and uncertainty; medical genetics; clinical medicine; ethics; occupational health and safety; radiation dosimetry and physics; epidemiology; and two former astronauts with clinical medicine expertise (see Appendix B for biographical sketches of the committee members and staff).

NASA provided additional context and clarity on what was in, and out, of scope for this study during public presentations and discussion with the committee (see Box S-2).

NASA'S CURRENT SPACE RADIATION HEALTH STANDARD

The NASA Space Permissible Exposure Limit for Spaceflight Radiation Exposure Standard 4.2.10 ("the standard") informs crew mission assignments, crew health care (preflight, in-flight, and postflight), space vehicle design and layout, and mission operational profiles for human spaceflight missions. The standard currently states:

> Planned career exposure to ionizing radiation shall not exceed 3 percent risk of exposure-induced death (REID) for cancer mortality at a 95 percent confidence level[2] to limit the cumulative effective dose (in units of Sievert) received by an astronaut throughout his or her career.

[2] Based on the committee's review of NASA's document NASA/TP-2020-5008710, Section II.I, "95 percent confidence level" refers to the 97.5 percentile (also the upper limit of a 95 percent probability interval) of an uncertainty distribution of REID. This distribution is obtained by varying the input parameters of the NSCR NASA risk model according to "parameter uncertainty distributions" determined by NASA based on expert judgment.

BOX S-1
Statement of Task

An ad hoc committee of the National Academies of Sciences, Engineering, and Medicine will convene to review and assess the National Aeronautics and Space Administration's (NASA's) processes for long-term risk assessment and management for currently anticipated crewed missions with respect to cancer (excluding current and post mission effects of radiation) due to exposure to space radiation. Specifically, the committee will:

- Review the data on the association between radiation exposure and cancer risk, and consider the best ways for NASA to apply the data to manage the risk assessment process to currently anticipated crewed missions. With respect to NASA processes, the review will consider a broad range of factors and analytic techniques that may include uncertainty management utilizing confidence intervals around cancer mortality, radiation quality factor determination and utilization, and the use of the dose and dose-rate effectiveness factor.
- Review and assess NASA's proposed process and strategies for managing cancer risks as a result of exposure to space radiation. Provide a written report with recommendations on the best process and strategies for NASA to use in addressing and managing the uncertainties of long-term cancer risks due to radiation exposure in crewed space missions beyond low Earth orbit.

In conducting the review, the committee will consider the following:

- NASA's present processes for assessing uncertainty from radiation risk exposure in crewed space missions compared to terrestrial methods for clinical applications, and how data from ground-based research on the relationship between radiation exposure and cancer risk should inform NASA's approach to risk management for crewed missions.
- How to consistently manage the uncertainty of space radiation exposure risk assessments across spaceflight with respect to anticipated NASA space missions, and known clinical risks.
- How to express what is needed in the form of a radiation risk management process or approach NASA could apply to determine astronaut eligibility for crewed missions.

Based on the committee's review and assessment of NASA's proposed strategies, the committee will make recommendations to NASA for assessing and managing the processes for addressing space radiation risk for astronauts.

BOX S-2
Additional Context on the Study Scope

The National Aeronautics and Space Administration (NASA) asked the committee to review and assess the agency's proposed updates to the space radiation health standard. During the course of the study the committee considered white papers provided by NASA, public presentations and discussion with NASA leaders, as well as the scientific literature and relevant reports from other expert panels on this topic. This committee did not conduct original data analysis.

Specific questions from NASA to the committee included

- Are the proposed bands in the dose-based standard an effective method to control and communicate the risk?
- How should the dose/risk bands be set? Options include
  - Continue utilizing a 95 percent confidence level
  - Utilize a 75 percent confidence level
  - Utilize the mean and also communicate an interval (95 percent, 75 percent, or other)
- How should the standard calculate the risk of exposure-induced cancer concerning sex differences? Options include
  - Sex averaged for non-sex organs
  - Average for lung and non-sex organs
  - Utilize the most protective case
- Are bioethics considerations adequately addressed?

Due to prior and on-going reviews by NASA, the International Commission on Radiological Protection, the National Council on Radiation Protection and Measurements, and the National Academies, NASA specified that they were *not* asking this committee to

- Develop a standard;
- Perform a detailed evaluation of the NASA stochastic cancer model;
- Assess NASA research approaches;
- Assess cardiovascular and/or central nervous system risk;
- Assess aspects of genetic testing; or
- Assess aspects of informed consent and other legal considerations.

NASA's current cancer risk model, NASA Space Cancer Risk (NSCR) 2012 provides the output that NASA uses to set the 3 percent risk of exposure-induced death (REID) for cancer mortality within the standard. REID estimates the probability that an individual will die from cancer associated with the radiation exposure. For example, in this report, 3 percent REID implies that within a cohort of 100 astronauts, 3 are likely to die of radiation-induced cancer at some point in their lifetime. The current standard is intended to apply only to radiation exposure incurred during missions in low Earth orbit (LEO).

Why NASA Is Considering Revisions to the Current Radiation Exposure Standard

NASA has indicated that the primary reason for updating the space radiation exposure standard is because the current standard is for LEO missions exclusively. Now that the Artemis lunar mission, additional longer-duration lunar missions, and missions to Mars are in planning and development, NASA needs to define a radiation exposure standard that considers both missions in LEO and missions into deeper space. NASA is also aware that recent updates from epidemiological and radiobiological studies on sex differences in radiation-induced cancer risks may affect its cancer risk assessment model and what is an acceptable level of radiation exposure for astronauts. NASA is seeking advice on the longstanding concern that the current radiation standard results in an unequal work environment that limits female astronauts to shorter space careers because of scientific data indicating that females have an increased risk of cancer from exposure to ionizing radiation compared to men.

NASA'S PROPOSED SPACE RADIATION HEALTH STANDARD

NASA provided the committee with details about the possible changes to its space radiation exposure standard and the draft language of the proposed changes to section 4.2.10.1 of the standard (see Box S-3):

- NASA is proposing to move from a standard built on and conveyed as a risk limit to a standard that is still based on risk but conveyed as a dose-based limit.
- The proposed maximum allowable effective dose has been determined by applying the cancer risk model, NSCR 2012, to the most susceptible case—that of a 35-year-old female—to calculate her mean REID and REIC. These acceptable mean REID values were converted to effective-dose values.
- NASA intends to use a mean 3 percent REID as the basis for the dose-based limit. Hence, for all astronauts, the maximum allowable space radiation exposure would be the effective-dose equivalent for a 35-year-old female astronaut whose mean REID is at 3 percent.
- The standard would delineate an effective-dose career limit of approximately 600 millisieverts (mSv)[3] that applies equally to male and female astronauts, regardless of an astronaut's age.

[3] NASA has indicated that the proposed limit of 600 mSv is an approximate value and will be verified prior to establishing a new standard. The final standard will be +/– 10 percent of the 600 mSv estimate.

BOX S-3
NASA's Proposed Language for Revised Spaceflight Radiation Permissible Exposure Limit

An individual astronaut's total career effective radiation dose attributable to spaceflight radiation exposure shall be less than 600 mSv. This limit is universal for all ages and sexes.

The total career dose limit is based on ensuring all astronauts (inclusive of all ages and sexes) remain below 3 percent mean risk of cancer mortality (REID) above the non-exposed baseline mean. Individual astronaut career dose includes all past spaceflight radiation exposures, NASA biomedical research exposures, plus the projected exposure for an upcoming mission. Any total exposure (which includes past exposures plus projected exposure) that exceeds the limit would require a waiver by the agency prior to the mission.

Contemporary space exploration is an increasingly cooperative effort. Multiple companies are developing their own space vehicles and business plans, and international collaborations have propelled space exploration efforts. Compared to other international space agencies, both the current and proposed NASA standards are generally more restrictive with respect to career dose limits (see Table S-1).

Considering 3 Percent REID

While 3 percent REID has been used by NASA since the 1989 NCRP report, the committee discussed that it may be time for NASA to reconsider the level of REID on which to base the standard. The initial occupation hazards that were used to decide on 3 percent have changed and are constantly evolving. Indeed, NCRP Report No. 132 noted that the use of comparisons to fatalities in the "less-safe" industries, such as mining and agriculture, in the 1989 NCRP report was no longer viable due to the large improvements made in ground-based occupational safety.

3 percent REID also exceeds the current level of risk in other high-hazard occupations in the United States and could be due for reconsideration by NASA and other external experts. Though not directly comparable, risk of fatal occupational injury is more than an order of magnitude lower than a 3 percent REID for hazardous occupations. NASA is unique in its mission of space exploration and discovery. Another unique feature that sets the agency apart from traditional terrestrial employers subject to federal occupational safety regulations is that NASA is self-regulating and uses its own frameworks to set protective standards in order to minimize, manage, and effectively communicate risks of space

TABLE S-1 Radiation Exposure Career Limits Summary: International Space Station Partner Agencies

Space Agency	Career Dose Limit	Sex/Age Dependency
Canadian Space Agency	1,000 mSv	No sex or age dependency
European Space Agency	1,000 mSv	No sex or age dependency
Russian Federal Space Agency	1,000 mSv	No sex or age dependency
Japanese Aerospace Exploration Agency	3 percent REID @ the mean	Yes Lower limit: 500 mSv for 27- to 30-year-old female Upper limit: 1,000 mSv for > 46-year-old male
National Aeronautics and Space Administration (**current**)	3 percent REID @ the 95 percent confidence level	Yes Lower limit: ~180 mSv for 30-year-old female Upper limit: ~700 mSv for 60-year-old male
National Aeronautics and Space Administration (**proposed update**)	600 mSv[a]	No sex or age dependency

[a] Proposed career dose limit. Could be exceeded with individual waiver.

travel to astronauts. Views also differ on the appropriateness of comparing NASA to terrestrial occupational standards given the different nature of work, the work environment, and relationship between employer and employee.

NASA's limit of 3 percent REID was taken as a starting point for this committee's work as it was not part of the study task to consider NASA's underlying risk model or the use of any particular REID limit. However, the committee believes an important, near term opportunity exists for NASA to conduct an independent analysis of the validity of 3 percent REID.

COMMITTEE'S ANALYSIS OF NASA'S PROPOSED SPACE RADIATION EXPOSURE HEALTH STANDARD

The committee's analysis includes scientific and ethical considerations related to the components that make up the proposed revised standard as well as the implications of their relationship and combination as part of a new health standard.

Considering the Interconnected Components of the Proposed Standard

REID informs or serves as the basis for the three components of the proposed revised radiation standard. The three components are interconnected

but each raises ethics and policy issues separately and when combined into the proposed standard:

1. Commitment to a single standard for male and female astronauts;
2. Selection of the age and sex category on which to base the standard; and
3. Choices made in calculating dose threshold. That is, setting the permissible exposure standard based on the mean, median, 95 percent or 75 percent confidence level of REID.

Notably, a commitment to a single standard requires that standard to have a reference point and justification for that choice, so 1 and 2 are linked to each other more closely than to 3. All three components taken together determine the acceptable dose to adopt for the standard.

Commitment to a Single Standard for Male and Female Astronauts

In a 2014 report, the Institute of Medicine (IOM) recommended that NASA should implement an ethics framework and its concomitant responsibilities as part of the agency's policies and procedures. The report included a recommendation to "provide equality of opportunity for participation in long duration and exploration spaceflights to the fullest extent possible." For this 2020–2021 study committee's consideration, NASA has proposed a revised radiation standard that is responsive to the 2014 committee's recommendation by proposing a single radiation standard that applies to all astronauts independent of sex and age. Such a single standard would provide equality of opportunity, at least to the extent that it avoids radiation exposure standards that differ by sex and result in differential opportunities for participation in crewed spaceflights. Principles of compensatory justice and distributive justice are also served by a single standard.

The decision to apply a single dose-based limit to all astronauts, regardless of sex and age, also aligns NASA with the majority of its international space agency partners.

Selection of the Age and Sex Category on Which to Base the Standard

NASA is proposing that the universal dose-based standard be determined based on the mean REID using a 35-year-old female as the reference. NASA indicates this is the "most protective" approach because this age group is projected to be at the highest risk. Therefore, setting the standard based on the 35-year-old female would be the most protective for any given age and sex. Compared to the option of calculating the REID based on sex-averaged for non-sex organs or the average for lung and non-sex organs,

calculating the REID using a 35-year-old female is a better option because it is more straightforward and more protective based on current science. On one hand, this approach sets a single, clear and consistent dose limit for all astronauts; but on the other hand it may result in a more restrictive limit than a more individualized approach would allow.

It is reasonable for NASA, in its role as a government agency asking astronauts to accept risk in the interest of society, to adopt an approach that provides the highest level of protection to those at greatest risk of radiation exposure-based harms, acting on the ethics principle of non-maleficence (preventing or removing harm to others).

Choices Made in Calculating Dose Threshold

NASA proposes to utilize the mean value for REID and resulting exposure threshold calculations. NASA's decision to use the mean REID would be a change from its current standard, which is based on the 97.5th percentile of REID. Other options that NASA considered include using the median, 75 percent or 95 percent. Among the considerations that suggest the approach of evaluating the risk at the mean rather than out in the tails of the uncertainty distribution are that the mean, while still imperfect, is representative of expected exposures, more stable and consistent than a quantile, more understandable by a wider audience, and could provide a better basis for decision making.

As is well recognized by NASA, estimation of REID associated with exposure to space radiation involves multiple sources of uncertainty. The mean of the REID distribution generated from NASA ensemble modeling is estimated with lower uncertainty, compared with the currently used 97.5th percentile of this distribution.

Using the mean will warrant focused attention on communicating with astronauts about the uncertainties surrounding the exposure limit. Using the risk distribution (including description of the tails) and confidence levels in communicating with astronauts, policy makers, and the public, is warranted.

The committee notes that NASA's proposal to set the permissible dose based on the mean, while maintaining the 3 percent REID limit previously applied to the 97.5th quantile, results in a higher dose than the current standard. This higher probability of harm seems to conflict with an ethics commitment to protection from harm, minimization of risk, and NASA's requirement to ensure astronaut safety by keeping exposures as low as reasonably achievable (ALARA). The committee recognizes that NASA is engaging in policy decisions and standard setting to protect crews to the greatest extent possible to limit mission risk as well as long-term risk to astronaut health and wellbeing as they consider long duration missions.

Revised calculations for dose threshold within the limits imposed by 3 percent REID may be acceptable with appropriate justification.

Combined Implications of NASA's Proposed Radiation Health Standard

In NASA's proposed radiation health standard, career thresholds are driven by mean REID calculations for a 35-year-old female and would be applied to all astronauts, regardless of sex and age. The effective dose equivalent to 3 percent REID, for a 35-year-old female, is ~600 mSv (although NASA notes that values presented are approximate, +/– 10 percent, and will be verified prior to establishing a new standard). Compared with the existing standard, this proposed standard will increase the allowable exposure for a 35-year-old female by a factor of ~3 and for a 55-year-old male by a factor of ~1.5. Future modifications to this standard could be warranted if, for example, improved models suggest that 3 percent REID is associated with a different dose, or if a different REID cutoff is justified as more appropriate, or if NASA determines that the 3 percent REID is inadequately protective.

Ethical Considerations

This committee notes that among the consequences of the proposed single standard are that (1) the revised standard creates equality of opportunity by applying the same dose limits to all astronauts without reference to age or sex; (2) some astronauts (primarily women) would be exposed to greater doses of radiation and therefore greater risk than would have been the case with current criteria-based standards adjusted for sex and age, creating a more risky work environment for some; and (3) a single standard with dose limits based on risk to 35-year-old females comes at the expense of potential greater allowable exposures for some older and male astronauts which could be seen as an unfair restriction of opportunity for them. Taken together, the proposed standard creates equality of opportunity for spaceflight with the trade-offs of somewhat higher allowable exposure to radiation for a subset of astronauts (primarily women) and limiting exposures below otherwise acceptable doses for others (primarily older men).

Such an approach can be defended on ethics grounds, but doing so requires weighting some ethics-related commitments more heavily than others in support of the revised standard—equality of opportunity over more individualized risk assessment, and equality of opportunity over commitments to limiting risk (at least for some astronauts). It will be important for NASA to offer explicit ethics justifications for the approach adopted and the resulting standard, to be shared with astronauts and their families, as well as made publicly accessible.

The committee makes the following recommendations regarding NASA's proposed space radiation health standard:

Recommendation 1: NASA should proceed with the proposed approaches to revising the space radiation health standard. As proposed by NASA, the agency should:

- **Apply a single space radiation standard to all astronauts;**
- **Utilize the most protective approach in setting the space radiation standard;**
- **Set the standard as a dose limit; and**
- **Utilize the mean value of the risk distribution based on 3 percent risk of exposure-induced death.**

In implementing this recommendation, NASA should make explicit the agency's own ethical and policy analysis justifying the revisions to the proposed standard.

Recommendation 2: In the near future, NASA should re-examine whether to use risk of exposure-induced death (REID) or other metrics, or a combination of metrics, in setting the dose-based space radiation health standard. NASA should conduct an independent analysis of the validity of 3 percent REID and make explicit the agency's justification for the metrics they choose.

The committee notes astronauts on a Mars mission will be expected to exceed the career limit of a 600 mSv effective dose (see Figure S-1), which would require a waiver. The committee recognizes that to complete a crewed mission, especially long-duration missions to other planets, there are a multitude of risks that the astronauts and mission support staff have to address. The committee encourages NASA to continue using the principle of keeping ionizing radiation exposure ALARA to guide it in eliminating, minimizing, and mitigating risks, and to follow a transparent and ethics-based framework for deciding on the granting of waivers for a mission and for astronauts, as recommended in previous National Academies reports and endorsed by NASA.

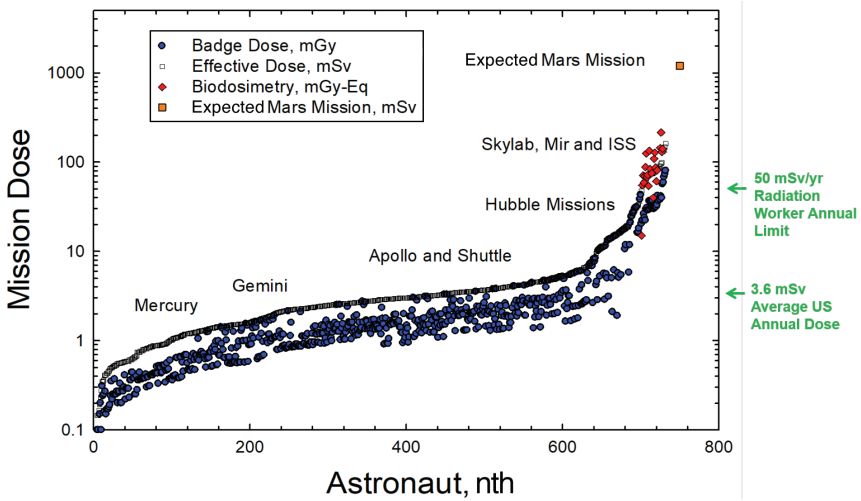

FIGURE S-1 Summary of mission personnel dosimetry for astronauts on all past NASA space missions through 2007, including Mercury, Gemini, Apollo, Skylab, Apollo-Soyuz, Space Shuttle, NASA-Mir, and the International Space Station, plus estimate of effective dose for an astronaut on a Mars mission, with radiation worker annual limit and average U.S. annual dose noted for context. Summary of results for doses comes from thermoluminescent dosimeters worn by astronauts, biodosimetry, and estimates of effective doses for all NASA missions to date and includes data from astronauts who have flown more than once in space, with the maximum being seven times by two astronauts.

The committee reached the following conclusion regarding NASA's consideration of revisions to the current radiation exposure standard:

Conclusion I: The committee concludes that astronauts who travel on long-duration spaceflight missions are likely to be exposed to radiation levels that exceed the proposed new space radiation standard of an effective dose of 600 mSv. For example, a mission to Mars is likely to exceed the exposure standard by up to 150 percent. Unless technological advancements and engineering controls provide improved radiation shielding or other protections to astronauts, for a mission to Mars to proceed, NASA would need to seek waivers to the radiation health standard both for the mission and for each astronaut.

COMMUNICATING RADIATION-INDUCED CANCER RISKS

A key component of risk management is evidence-based, thorough, and effective communication of the risks. Achieving risk communication aims in the context of NASA's space radiation standard requires an understanding of the risks and the standards themselves, and an understanding of how astronauts understand and interpret the risks, related standards, and both formal and informal communications about them.

NASA designed the system shown in Figure S-2 to communicate the proposed standard.

Identifying Risk Communication Recipients and Their Needs

The committee assumes that the primary audience for Figure S-2 is NASA astronauts. Several other communication recipients were proposed

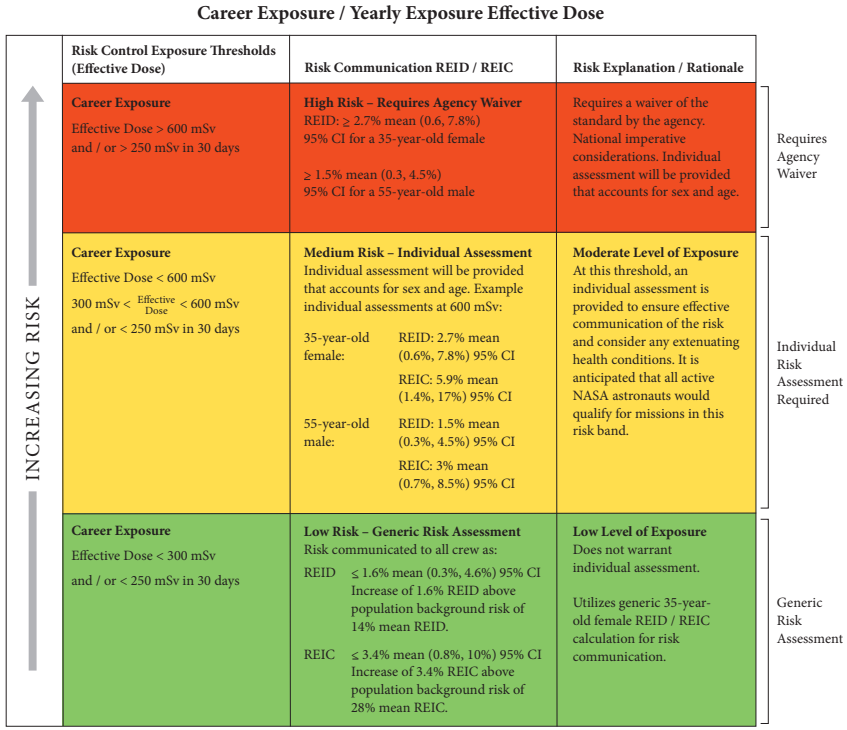

FIGURE S-2 NASA's proposed system for communicating its proposed space permissible exposure limit for spaceflight radiation exposure standard.
SOURCE: White paper provided by Dave Francisco to the committee, February 12, 2021.

or discussed with NASA, including program managers, commercial spaceflight astronauts, international space agencies, policy makers, and other interested members of the public.

NASA astronauts have prior training and significant expertise that is likely to influence their risk communication needs, including training in probability and statistics, and on radiation and its biological effects. Even among astronauts, as the committee heard anecdotally, there may be variations in decision contexts, such as concerns about reproductive health, which could influence their decision needs. NASA noted anecdotally that the astronauts find REID confusing, and that *dose* is more familiar to astronauts than *risk*. Similarly, NASA suggested that the use of "traffic light" color bands to represent the three-stage risk profile would be familiar to astronauts, given the widespread use of color-coded risk matrices at NASA.

While NASA astronauts are the primary audience for communication of radiation exposure risks, other audiences will also be recipients of this communication. Audiences outside of NASA may not have the same technical background as NASA personnel and might interpret and react differently to figures, data, and information about radiation-induced cancer risks.

Considering NASA's Risk Communication System for the Space Radiation Standard

The committee understood that Figure S-2 is intended to be NASA's primary system for communicating the space permissible exposure limit (SPEL). To evaluate this figure and related materials, the committee adapted a framework for communicating epistemic uncertainty. This framework assesses the message's source, content, format, and the anticipated effects of the communication.

Presentations and materials provided to the committee by NASA show that both formal and informal communications with astronauts about radiation risks come from multiple sources, including the Space Radiation Analysis Group at NASA, the Human System Risk Board, flight surgeons, and others. In addition to these communications, the committee notes that it could be valuable to allow astronauts to access information on cancer risks associated with space radiation on their own.

Tailored communications are generally found to be more effective than general communications and this would seem to be particularly the case in considering how best to communicate with individual astronauts.

Appropriately designed visual aids can improve both risk understanding and health-relevant decision making. Graphical presentations such as gradient bands, probability density functions, or cumulative distribution functions to represent the central tendency and associated uncertainty in

estimated risk appear to help convey the actual estimated distribution of probability for the risk estimates, and thus may reduce misinterpretation.

Although matrices like the "traffic light" in Figure S-2 can be helpful in tracking and prioritizing risks, they pose communication challenges. The categorization of risk consequences is subjective, as it reflects a specific risk attitude, and therefore it is best practice to be transparent about how risk categorization decisions are made. Colors can be helpful in risk communication, because they represent relative magnitude of risk and inherently provide evaluative descriptions of each band as "low," "medium," and "high." But, in the context of radiation, colors and evaluative descriptions may be misleading and inaccurately represent risk and any associated risk management decisions. Ideally, any proposed communication tool or message should be designed based on stated communication goals, the evidence from prior research regarding how best to achieve those goals with the targeted audience, and at least exploratory (i.e., formative) empirical evaluations of the message or tool with representatives from the targeted audience.

The committee reached the following conclusions:

Conclusion II: NASA has proposed to use a traffic light color-coded system to categorize and communicate space radiation risks. Without empirically testing the traffic light color-coded system, there is insufficient information to determine whether it is an effective way for NASA to communicate the space radiation risks to astronauts.

Conclusion III: There are two concerns with the proposed traffic light system:

- *At doses below the standard (i.e., in the green and yellow bands), there is insufficient clarity and detail about associated cancer risks.*
- *At doses above the standard (i.e., in the red band), inclusion of the waiver process suggests that an exception to the standard is built into the standard and its application.*

Communicating an Individual Risk Assessment to an Astronaut

The committee makes the following recommendations regarding NASA's strategies for communicating individual radiation-induced cancer risks.

Recommendation 3: To inform astronauts about their radiation risk, NASA should provide all astronauts with an individual radiation risk assessment and revise the risk communication system (i.e., the traffic light) for the updated space radiation standard to do the following:

- **Assess and communicate the radiation risk at an individual level (as opposed to generic risk assessments) for all astronauts independent of the actual or projected radiation exposure and risk.**
- **Communicate the mean value of the risk estimate associated with an astronaut's radiation exposure.**
- **Communicate the uncertainties for the risk distribution using both uncertainty intervals and limits, and visual representations of the risk distribution such as probability density curves, histograms, or heat maps.**
- **Address specific questions and concerns that individual astronauts may have regarding their overall health risks following communication of their actual or projected radiation dose, and help them place radiation risks into perspective compared to other mission risks and their baseline risk of developing cancer.**

Recommendation 4: NASA should communicate a comprehensive picture of an individual astronaut's cancer risks due to radiation exposure, beyond the information contained in the traffic light system. To do so, NASA should do the following:

- **Respond to questions from astronauts regarding their total radiation exposure, and help astronauts put their radiation-induced cancer risk in context.**
- **Continue to discuss any changes in radiation risks as part of routine health briefings for the astronaut office, crews, and individual astronauts.**
- **Provide astronauts with an up-to-date resource on their radiation risks that they can access outside of formal meetings with NASA's Office of the Chief Health and Medical Officer.**
- **Provide astronauts with easy access to summary information regarding what is known about the cancer risk factors that might interact with radiation exposures to influence long-term health outcomes for astronauts.**

RISK COMMUNICATION AND NASA'S WAIVER PROCESS

NASA has acknowledged that with current technology, a mission to Mars would expose all astronauts to space radiation that exceeds the SPEL, despite taking measures to keep radiation exposure as low as reasonably achievable (the ALARA principle). Therefore, it would be necessary for NASA to use a waiver process that evaluates any proposed mission and evaluates why individual astronauts would be asked to fly on such missions. As an employer, NASA has both the legal and ethical

responsibility to assure the health, safety, and well-being of its employees. The fact that NASA serves as both employer and the organization that establishes and assures compliance with its own health standards confers particular ethical responsibilities and opens NASA to a high level of public scrutiny.

Space exploration missions face challenges to risk mitigation that are not typically found in terrestrial high-hazard work. Terrestrial workers in high-risk jobs may choose to end their exposures by leaving their job. This is not the case for astronauts, particularly those on long duration missions beyond LEO. There may be missions that NASA believes are so time sensitive and have sufficient importance and urgency that there is justification for exceeding the established standard for all astronauts. In this instance, unlike employers subject to Occupational Safety and Health Administration standards, NASA may seek to obtain permission for a mission waiver that would permit the agency to subject all volunteers for that mission to an unusual level of risk that would be unacceptable in less time-sensitive and critical missions. Waivers for specific missions and for individual participation in any given mission were considered in depth by the 2014 IOM Committee on Ethics Principles and Guidelines for Health Standards for Long Duration and Exploration Spaceflights.

That committee recommended that NASA follow a three-level, ethics-based decision framework when considering a waiver to an existing standard or standards. The threshold consideration would be to consider and explicitly make a determination as to whether "any missions that are unlikely to meet current health standards are ethically acceptable" and if so, what "specific conditions must be fulfilled" to approve the waiver. The committee expected NASA would make this general determination to establish and articulate criteria independent of any specific mission and that these criteria would be known both to the NASA Astronaut Corps and the general public. If NASA decides a specific contemplated mission meets these criteria, the agency would then be in a position to consider individual astronaut participation and crew composition. This consideration would include the skills and expertise needed for the mission, as well as astronauts' individual health and risk considerations. Astronauts would be making these decisions alongside NASA at this stage.

The committee reached the following conclusion regarding NASA's waiver process:

> *Conclusion IV: The committee recognizes that NASA's inclusion of the waiver in its space radiation risk management process may be necessary to maintain the flexibility for the agency to pursue missions in which astronauts are exposed to radiation doses that exceed its standard. The committee concludes there is a need for an*

explicit and public framework for how NASA will consider both mission and individual waivers.

The committee makes the following recommendation regarding NASA's waiver process:

Recommendation 5: NASA should develop a protocol for waiver of the proposed space radiation standard that is judicious, transparent, and informed by ethics. To avoid the perception that an exception to the standard is built into the space radiation standard itself, NASA should follow the ethics decision framework in developing a waiver protocol and it should provide supporting analysis and explanation justifying any waiver to the standard.

Risk Communication Research Agenda for NASA

Given the unique needs and characteristics of spaceflight programs and astronaut populations, NASA would benefit from engaging in risk communication evaluation and research to better understand and improve the effectiveness of their communication strategies.

The committee makes the following recommendation regarding a NASA risk communication research agenda:

Recommendation 6: NASA should conduct research to develop evidence-based risk communication and the agency should develop a radiation risk communication research agenda to fill knowledge gaps such as (1) what information astronauts want; (2) how astronauts process risk information; and (3) who/what are the most effective sources of information for astronauts. In addition, NASA should carry out research to examine and improve the effectiveness of its current and proposed risk communication strategies and materials.

1

Introduction

The National Aeronautics and Space Administration (NASA) works to realize the benefits of space exploration and these benefits accrue, for the most part, to society through technological and scientific advances, as well as national and international pride and collaboration (IOM, 2014). Astronauts are in a unique class of employees as they work for an agency whose mission is exploration, which implies both a high level of risk and uncertainty as astronauts explore space as well as NASA's duty to care for their safety during a mission and throughout an astronaut's lifetime. NASA has long recognized that crewed space missions carry a range of unique hazards and challenges, including health-related risks.

As NASA prepares for space exploration missions that extend to greater distances into our solar system and for longer durations, including missions to near-Earth objects, the Moon, and Mars, as well as prolonged stays on the International Space Station, these challenges are further amplified. To ensure the safety and success of these missions, health and performance risks associated with spaceflight must be adequately characterized, controlled, and mitigated through novel tools and technologies (NASA, 2021a). NASA uses an evidence-based approach to assess the likelihood and consequence of a risk (Romero and Francisco, 2020), in which risks are assigned a rating for their potential to affect in-mission crew health and performance and for their potential to affect long-term health outcomes and quality of life.

NASA recognizes a range of physiological and behavioral impacts to the health of its astronauts during and after spaceflight. One of the most challenging risks to assess and communicate about is ionizing radiation (simply referred to as "radiation" throughout this report), because of

incomplete knowledge of the complicated radiation environment in space, limited data on the mechanisms of how space radiation causes cellular damage, and additional uncertainties associated with modeling radiation-induced health risks. Constant exposure to radiation places astronauts at an increased lifetime risk of cancer and non-cancer health problems, including central nervous system damage, cataracts, cardiovascular damage, potential heritable effects, impaired wound healing, and infertility (Blakely et al., 2010; Chylack et al., 2009, 2012; Cucinotta and Durante, 2006; Cucinotta et al., 2001; NRC, 2006). The great degree of uncertainty around whether an astronaut will develop any of these health problems, especially cancer, following exposure to space radiation contributes to the challenges of communicating these risks effectively to astronauts, NASA personnel, policy makers, and the public.

To protect astronauts from unacceptable risks due to space radiation exposure, NASA has set space permissible exposure limits (SPELs) (NASA, 2014). The current permissible exposure limit is set so that astronauts shall not exceed 3 percent risk of exposure-induced death from cancer (REID) adjusted for age and sex. REID estimates the probability that an individual will die from cancer associated with radiation exposure (UNSCEAR, 2000). As currently implemented by NASA, the SPEL is set from the calculated upper 95 percent confidence limit of the REID distribution, and is dependent on the age and sex of the astronaut. Based on detailed individual uncertainty calculations, an individual astronaut's permissible exposure limit can vary. For instance, under NASA's current approach, a 30-year-old female would be limited to ~180 mSv of radiation exposure in space, whereas a 60-year-old male would be limited to ~700 mSv. For reference, a 180-day mission to the International Space Station (ISS) would expose an astronaut to 50–120 mSv.[1]

NASA's exposure limit is based on recommendations from National Council on Radiation Protection and Measurements (NCRP) reports (NCRP, 2000, 2014), and is intended to apply only to radiation exposure incurred during missions in low Earth orbit (LEO).

Several reports and papers have cautioned NASA about the significant increases in radiation exposure expected on exploratory and long-duration missions and the increased cancer risks that will likely result. In *Safe Passage: Astronaut Care for Exploration Missions*, the authoring committee said:

> Deep space is a unique environment with special hazards for humans.... In addition, technological problems, such as radiation protection, re-

[1] From NASA's January white paper prepared for this committee. A copy of this white paper may be requested by contacting the National Academies' Public Access Records Office (PARO@nas.edu).

> main unsolved, making long duration space travel probably unacceptably dangerous. (IOM, 2001, p. 191)

Cucinotta and Durante concluded:

> Radiation-induced cancer is one of the main health risks for manned exploration of the Solar system.... The issue of radiation risk during space exploration is unlikely to be solved by a simple countermeasure, such as shielding or radioprotective drugs. The risk will be understood and controlled only with further basic research in cancer induction by charged particles. (Cucinotta and Durante, 2006, p. 434)

NCRP reported, "The issue of radiation protection limits for exploratory missions is more complex given the likelihood that radiation exposures will be increased in magnitude and biological effectiveness" (NCRP, 2014, pp. 1–2). NASA scientists have also noted that staying below the current radiation SPEL can be difficult for astronauts with previous spaceflight experience and for young female astronauts selected for lunar surface missions (Simonsen and Slaba, 2020). In addition, the authors concluded that all astronauts on a Mars mission will exceed the SPEL for space radiation (Cucinotta et al., 2013; Simonsen and Slaba, 2020).

To assess cancer risks from space radiation, NASA uses the NASA space cancer risk model (currently NSCR 2012) (Cucinotta et al., 2013). This model incorporates the current state of knowledge about the physics of space radiation, its effect on the induction of carcinogenesis, and the translation of terrestrial epidemiological data along with other factors such as mission duration and where the Sun is in the solar cycle. Because REID is calculated probabilistically, uncertainties are defined for every model component. The REID output of the model significantly affects many facets of a mission, such as engineering (e.g., shielding and propulsion systems), design of habitable spaces in spacecraft and planetary habitats, and flight eligibility of astronauts. NASA also uses REID when communicating with astronauts about radiation-induced health risks.

In the near future, as NASA prepares for a crewed space mission to the Moon and, eventually, Mars, the agency is proposing changes to its health standard for space radiation exposure limits and its approach to managing and communicating the cancer and non-cancer risks associated with space radiation exposure. There are a number of reasons why NASA feels these changes are necessary. These are described in the next section.

WHY NASA IS CONSIDERING REVISIONS TO THE CURRENT RADIATION EXPOSURE STANDARD AND ASSOCIATED RISK MANAGEMENT

According to presentations by NASA at the committee's public session in January 2021, there are several reasons why an update to the radiation exposure standard is being considered. The initial reason was because the current standard is for LEO missions exclusively. Now that the Artemis lunar mission, additional longer-duration lunar missions, and missions to Mars are in planning and development, NASA needs to define a radiation exposure standard that considers both missions in LEO and missions into deeper space. This is supported by section 4.2.10.4 of NASA-STD-30001, volume 1 (NASA, 2014, p. 23), which says:

> Exploration Class Mission radiation exposure limits shall be defined by NASA based on NASA-requested recommendations from the National Academy of Sciences, the Institute of Medicine, and the National Council on Radiation Protection (NCRP).

The other reasons presented to the committee for revising the standard and associated risk management are the following:

- NASA is aware that recent updates from epidemiological and radiobiological studies on sex differences in radiation-induced cancer risks may affect its cancer risk assessment model and what is an acceptable level of radiation exposure for astronauts (see Box 1-1 and Figure 1-1).

BOX 1-1
Permissible Mission Duration for Male and Female Astronauts Often Differs Due to Space Radiation Exposure

Under the current standard, risk of exposure-induced death (REID) is dependent on both sex and age. For two astronauts of both the same age and previous space radiation exposure, a female astronaut would have a higher REID than her male colleague; however, the magnitude of the difference would depend on the female astronaut's age at exposure. This means that the number of days a female astronaut could fly is significantly fewer than the permissible mission duration of the male astronaut, because she will reach the radiation limit sooner, depending on her age of exposure. NASA provided the committee an illustrative example (see Figure 1-1). This difference in the number of flight days is becoming more significant as women make up an expanding percentage of the NASA Astronaut Corps.

NSCR Example Realistic Case

Results for first mission and Permissible Mission Duration (PMD) for a 2nd mission assignment

	Mission Duration [d]	Crew Dosimeter [mGy]	Effective Dose [mSv]	REIC P97.5% [%]	REID P97.5% [%]	Remaining PMD [d]
Male age 44y	320	135	210	3.9	1.9	211
Female age 44y	320	135	214	5.1	2.7	43

For the first ISS mission, the radiation exposure is less than the NASA SPEL (career limit for cancer is 3 percent REID evaluated at the upper 95th percent confidence interval).

For the astronaut's second ISS mission 3 years later (age 47y, same altitude but lower rates of radiation exposure):

The male's career exposure would meet the SPEL for a planned ISS mission duration of 211 days.
The female's career exposure would meet the SPEL for a planned ISS mission duration of 43 days.

FIGURE 1-1 Female astronauts have lower permissible mission duration than male astronauts owing to differing assessed cancer risks under the current NASA risk model.
NOTE: ISS = International Space Station; NASA = National Aeronautics and Space Administration; NSCR = NASA Space Cancer Risk; PMD = permissible mission duration; REIC = risk of exposure-induced cancer; REID = risk of exposure-induced death; SPEL = space permissible exposure limit.
SOURCE: Semones, 2021.

- NASA formed a Bioethics Advisory Panel in 2019 charged to perform a bioethical review and counsel NASA on a range of issues including the long-standing concern that NASA's current radiation exposure results in an unequal work environment that limits female astronauts to shorter space careers because of scientific data indicating that, compared to men, females have an increased risk of cancer from exposure to ionizing radiation.
- In 2020, NASA convened an advisory panel of clinicians with expertise in cancer and other radiation health effects to individually advise NASA on both radiation risk characterization and how the standard can be aligned and viewed in context with other risks. Panelists recommended increasing the exposure limit, revising how both REID and the risk of exposure-induced cancer (REIC) are communicated, encouraging conversation with astronauts on risk limits and risk communication, and expanding the model

input data to include more epidemiological data from occupational exposure studies.[2]

- Space missions are increasingly carried out as collaborations among international space agencies and commercial enterprises. NASA relies on other governments, their space agencies, and commercial rockets to provide LEO transportation for its astronauts to NASA-supported facilities in space since the retirement of the Space Shuttle Program (IOM, 2014; NASA, 2021b). This increase in collaboration has led to challenges associated with coordinating regulations and policies, including those that address health risks to astronauts. Because each agency sets its own radiation exposure limits, NASA thought it prudent to reconsider its space radiation health standard in that context.
- The U.S. government is developing a space-based branch of the military, and U.S. commercial enterprises are planning for crewed spaceflight ventures, which may be regulated by the Federal Aviation Administration. While NASA will not be responsible for these endeavors, NASA recognizes that the technical and health standards it establishes and follows within its agency are frequently used by other agencies as the benchmarks to follow.
- NASA recognizes that a key component of managing risk is appropriate risk communication with astronauts and other stakeholders. While considering revisions to the radiation exposure standard, NASA is also evaluating how best to communicate that risk to its astronauts.

COMMITTEE'S CHARGE AND APPROACH

In 2020, NASA asked the National Academies of Sciences, Engineering, and Medicine (the National Academies) to convene a committee of experts to review and assess NASA's processes for long-term risk assessment and management for currently anticipated crewed missions with respect to cancer (see Box 1-2 for the committee's complete Statement of Task). This report provides the committee's recommendations to NASA for assessing, managing, and effectively communicating about the space radiation–induced cancer risk for astronauts. The study committee was not asked to develop a new radiation exposure health standard or to perform a detailed evaluation of the NASA stochastic cancer model that informs the standard.

To accomplish the task, the National Academies empaneled a committee of 18 members with expertise in the areas of radiation and cancer

[2] A copy of a document prepared by NASA summarizing the discussion of this advisory panel may be requested by contacting the National Academies' Public Access Records Office (PARO@nas.edu).

BOX 1-2
Statement of Task

An ad hoc committee of the National Academies of Sciences, Engineering, and Medicine will convene to review and assess the National Aeronautics and Space Administration's (NASA's) processes for long-term risk assessment and management for currently anticipated crewed missions with respect to cancer (excluding current and post mission effects of radiation) due to exposure to space radiation. Specifically, the committee will:

- Review the data on the association between radiation exposure and cancer risk, and consider the best ways for NASA to apply the data to manage the risk assessment process to currently anticipated crewed missions. With respect to NASA processes, the review will consider a broad range of factors and analytic techniques that may include uncertainty management utilizing confidence intervals around cancer mortality, radiation quality factor determination and utilization, and the use of the dose and dose-rate effectiveness factor.
- Review and assess NASA's proposed process and strategies for managing cancer risks as a result of exposure to space radiation. Provide a written report with recommendations on the best process and strategies for NASA to use in addressing and managing the uncertainties of long-term cancer risks due to radiation exposure in crewed space missions beyond low Earth orbit.

In conducting the review, the committee will consider the following:

- NASA's present processes for assessing uncertainty from radiation risk exposure in crewed space missions compared to terrestrial methods for clinical applications, and how data from ground-based research on the relationship between radiation exposure and cancer risk should inform NASA's approach to risk management for crewed missions.
- How to consistently manage the uncertainty of space radiation exposure risk assessments across spaceflight with respect to anticipated NASA space missions, and known clinical risks.
- How to express what is needed in the form of a radiation risk management process or approach NASA could apply to determine astronaut eligibility for crewed missions.

Based on the committee's review and assessment of NASA's proposed strategies, the committee will make recommendations to NASA for assessing and managing the processes for addressing space radiation risk for astronauts.

biology; biostatistics and mathematical modeling; risk communication, management, and uncertainty; medical genetics; clinical medicine; ethics; occupational health and safety; radiation dosimetry and physics; epidemiology; and two former astronauts with clinical medicine expertise (see Appendix B for biographical sketches of the committee members and staff).

From December 2020 through May 2021, the committee held five full committee meetings, including two public information-gathering sessions with NASA, as well as a joint meeting with the International Commission on Radiological Protection, and many working group meetings (all meetings were held virtually) and email communications. At the first public session in January 2021, NASA provided more specifics on its objectives for the study; factors considered and background on the proposed radiation standard; health and medical risk characterization; sex difference considerations; cancer incidence within the NASA Astronaut Corps; and a crew perspective (see Appendix A for the public session agendas). At the second public session in February 2021, NASA presented an updated set of options for updating the standard for the committee's consideration and answered clarifying questions about the options.

Over the course of the study, NASA submitted three white papers to the committee, each building on, providing additional context for, and sometimes revising NASA's proposed approach for updating the space radiation health standard.[3] In the first white paper (shared with the committee in advance of the January 2021 public meeting), NASA provided background information and additional context on the scope of the task. NASA also posed specific questions to the committee related to a set of options NASA proposed for updating the standard. NASA laid out what they were asking (and not asking) the committee to consider (see Box 1-3). Then, in response to the committee's questions at the January meeting, NASA provided a second white paper in February 2021 that answered specific questions from the committee and provided updates to NASA's preferred strategy for updating and communicating the standard. In March 2021, NASA provided a final white paper in response to additional questions posed by the committee at the February public session meeting.

There were several important updates to NASA's proposed approach as communicated to the committee throughout the study process. In the January white paper and public meeting, NASA proposed to use 75 percent confidence level to set the career total dose limit, but solicited the committee's input on other options (using a 95 percent confidence level or using the mean). In the February white paper, NASA indicated that they instead preferred to use the mean REID to set the limit and to use a confidence

[3] NASA's white papers prepared for this committee may be requested by contacting the National Academies' Public Access Records Office (PARO@nas.edu).

BOX 1-3
Additional Context on the Study Scope

The National Aeronautics and Space Administration (NASA) asked the committee to review and assess the agency's proposed updates to the space radiation health standard. During the course of the study the committee considered white papers provided by NASA, public presentations and discussion with NASA leaders, as well as the scientific literature and relevant reports from other expert panels on this topic. This committee did not conduct original data analysis.

Specific questions from NASA to the committee included

- Are the proposed bands in the dose-based standard an effective method to control and communicate the risk?
- How should the dose/risk bands be set? Options include
  - Continue utilizing a 95 percent confidence level
  - Utilize a 75 percent confidence level
  - Utilize the mean and also communicate an interval (95 percent, 75 percent, or other)
- How should the standard calculate the risk of exposure-induced cancer concerning sex differences? Options include
  - Sex averaged for non-sex organs
  - Average for lung and non-sex organs
  - Utilize the most protective case
- Are bioethics considerations adequately addressed?

Due to prior and on-going reviews by NASA, the International Commission on Radiological Protection, the National Council on Radiation Protection and Measurements, and the National Academies, NASA specified that they were *not* asking this committee to

- Develop a standard;
- Perform a detailed evaluation of the NASA stochastic cancer model;
- Assess NASA research approaches;
- Assess cardiovascular and/or central nervous system risk;
- Assess aspects of genetic testing; or
- Assess aspects of informed consent and other legal considerations.

interval to communicate the wide distribution of the risk produced by the model. They also proposed the use of dose-based thresholds universal for sex and age and using a 35-year-old female astronaut as the basis for setting the universal standard. In the March white paper, NASA provided the final proposed language for the updated standard, which utilized the mean REID to set the career total dose limit (universal for sex and age). NASA also indicated that they would use the 95 percent confidence interval to communicate the broad distribution of the risk, along with the mean risk.

The March white paper also included additional information on median and mean calculations, and examples of how NASA communicates risks to astronauts post-mission.

There was also a change to NASA's proposed three-band risk communication tool (see Figures S-2 and 4-1) for the standard. In January, the risk band figure was black and white. In the February update, NASA redesigned this figure to have a "traffic light" color-coding scheme to communicate "high," "medium," and "low" risk. The table was also reorganized and additional information on the rationale behind the bands and NASA management protocols was included.

In the materials that NASA provided the committee and during the public information-gathering sessions, the updated standard and the risk communication strategies were often presented together. This sowed some confusion and highlighted for the committee the importance of establishing a clear separation between the space radiation standard and the strategies for communicating radiation-induced cancer risks to astronauts and other stakeholders. One way that the committee has emphasized the separation between their evaluation of the proposed radiation standard and how best to communicate cancer risk caused by radiation is to cover each topic in a separate chapter. Throughout the report the committee acknowledges the interconnectedness of the steps in the risk management process, while emphasizing the importance of risk communication as distinct from the standard itself.

NASA recognizes that there are bioethical considerations that must be addressed adequately as it executes its plan for a mission to Mars. NASA has asked the committee to confirm whether these considerations have been addressed adequately in its proposed standard and in the assessment, management, and communication of radiation-induced cancer risks. NASA has acknowledged that under current conditions, a mission to Mars would expose all astronauts to space radiation that exceeds the SPEL, despite taking measures to keep radiation exposure as low as reasonably achievable (the ALARA principle). It would therefore be necessary for NASA to use a waiver process that evaluates and explains why such a mission is critical and why astronauts would be allowed to fly. The committee has considered NASA's likely need for both mission and individual waivers for certain long-duration missions and has addressed that need in the context of the ethical framework previously recommended to NASA (IOM, 2014).

A glossary of terms used in this report is presented in Box 1-4.

ORGANIZATION OF THE REPORT

This report is organized into four chapters. Chapter 1 provides general background and context on the issues to be addressed and also describes

BOX 1-4
Glossary

Health standards—Requirements used throughout occupational settings to protect workers and guide design, research, and engineering efforts. NASA refers to them as spaceflight human system standards that aim to provide a healthy and safe environment for astronauts and to provide health and medical programs for astronauts during all phases of spaceflight (IOM, 2014).

Individual risk—A specific issue of concern to the health, safety, or well-being of one or more stakeholders, which can relate to the mission risk if the individual is perceived as presenting a risk to the achievement of one or more performance requirements. Collectively, individual risks represent the identified set of undesirable scenarios that put the achievement of performance requirements at risk (NASA, 2011).

Individual risk assessment—A process that considers the probability that a specific exposure will lead to the development of cancer in a person's lifetime (Shields, 2006). NASA currently considers only age and sex in its individual cancer-from-radiation risk assessments.

Most susceptible case/group—The population group that is considered to have the highest risk of radiation-related cancer based on a consideration of age and sex.

Risk assessment—A systematic methodology for analyzing a system, a process, or an activity to answer three basic questions: (1) What can go wrong that would lead to loss or degraded performance (i.e., scenarios involving undesired consequences of interest)? (2) How likely is it (probability of scenarios)? and (3) What is the severity of the degradation (consequences)? (Prassinos et al., 2011).

Risk communication—Any formal or informal exchange of information about risk, including but not limited to information in any format about magnitude, probability, exposure sources or pathways, adverse consequences, other characteristics, or management of risk. Risk communication is a part of the science of risk assessment.

Risk of exposure-induced death (REID) from cancer—The probability that an individual will die from cancer associated with the radiation exposure (UNSCEAR, 2000). For example, in this report, 3 percent REID implies that within a cohort of 100 astronauts, 3 of them are likely to die of radiation-induced cancer at some point in their lifetime.

Radiation Terminology

The committee recognizes that the precise meanings of terms related to radiation and its effects on the human body may vary somewhat depending on the practitioner, be they a professional in radiation physics, epidemiology, health

continued

BOX 1-4 Continued

physics, radiation biology, clinical medicine, or occupational health. In this report, such terms are used based on the following definitions.

Exposure—The state or condition of being exposed to irradiation (ICRP, 2015).

Absorbed dose (D)—The absorbed dose is the quotient of d by d*m*:

$$D = d/dm$$

where d is the mean energy imparted by ionizing radiation to matter of mass d*m*.

The SI unit of absorbed dose is joule per kilogram (J kg^{-1}), and its special name is gray (Gy) (ICRP, 2013).

Effective dose (E)—The tissue weighted sum of equivalent dose in an organ or tissue from all specified organs and tissues of the body, given by the expression:

$$E = \sum_T w_T \sum_R w_R D_{T,R} = \sum_T w_T H_T$$

where H_T is the equivalent dose (evaluated as the absorbed dose multiplied by the quality factor for the specific radiation) in an organ or tissue T, $D_{T,R}$ is the mean absorbed dose in an organ or tissue T from radiation of type R, w_R is the radiation weighting factor, and w_T is the tissue weighting factor. The sum is performed over organs and tissues considered to be sensitive to the induction of stochastic effects. The SI unit of effective dose is joule per kilogram (J kg^{-1}), and its special name is sievert (Sv) (ICRP, 2013).

Dose limit—Recommended value of a dose to an individual that should not be exceeded in planned exposure situations (ICRP, 2013).

Exposure limit—The maximum amount of ionizing radiation an astronaut is permitted to encounter, which is defined as a dose limit. An exposure limit is defined in a health standard. It has the primary functions of preventing in-flight risks that would jeopardize mission success and limiting chronic risks to acceptable levels based on legal, ethical, moral, and financial considerations (Cucinotta, 2010).

Relative risk—the ratio of the rate of disease among groups having some risk factor, such as radiation, divided by the rate among a group not having that factor (NRC, 2006).

Excess relative risk (ERR)—the relative risk minus 1.0 (NRC, 2006).

Sievert (Sv)—The unit of measure for an absorbed dose of radiation. 1 Sv = 1,000 millisieverts (mSv). Millisieverts measure the health effect of low doses of ionizing radiation on the human body. For a useful pictorial of radiation doses from various sources, see https://xkcd.com/radiation.

the Statement of Task and the committee's approach. Chapter 2 provides an overview of ionizing radiation in space, its impact on cancer risk, and cancer risk models used to assess and project the risk of cancer from exposure to ionizing radiation. Chapter 3 considers NASA's proposed changes to its radiation exposure standard, and provides the committee's recommendations on the implementation and application of the updated standard and on risk assessment for cancer risks associated with radiation exposure during crewed space missions. Chapter 4 considers the aims and methods of communicating to astronauts the cancer risk from ionizing space radiation, and offers conclusions and recommendations on communicating cancer risks associated with radiation exposure during crewed space missions, as well as considerations of waivers for missions that exceed the radiation exposure standard. Finally, Appendix A contains the methods used by the committee to develop this report, information on materials provided by NASA to the committee, as well as the committee's public session meeting agendas. Appendix B presents short biographical sketches of the committee members and staff.

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2

Space Radiation and Cancer Risks to Astronauts

When ionizing radiation interacts with biological tissue, it can harm cells directly by damaging the deoxyribonucleic acid (DNA) and other macromolecules or it can harm cells indirectly by ionizing water molecules, which in turn form free radicals that oxidize cellular molecules and break chemical bonds. In the context of the exposure of astronauts, radiation can have both acute and long-term health effects depending on the dose and dose rate. Acute effects include acute radiation sickness and cutaneous effects, and long-term health effects include cataracts, cancer, cardiovascular diseases, and degenerative tissue effects.

This chapter examines the risks to astronauts due to radiation exposure during spaceflight. It includes a brief background on the space radiation environment, the cellular and molecular damage that space radiation can cause, and the potential health impacts. The chapter also includes an overview of both the cancer risk model used by the National Space and Aeronautics Administration (NASA), which provides the basis for the agency's space radiation health standard, and sex, age, and genetic factors that affect radiation-induced cancer risk.

THE SPACE RADIATION ENVIRONMENT AND ITS IMPACT ON HUMAN HEALTH

Beyond the protection of Earth's magnetic field, astronauts are exposed to a complex radiation environment (Simonsen and Nealy, 1991) comprised of galactic cosmic rays (GCR) and solar particle events (SPEs) (Cucinotta et al., 2013; Kronenberg and Cucinotta, 2012). GCR has the same intensity

regardless of the direction of the measurement (i.e., isotropic) and is composed of mostly highly energetic protons (85 percent), helium ions (14 percent), and high atomic number, high-energy (HZE) particles, defined as having an electric charge greater than 2+ (1 percent) (Schimmerling, 2011; Zeitlin et al., 2013). GCR ions of primary concern have an atomic number up to 28 and energies from less than ~1 mega-electronvolt (MeV) to greater than ~10 giga-electronvolt (GeV) per nucleon. They are highly penetrating and cannot readily be attenuated or stopped by shielding. GCR fluence rate for ions of less than 2 GeV per nucleon varies about a factor of two with the 11-year solar cycle (higher at solar minimums and lower at solar maximums). SPEs include particles, primarily protons with energies from ~1 MeV to several hundred MeV and with fluences exceeding 10^9 protons cm^{-2}. SPEs can include other nuclei such as helium ions and HZE ions. SPEs occur sporadically with frequency also varying with the solar cycle, although both their frequency and intensity are unpredictable. SPE protons of less than 30 MeV are unable to penetrate spacecraft or extravehicular activity suits while higher energy protons will also contribute to radiation exposure in space (Schimmerling, 2011).

When considering the health effects of space radiation, two quantities are relevant:

- Linear energy transfer (LET) is the amount of energy that is deposited in matter (such as biological tissue) per unit distance that the ionizing radiation travels; and
- Relative biological effectiveness (RBE) is used to compare how damaging radiation is, using X-rays or gamma rays as a reference. A radiation that is 10 times more effective per unit dose than X-rays would have an RBE of 10. RBE varies with dose, dose rate, and measured endpoint, among other factors.

The biological damage caused by ionizing radiation depends on both the dose and the type of radiation as defined, for example, by its LET. The division between high- and low-LET radiations is often difficult to define, but many NASA investigators consider low LET radiation to be <10 KeV/μm. Different types of ionizing radiation possess different energies, which affects both how these types interact with cells and tissues and the damage they cause. So absorbed dose is insufficient to fully account for the estimated risk. To properly account for this variation in damage (RBE), the absorbed dose is multiplied by a radiation quality factor, yielding what is described as the equivalent dose (ICRP, 2007).

Depending on their atomic number and energy, GCR particles are typically characterized as high-LET compared to the low-LET of sparsely ionizing gamma rays and X-rays. High-LET HZE particles traversing material

deposit a large fraction of their energy as secondary electrons produced along the particle track, resulting in high ionization density along the track (Blakely, 2012; Katz et al., 1971). Depending on their atomic number and energy, HZE particle interactions can produce clustered damage in DNA (Cucinotta et al., 2000; Goodhead, 1994; Hada and Sutherland, 2006; Nikjoo et al., 1999; Rydberg, 1996) that are harder for a cell to repair and likely account for the high RBE for cell death, mutation, chromosome aberrations, and carcinogenesis (Held, 2009). SPE radiations, largely lacking the HZE particles included among GCR, have a different distribution of RBE with energy than the HZE particles. None of these experiments are at dose-rates that one would expect in space exposures, which also contributes to uncertainties. NASA recognizes that the specific biological effects of these highly ionizing particles are poorly understood, leading to large uncertainties in risk estimation (Cucinotta et al., 2013; NCRP, 2012; Simonsen and Slaba, 2020).

Health Impacts of Exposure to Space Radiation

While spacecraft shielding and protected spaces within the spacecraft can protect against SPEs and therefore protect astronauts, SPEs could affect astronauts on an extravehicular activity in space or on a planetary surface. Exposure to high amounts of radiation (1 or 2 gray [Gy] with some variation among individuals) could cause astronauts to develop an acute radiation syndrome (ARS). Symptoms can include anemia, leukopenia, and hemorrhage; gastrointestinal distress, damage, and pain; and fever and shock. The lethal dose to 50 percent of the human population (LD_{50}) is at approximately 4–4.5 Gy (varying depending on medical support) (DOE, 2017). Doses above 8 Gy are almost always fatal, and at doses above 30 Gy, neurovascular symptoms (seizure, tremor, ataxia) occur prior to death. Lower levels of radiation are insufficient to cause acute radiation sickness but can increase the risk of several long-term health effects, including cancer, cardiovascular disease, cataracts, and degeneration of central nervous system tissue.

CANCER RISK PROJECTION MODELS

Ionizing radiation increases the risk of cancer with increasing dose and the effects are cumulative (IARC, 2012).

Risk models have been developed to assess an individual's risk of developing cancer in general or at a specific site due to radiation exposure. Typically these models provide an average value and a range of possible values that capture key uncertainties. A minimal dose–response model contains parameters that reflect the dose of radiation received, the sex of

the individual, the age at exposure to radiation, and the attained age of the individual.

When designing or selecting an appropriate cancer risk model, experts need to carefully consider and evaluate the model's performance in describing currently available human and/or animal radiation carcinogenesis data, as well as the mechanistic and biological plausibility of the model's assumptions.

Input Data

In general, cancer risk models from low-LET radiations are often fitted with data from acute exposures and relatively large doses (typically the Japanese atomic bomb survivor data and specifically the Life Span Study [LSS]). It is therefore necessary to incorporate factors that account for potential differences in extrapolating from high to low dose and from high to low dose rates. The approach uses the dose and dose-rate effectiveness factor (DDREF). The values of the DDREF recommended by national and international committees range from about 1.5 to about 3. Whenever it is applied, the DDREF functions to lower the slope of the linear-nonthreshold (LNT) function.[1] Because only the dose is used in most determinations of both the dose and the dose-rate components of the DDREF, many groups have suggested separating the dose-rate effect (DREF) from the low dose effect (LDEF) (NCRP, 2020).

Although most radiation risk models are based primarily on the Japanese atomic bomb survivors, there are a large number of other epidemiological studies of radiation and cancer. Most relevant to NASA's risk models are the growing number of studies of occupational radiation exposures including the multicenter international nuclear worker cohort study INWORKs, the U.S. Radiologic Technologists Study, and the Million Person Study. Results from these studies, particularly for total cancer risk, are broadly consistent with the LSS (Ozasa et al., 2018); this provides some level of assurance for the radiation risk models. There are some exceptions though, such as the sex differences in lung cancer risk (see below for more details).

Transfer of Risks Across Populations

Other parameters built into the models that affect the output values of estimated risk relate to the transfer of risks across populations. These

[1] The appropriateness of using the LNT model to extrapolate risks at low (less than 100 mSv) doses has been strongly debated for some time. NCRP Commentary 27 (NCRP, 2018a) concluded that recent epidemiological studies are compatible with the continued use of the LNT model for radiation protection. The committee was not tasked with assessing the appropriateness of the LNT model in setting radiation protection standards for astronauts, which are set at doses above the typical level of dispute of the LNT model.

parameters account for the differences in background incidence rate for specific cancers between two populations, as well as accounting for the synergistic effects between radiation and other risk factors such as smoking.

Studies have shown that the background rates for various cancers differ across populations. For example, the LSS cohort and contemporary Japanese populations have a greater background incidence rate of stomach cancer and a lower rate of breast cancer compared with a contemporary U.S. population (IARC, 2017; Thompson et al., 1994). These differences manifest when considering whether to use excess relative risk (ERR) or the excess absolute risk (EAR) to transfer the risk model from the Japanese population to a contemporary U.S. population. The increase in cancer risk attributable to a particular absorbed dose of radiation is given as excess risk relative to the background (ERR) or in addition to the background (EAR) risk of developing a particular cancer type. The decision to use ERR indicates that the radiation interacts, in some fashion, with other risk factors that comprise the background risk for a particular cancer. Perhaps the most studied example is for the interactions between radiation exposure and tobacco consumption and their effects on lung cancer risk (ICRP, 2010; NRC, 1999; Pierce et al., 2003).

Relative Biological Effectiveness

RBE values derived from irradiation of animals provide a better model for the human space situation than RBE values from irradiated cellular systems. RBE studies have been performed with mice and other animal models irradiated to mimic HZE radiation and SPE proton storms in space. The RBE value changes significantly depending on the survival level of cells (and animals), and thus all RBE calculations present uncertainty in predicting the human situation, since exposure conditions, cellular endpoints, and even numbers of cells exposed in a person would vary from one exposure to another. Despite these concerns about uncertainty, space-irradiation experiments in animal systems have provided useful RBE values to include in cancer risk models.

For example, $LD_{50}/30$[2] values for C57BL/6J mice, demonstrated RBEs of 1.4 for Si-28 and 0.99 for C-12 (Suman, 2012). Tumor induction using C ions in C3H female mice revealed an RBE of 1–2.1 when lifetime tumorigenesis was examined (Ando et al., 2014). The RBE for GCR/HZE ions is likely to be higher than for protons, demonstrated in tumor induction using the plateau region of those GCR ions that were present (Shuryak, 2017; Suman, 2016). Using a jejunal crypt microcolony assay to examine

[2] $LD_{50}/30$ is defined as "the dose of radiation expected to cause death to 50 percent of an exposed population within 30 days" (USNRC, 2021).

the RBE for single cell survival in vivo, Mason et al. (2007) identified an RBE of 1.1 for protons, and a similar study examining the RBE at the Spread Out Bragg Peak (SOBP) of the proton beam revealed an RBE of 1.1–1.2 (Gueulette et al., 2005). These studies allow one to conclude that RBEs range higher (2–5-fold) for GCR exposure than for protons, whose RBEs are very close to those of gamma rays when tested in animals for single-cell survival assays or for carcinogenesis. Studies on the induction of Harderian gland tumors (a tumor found uniquely in rodents) have shown higher RBE values of space radiation exposures than other cancer-related endpoints; these RBE values have also been shown to vary considerably with dose rate (Chang et al., 2016).

Uncertainties

There remain a number of uncertainties associated with the development of radiation risk estimates from epidemiology studies, including the LSS data. These are, in general, dosimetric uncertainties, epidemiological and methodological uncertainties, uncertainties in modeling epidemiological data, and when considering the potential effects of other radiation-induced outcomes, uncertainties in assessment of non-cancer data and uncertainties in assessment of heritable effects (NCRP, 2012).

FACTORS AFFECTING RADIATION-INDUCED CANCER RISK

Sex Differences and Radiation-Induced Cancer Risk

There are several important considerations regarding the incorporation of sex differences into the calculation of risk of exposure-induced death (REID), and the application of these on occupational exposure limits for female and male astronauts.

Based on reviews of the literature on lifetime risks associated with radiation (NCRP 2000, 2014), it was concluded that women had a higher excess risk of cancer than men from the same level of radiation exposure. NASA subsequently incorporated the difference in sex-specific response to radiation into their protection guidance for astronauts (NASA, 2014) noting that planned career exposure for radiation shall not exceed 3 percent REID for cancer mortality, adjusted for age and sex, as estimated under the current NASA computational model for space radiation cancer risk projections (Cucinotta et al., 2013). The operational outcome was that female astronauts were allowed to have less time in space than their male counterparts.

The NASA computational model for space radiation cancer risk projections (Cucinotta et al., 2013) incorporates information on the background

rates of lung cancer. Lung cancer is the leading cause of cancer death in the United States, excluding skin cancer (Howlader et al., 2021); however, the rates have been declining for men and women (particularly over the past two decades), even in never-smokers (Thun et al., 2013), with higher decline rates in men (Siegel et al., 2021). Although lung cancer has the largest contribution of all cancers to the calculation of REID for fatal cancers, it is unclear how much taking into account sex-specific differences in radiation risks of lung cancer would affect the overall calculations of REID.

Evidence suggesting the potential for significant sex differences in radiation risks of lung cancer (as well as esophagus and stomach) continues to derive primarily from one study—the study of the Japanese atomic bomb survivors. The latest cancer risk updates from this population continues to show that the risk of death from radiation-induced lung cancer in nonsmokers was nearly three times higher for women than for men (Furukawa et al., 2010; Ozasa et al., 2012). A summary of relevant studies (organized by high- and low-LET radiation) is presented in Table A-1. The committee conducted a systematic search of publications in English from PubMed using MeSH terms. Studies were selected which presented either estimates of external radiation doses, frequencies of lung cancer deaths or estimates of radiation risks of lung cancer separately by sex. Studies of internal radiation exposures were included only if study participants were also exposed to external radiation and risks of these exposures were analyzed separately. Studies which presented radiation risks estimates for males and females together were included if the authors stated that there were no differences in risks between them.

The majority of studies of occupationally exposed populations (Boice et al., 2011, 2014, 2019; Cardis et al., 2007; Golden et al., 2019; Haylock et al., 2018; Muirhead et al., 2009; Richardson et al., 2018; Silver et al., 2013; Velazquez-Kronen et al., 2020) did not find significant differences in risks of death from lung cancer caused by radiation between men and women, but not all studies adequately assessed smoking. Studies of occupationally exposed workers frequently include very few women and many of them tend to have doses of radiation exposures which are lower than doses for men, which complicates analyses of sex-specific risks due to low statistical power. Differences in radiation risks of lung cancer have been reported for Mayak workers from Russia (Gilbert et al., 2013) but the differences in risk were only observed in analyses with plutonium and there were no differences in risks due to external exposures (Gilbert et al., 2013; Gillies et al., 2017). Similarly, studies of long-term effects of exposures to significant fluoroscopy doses to tuberculosis patients (Boice et al., 2019; Davis et al., 1989; Howe, 1995) or to high-dose radiation treatment for primary cancer or peptic ulcer (Carr et al., 2002; Gilbert et al., 2003; Little et al., 2013; NCRP, 2011) did not find significant differences in risks of death from lung

cancer caused by radiation between men and women. The available epidemiological evidence is currently being evaluated by the National Council on Radiation Protection and Measurements (NCRP) Scientific Committee SC 1-27, charged with assessing radiation-induced lung cancer in populations exposed to chronic or fractionated radiation and developing methods for analyzing these data for sex-specific differences (NCRP, 2019). The reasons for the differences between these studies and the LSS are uncertain, but they could be due to low statistical power to assess sex-specific differences in studies of occupationally exposed workers or some limitations inherent to the LSS (e.g., underestimation of smoking among Japanese women, including passive smoking exposure).

Current ground-based systems of radiation protection do not differentiate between sex in either their limitation or numeric protection criteria structures (ICRP, 2007; NCRP, 2018b). The dosimetric quantity recommended for radiological protection, effective dose, is computed by averaging age and sex (ICRP, 2007; NCRP, 2018b).

Under the International Commission on Radiological Protection (ICRP) system for adults, equivalent doses for specific organs are calculated by the sex averaging of values obtained using male and female phantoms. Effective doses are then calculated using age- and sex-averaged tissue weighting factors, based on risk data and are "intended to apply as rounded values to a population of both sexes and all ages" (ICRP, 2007, p. 13). ICRP specifically noted the following with respect to the application of the system of radiation protection for both sexes for ground-based applications:

> In view of the uncertainties surrounding the values of tissue weighting factors and the estimate of detriment, the Commission considers it appropriate for radiological protection purposes to use age- and sex-averaged tissue weighting factors and numerical risk estimates. The system of protection is sufficiently robust to achieve adequate protection for both sexes. Moreover, this obviates the requirement for sex- and age-specific radiological protection criteria which could prove unnecessarily discriminatory. (ICRP, 2007, p. 42)

Similarly, NCRP addresses this point as follows:

> While recognizing that there are variations in cancer risk between organs, between males and females, and at different ages, the system of protection needs to be applied consistently to all individuals in the population. Thus, numeric protection criteria for stochastic effects are specified as a single value based on a population average over both sexes and all ages. (NCRP, 2018b, p. 41)

Age and Radiation-Induced Cancer Risk

Population mortality rates of lung cancer increase with age in both men and women. The highest rates have been reported for men aged 75 years and over (439 per 100,000 per year in 2017; Howlader et al., 2021). Evidence of the modifying effects of age at exposure on the association between radiation exposure and lung cancer comes primarily from the study of atomic bomb survivors from Japan (Cahoon et al., 2017). Radiation risks increased with increasing age at exposure, but declined with increasing attained age. There were no indications of sex dependence in effect modification by attained age or age at exposure. Analyses of nuclear workers (Cardis et al., 2007; Haylock et al., 2018; Richardson et al., 2018) either did not examine (Haylock et al., 2018) or did not find (Cardis et al., 2007; Daniels et al., 2017; Muirhead et al., 2009) variations in radiation risks of lung cancer with attained age or age at exposure, most likely owing to low statistical power for such analyses. Pooled analysis of uranium miners showed a decrease in radiation risks of lung cancer with attained age (both in exposure-age-concentration and exposure-age-duration models) (NRC, 1999).

Genetics and Radiation-Induced Cancer Risk

It is well recognized that certain rare genetic mutations significantly increase an individual's risk of developing cancer. For example, inheritance of mutations in genes that regulate genome integrity, such as the *TP53* or *BRCA1* tumor suppressors, lead to increased risk of cancers, by 50–85 percent over an individual's life span. *TP53* mutation carriers develop multiple types of cancer, such as sarcomas, breast, brain, leukemias, and adrenocorticoid carcinomas, and *BRCA1* patients develop breast, ovarian, and prostate cancers. Radiation treatment of individuals with *TP53*-mutant cancers increases the number of second cancers (Heymann, 2010). Other less penetrant variants, known as single nucleotide polymorphisms, present in the genome also contribute to increased risk of various diseases (Wand, 2021).

Among individuals with certain genetic polymorphisms, radiation has been found to further increase cancer risk. For example, in a recent study of long-term childhood cancer survivors, radiation therapy increased the occurrences of subsequent cancers among individuals with genetic polymorphisms in genes that regulate DNA double strand break repair (Morton et al., 2020). Efforts are under way to quantify the contributions of these genetic polymorphisms to provide reliable estimates of disease risk, including cancer (Wand, 2021).

THE CURRENT NASA MODEL FOR ESTIMATING CANCER RISK

NASA requested that this study committee consider the agency's space radiation risk management process, including the management of uncertainties related to cancer risk from exposure to space radiation. This committee was not tasked with performing an evaluation of NASA's cancer risk model. The following overview of NASA's cancer risk model serves to describe the foundation on which NASA's risk management process and Permissible Exposure Limit for Spaceflight Radiation Exposure Standard are based.

Overview of the NSCR 2012 Model

The current NASA cancer risk model (NSCR 2012) is based on the model developed by Cucinotta et al. (2013) and incorporates input from the National Research Council (2012) review committee. The general formulation closely follows those developed by other national and international committees (NRC, 2006; UNSCEAR, 2008). The risk for each of 20 radiosensitive tissues is estimated separately according to age at exposure using risk models developed primarily from the LSS of the Japanese atomic bomb survivors. A DDREF is applied to scale from an acute exposure (received from the atomic bomb) to the chronic exposure received by space travel. Radiation dose estimates include quality factors that account for the increased RBE of particle radiation encountered in space compared to gamma rays.

To transfer the risk models from the Japanese population to a contemporary U.S. population, NSCR 2012 uses a mixture model in the risk projection that randomly combines EAR, in which the risk of radiation exposure is calculated as a separate number from the baseline risk of cancer for unexposed individuals in the atomic bomb survivor cohort, and ERR, in which the risk of radiation exposure is calculated as a multiple of the baseline risk.

Background cancer rates for U.S. never-smokers are used to approximate the likely cancer risks in the astronaut population, which results in lower risk estimates for smoking-related cancers. Radiation-induced cancer incidence estimates for each tissue are converted to cancer mortality using cancer-specific, incidence-based mortality factors. The REID from cancer is then estimated by summing risks across cancer sites and attained age, with adjustment for competing causes of death using a life table approach.

Uncertainties in the NSCR 2012 Model

The NSCR 2012 model includes key uncertainties in inputs currently used in other radiation risk models for the U.S. population:

1. The Poisson regression uncertainty in the risk coefficients from the atomic bomb survivors, which include the sex of the survivor, the age at exposure, and the attained age for which the risk is being calculated;
2. Uncertainty estimates for the doses assigned to the atomic bomb survivors;
3. Uncertainty in the DDREF for protracted exposures in contrast to the acute exposures received by the atomic bomb survivors; and
4. Uncertainty in the risk transfer from the Japanese atomic bomb survivors to a contemporary U.S. population.

The NSCR 2012 model has incorporated a set of uncertainty estimates for the biggest uncertainty contributor, which is the radiation quality of the HZE particulate radiations that form the great majority of the astronauts' exposure, which have very high LET, in contrast to the low-LET gamma radiation that was the predominant exposure of the Japanese atomic bomb survivors. The NSCR 2012 model also has incorporated uncertainty estimates for the radiological physics aspects of the dose estimates for the astronauts.

NSCR 2012 appears to lack a few types of uncertainty estimates in the atomic bomb survivor data, however, that are considered in the radio-epidemiological model used by the U.S. Environmental Protection Agency (Pawel, 2013). These include uncertainty owing to incomplete follow-up with the atomic bomb survivors, the uncertainty caused by errors in disease detection and diagnosis in the atomic bomb survivors, uncertainty caused by failure to capture diagnostic exposures, and the uncertainty caused by potential selection bias in the atomic bomb survivor cohort. Note, however, that these uncertainties, while absent from the NSCR 2012 model, are relatively small compared to the uncertainties that govern in the NSCR 2012 calculations. NASA may consider utilizing an influence diagram as a visual tool to explain the relationship between the various uncertainties.

The NSCR 2012 model also does not consider a number of other known possible sources of uncertainty related to the effects of radiation, one of which is the possibility of non-targeted effects in which the risk of cancer in a given organ results from a dose to a different organ (Desouky et al., 2015). A number of other uncertainties not currently considered in NSCR 2012 are listed elsewhere (see Figure 5 of Simonsen and Slaba, 2020). These include

1. The uncertainty in scaling space radiation carcinogenesis from that due to gamma rays, including possibly both different latency and different lethality of tumors;
2. Shape of dose response at low doses—linear-non-threshold as assumed or linear quadratic (the 2012 UNSCEAR report emphasizes the uncertainty in the dose–response model and suggests such approaches as multi-model inference);
3. Mixed field additivity for high- and low-LET radiations and DREFs;
4. Translation of animal experimental data to humans;
5. Individual radiation sensitivity; and
6. The effect of other combined stressors of spaceflight on cancer risk.

The NASA model includes assumptions for radiation-induced excess risk in relation to time since exposure, for the DDREF, and for radiation quality. Note that various combinations of models for these three factors substantially increase the upper tail of the uncertainty distribution for the ensemble compared to the NSCR 2012 model, which does not include the other uncertainties just mentioned (Desouky et al., 2015; Pawel, 2013).

The UNSCEAR 2012 report suggests that for estimates of lifetime risk for all solid cancers combined, "Addressing known sources of uncertainty, the 95 percent credible [confidence][3] intervals span about an order of magnitude," and that "estimates of site-specific cancer risks have larger uncertainties still" (UNSCEAR, 2015, p. 22). NASA has provided a plot (see Figure 3 of Simonsen and Slaba, 2020) that suggests that in NSCR 2012 the ratio is only about 3/0.83 = 3.6 between the 50th and 95th percentile (Simonsen and Slaba, 2020). This is close to an order of magnitude for a 95 percent credible interval, as shown in Figure 4-1. The NSCR 2012 estimate includes the particularly large uncertainty of radiation quality for HZE radiations that is not included in the interval suggested in the UNSCEAR report.

The resulting risk distribution from NSCR 2012 is unimodal, with a peak, but it is asymmetrical and has a long "upper tail," where risk magnitudes several fold higher than the mean or median have non-negligible probabilities. Such a complicated shape for the risk predictions poses challenges for (1) determining which part(s) of the distribution (e.g., mean, median, 97.5 percent or some other percentile of the cumulative distribution) are most useful for setting a corresponding radiation dose limit for astronaut exposures; and (2) effectively communicating the radiation-induced risk

[3] UNSCEAR defines a credible interval as "an interval defined from the distribution of the degree of belief of the value of the quantity of interest within which a certain probability is assigned (e.g. 95%) representing the assessor's degree of belief that the true value of a quantity of interest falls within the interval" (UNSCEAR, 2019, p. 8).

from space missions to astronauts. Using a high percentile of the cumulative predicted risk distribution for these tasks appears to be conservative in terms of protecting astronaut health because, by definition, the model predicts that the risk will be lower than the communicated value with very high probability. In other words, an astronaut could interpret such a number as a plausible upper bound on his or her risk at the given accumulated dose. However, the accuracy of the high percentiles of the risk distribution is likely to be relatively low because of the inherent limitations of currently available input data for the risk model, and assumptions that are unavoidable in the modeling process (described above), for example.

It is likely that improvements in data quality and amount over time, as well as evolution and improvement of risk modeling strategies, can substantially alter the predicted upper percentiles of the risk distribution. In other words, the shape and length of the "upper tail" of this distribution are not very well known. In contrast, it is likely that improved data and modeling methodologies will have less effect on altering the central portions of the risk distribution such as the mean or median, which are generally more stable than the extremes, as shown in NASA's report on ensemble models (Simonsen and Slaba, 2020).

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3

NASA's Spaceflight Radiation Exposure Standard

Health standards have multiple purposes. They are an occupational exposure limit, setting a ceiling for exposure in the course of a working lifetime. They are an expression of the maximum level of risk that is acceptable to the employer and that should be clearly understood by the employee—in this case the astronaut. Health standards also frame and direct the engineering and administrative controls of exposure that are needed to mitigate risk to the achievable level. In the case of the National Aeronautics and Space Administration (NASA), the risk to an individual astronaut that is reflected in the standard includes both a concern for long-term astronaut safety and, in the setting of long-duration missions beyond low Earth orbit (LEO), the consequences of any harm to an astronaut within the mission that could adversely affect the mission's outcome. As a rule, health standards are established based on the best available science and are revised as the scientific information evolves.

NASA's Space Permissible Exposure Limit for Space Flight Radiation Exposure Standard 4.2.10 ("the standard") informs crew mission assignments, crew health care (preflight, in-flight, and postflight), space vehicle design and layout, as well as mission operational profiles for human spaceflight missions (Polk, 2021). The standard currently states:

> Planned career exposure to ionizing radiation shall not exceed 3 percent risk of exposure-induced death (REID) for cancer mortality at a 95 per-

> cent confidence level[1] to limit the cumulative effective dose (in units of sievert) received by an astronaut throughout his or her career. (NASA, 2014, pp. 21–22)

As described in Chapter 2, NASA's current cancer risk assessment model, NASA Space Cancer Risk (NSCR) 2012, estimates REID from cancer for a set of mission-specific conditions. NASA is proposing to revise the standard's subsection 4.2.10.1, such that the space permissible exposure limit (SPEL) will remain based on risk (REID) but expressed as a dose-based limit. Under the proposed standard, the maximum allowable effective dose of ionizing radiation for an astronaut's career would apply equally to male and female astronauts and be independent of an astronaut's age. NASA is also proposing setting the dose thresholds based on mean REID and risk of exposure-induced cancer (REIC) calculations for a 35-year-old female.

The committee has considered the changes that NASA is proposing for its space radiation exposure standard, how the current and proposed standards differ, and the benefits and drawbacks of the proposed standard vis-à-vis its intended purposes. The committee's conclusions and recommendation concerning these matters are found in this chapter. In addition, because NASA asked the committee to compare NASA's processes for assessing uncertainty in radiation-induced cancer risk with terrestrial methods used for clinical applications, this chapter discusses briefly how standards are used to manage terrestrial radiation exposure, as well as standards used by other space agencies.

RADIATION EXPOSURE STANDARDS USED BY OTHER AGENCIES

Standards Used to Manage Terrestrial Radiation Exposure

The objective for managing terrestrial radiation exposure is grounded on reducing the potential for the radiation detriment related to stochastic effects. The system of radiological protection as recommended by the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP) includes implementation of the principles of justification, optimization of protection, dose constraints, and dose limits (ICRP, 2007; NCRP, 1993, 2018a,b). Specifically, occupational dose limits are recommended based on an implied calculation of the risk of stochastic effects (primarily the probability of

[1] Based on the committee's review of NASA's document NASA/TP-2020-5008710, Section II.I "95 percent confidence level" refers to the 97.5 quantile of an uncertainty distribution of REID. This distribution is obtained by varying the input parameters of the NSCR NASA risk model according to "parameter uncertainty distributions" determined by NASA based on expert judgment.

cancer and heritable effects) as a function of dose. In terrestrial radiation exposures, such doses can be reasonably well estimated or evaluated by direct measurements for individuals or groups.

Recommended dose limits for occupational planned exposure situations are based on the concept of effective dose and a linear-non-threshold model for dose response (ICRP, 2004, 2007; NCRP, 1993, 2018a,b). For occupational exposure, a judgment was made by ICRP and NCRP to control the lifetime effective dose to be on the order of 1 Sv, with a corresponding nominal radiation detriment-adjusted risk coefficient for cancer and heritable effects on the order of 5 percent Sv^{-1} (ICRP, 2007; NCRP, 2018b). ICRP sets the occupational effective-dose limit at 20 mSv per year, averaged over defined periods of 5 years (ICRP, 2007). NCRP recently updated its recommendations and has developed numeric protection criteria for managing the dose to an individual that are similar—but not identical—to those made previously by NCRP (1993) and ICRP (2007). NCRP now recommends that the annual effective dose to an individual from occupational exposure should not exceed 50 mSv and that the cumulative lifetime effective dose for an individual from occupational exposure should not exceed 10 mSv multiplied by the individual's current age in years (NCRP, 2018b). NCRP further emphasizes that "Optimization of protection together with the recommendations related to annual and lifetime management of effective dose provide flexibility and are expected to maintain the individual lifetime effective dose well below 1 Sv" (NCRP, 2018b, p. 49).

As currently implemented, NASA radiation limits differ substantially from radiation limits used for radiation workers on Earth in that they are specific risk limits (NCRP, 2014). NASA's proposal to revise its space radiation standard in terms of effective dose based on a mean of less than 3 percent REID and applied universally for sex and age would be more consistent with the approaches of current standards used to manage terrestrial radiation exposure. However, the unique and complex nature of radiation exposures in space (see Chapter 2) introduces significant uncertainties in such a risk-to-dose transfer, which would require NASA's continued review of the evolving scientific knowledge about the relationship between risks and dose and consideration of future modifications of the standard when appropriate.

Standards Used by Other Space Agencies

When considering deterministic effects, all space agencies set similar limits for acute radiation exposures, such as from solar particle events (SPEs). These limits are based on threshold doses and tissue tolerances as published in ICRP Publication 41 and NCRP Report 142 (ICRP, 1984; NCRP, 2002). However, for stochastic health risks such as development of

cancer, there is no harmonization across space agencies in setting radiation standards. ICRP Task Group 115 is currently working on risk and dose assessment for radiological protection of astronauts and cosmonauts and aims to establish a framework that could be applied uniformly by all of the space agencies during international crewed missions (Durante, 2021).

Like NASA, other space agencies set career limits for astronauts based on a level of acceptable cancer risk due to space radiation. The agencies use different approaches for establishing these career limits, and the limits themselves may differ (Durante, 2021; McKenna-Lawlor et al., 2014). The European, Canadian, and Russian space agencies use a dose-based standard and limit career exposures to an effective dose of 1 Sv (or 1,000 mSv) independent of age and sex (see Table 3-1). This dose limit corresponds to a 5 percent risk of cancer mortality (ICRP, 1991, 2007). The Japanese space agency (JAXA), similar to NASA's current standard, is risk based and sets the career limit for astronauts at 3 percent lifetime-attributed cancer mortality (LCM) and is sex and age dependent.

The committee did not conduct a comprehensive review of the models used to derive the different radiation health standards, but it recognizes that different space agencies may develop and adopt their own cancer risk model. For example, the Russian Space Agency's (RSA's) cancer risk

TABLE 3-1 Radiation Exposure Career Limits Summary: International Space Station Partner Agencies

Space Agency	Career Limit	Sex/Age Dependency
Canadian Space Agency	1,000 mSv	No sex or age dependency
European Space Agency	1,000 mSv	No sex or age dependency
Russian Federal Space Agency	1,000 mSv	No sex or age dependency
Japanese Aerospace Exploration Agency	3 percent REID @ the mean	Yes Lower limit: 500 mSv for 27- to 30-year-old female Upper limit: 1,000 mSv for > 46-year-old male
National Aeronautics and Space Administration (**current**)	3 percent REID @ the 95 percent confidence level	Yes Lower limit: ~180 mSv for 30-year-old female Upper limit: ~700 mSv for 60-year-old male
National Aeronautics and Space Administration (**proposed update**)	600 mSv[a]	No sex or age dependency

[a] Proposed career dose limit. Could be exceeded with individual waiver.
SOURCE: Adapted from Semones, 2021.

projection model replaces ICRP's effective dose concept with one called *generalized dose*, which, in addition to the dose and the radiation quality factor, incorporates a temporal factor that converts the effects of persistent radiation to a single acute exposure; a spatial factor that is analogous to tissue weighting factors; and a modification factor that accounts for the contributions that the space environment (e.g., microgravity) has on the equivalent dose. Another distinction of the RSA model is that it calculates total radiation risk as the sum of the radiation risk of cancer plus the radiation risk of other detrimental health effects (Shafirkin et al., 2002). In addition to the risk-based dose limit, RSA calculates years of life lost (YLL) because of radiation.

The European Space Agency (ESA) is developing a radiation-attributed decrease of survival (RADS) risk model that calculates the cumulative decrease in survival at attained age owing to previous radiation exposure (Walsh et al., 2019). While the RADS model is similar to the risk projection models used by JAXA and NASA, unlike those two, the RADS model uses all solid cancers (rather than organ-specific cancers) along with major organ models, such as lung and breast. The RADS model also uses different relative biological effectiveness (RBE) and DDREF values, and it uses cancer incidence rather than mortality risk to account for the improved ability to cure people who have developed cancer (Ulanowski et al., 2019).

Space agencies recognize that a mission to Mars will result in most astronauts exceeding the agencies' career limits for radiation exposure. To the committee's knowledge, only NASA has a process for granting a waiver to an astronaut that would allow him or her to fly on a mission that exceeds the career limit. The other agencies acknowledge that a waiver process may be needed as they plan for long-duration missions (NASEM, 2021).

NASA'S PROPOSED SPACE RADIATION EXPOSURE HEALTH STANDARD

NASA provided the committee with details about the proposed changes to its space radiation exposure standard including draft language for section 4.2.10.1 of the standard (see Box 3-1). To summarize:

- NASA is proposing to move from a standard built on and conveyed as a risk limit to a standard that is still based on risk for the most susceptible population but conveyed as a dose-based limit.
- The proposed maximum allowable effective dose has been determined by applying the cancer risk model, NSCR 2012, to the most susceptible case—that of a 35-year-old female—to calculate mean REID and REIC. These mean values will be converted to effective-dose values.

BOX 3-1
Proposed Language for Revised Spaceflight Radiation Permissible Exposure Limit

An individual astronaut's total career effective radiation dose due to spaceflight radiation exposure shall be less than 600 mSv. This limit is universal for all ages and sexes.

The total career dose limit is based on ensuring all astronauts (inclusive of all ages and sexes) remain below 3 percent mean risk of cancer mortality (REID) above the non-exposed baseline mean. Individual astronaut career dose includes all past spaceflight radiation exposures, NASA biomedical research exposures, plus the projected exposure for an upcoming mission. Any total exposure (which includes the past exposures plus projected exposure) that exceeds the limit would require a waiver by the agency prior to the mission.

SOURCE: NASA white paper prepared by NASA's Office of the Chief Health and Medical Officer and provided to the committee on March 18, 2021.

- NASA proposes a 3 percent mean REID as the basis for the dose-based limit. Hence, for all astronauts, the maximum allowable space radiation exposure would be the effective-dose equivalent for a 35-year-old female astronaut whose mean REID is at 3 percent.
- The standard would delineate an effective-dose career limit of ~600 mSv[2] that applies equally to male and female astronauts regardless of an astronaut's age.

Before moving to a discussion of the committee's analysis of the proposed changes to the space radiation standard, it is important to begin with an overview of the basis for NASA's current space radiation standard.

THE BASIS FOR NASA'S CURRENT SPACE RADIATION EXPOSURE STANDARD

In 1970, the National Academies' Space Studies Board made recommendations to NASA for guidelines for career doses for long-term mission design and manned operations (NRC, 1970). At that time, NASA employed only male astronauts and the typical age of astronauts was 30–40 years. A "primary reference risk" was proposed by the 1970 National Academies committee equal to the natural probability of cancer over a

[2] NASA has indicated that the proposed limit of 600 mSv is an approximate value. The final standard will be +/– 10 percent of the 600 mSv estimate.

period of 20 years following the radiation exposure (using the period from 35 to 55 years of age) and was essentially a doubling dose. The estimated doubling dose of 382 rem (3.82 Sv), which did not include a dose-rate reduction factor, was rounded to 400 rem (4 Sv). The 1970 National Academies recommendations were implemented by NASA as dose limits and used operationally for all missions until 1989 (Semones, 2021).

REID is a calculation that has been at the core of NASA's risk management process for decades. REID estimates the probability that an individual will die from cancer associated with the radiation exposure (UNSCEAR, 2000). For example, in this report, 3 percent REID implies that within a cohort of 100 astronauts, 3 of them are likely to die of radiation-induced cancer at some point in their lifetime.

Following the recommendation of NCRP Report 98 (1989), which provided guidance to NASA concerning radiation protection in LEO, the NASA space radiation standard has been set at 3 percent REID for both sexes and all ages since 1995. The NCRP recommendation was based on an assessment of risks of fatal cancer of highly exposed terrestrial radiation workers and of lifetime risks of fatal accidents among workers in other occupations that were described as "less safe" and "most hazardous." Comparison of space radiation risks with the "most hazardous" terrestrial occupations was found not to be reasonable because astronauts are exposed to many risks other than radiation. At the time of the NCRP analysis, occupational dose to radiation workers including those who work in fuel cycle facilities and nuclear power plants, industrial radiographers, and medical professionals was limited to 50 mSv per year and could reach 2.5 Sv throughout their career, assuming a 50-year career in the industry. This corresponded to a 5 percent risk of excess cancer mortality.

For "less safe" industries (e.g., agriculture and construction), the lifetime risks of fatal accidents at the time ranged from 2 to 5 percent. NCRP noted that "comparison of the radiation risks with the middle group of 'less safe' [within the range of safe, less safe, and most hazardous] occupations with lifetime risks of about three percent seems the most reasonable" (NCRP, 1989, p. 162). The appropriateness of using 3 percent risk of fatal cancer as the basis for the NASA space radiation standard has been reviewed and endorsed in subsequent NCRP reports (NCRP, 2000, 2014); NCRP Commentary 23 specifically recommended that "planned career exposure to ionizing radiation shall not exceed 3 percent REID for cancer mortality at a 95 percent confidence level" (NCRP, 2014).

As described earlier, setting the REID at 3 percent for both sexes and all ages has resulted in different permissible radiation dose limits for male and female astronauts under the current space radiation health standard. In the most recent review focused on age and sex differences in the standard, NCRP Report No. 132 (2000), stated that it

> continues to recommend gender and age differences in dose limits … because the overall risks per unit dose for women appear higher than for men due to the greater probability of women developing some radiation induced cancers, such as stomach, thyroid and breast, the longer average lifespan of women, and the decrease in risk with age for both sexes.

In light of newer scientific data (see Table A-1 for a summary of the current evidence on sex-specific radiation risks) that show large sex-differences in lung cancer risk following exposure to radiation among the atomic bomb survivors from Japan, NASA requested in 2019 that NCRP (SC 1-27) examine whether similar sex differences in radiation-induced lung cancer exist among other populations exposed to chronic or fractionated radiation.[3]

The NASA Space Cancer Risk (NSCR) Model is used to calculate REID using available epidemiological data, physics-based transport, radiation quality and dose rate, U.S. site-specific cancer rates, and other information (see section on the NSCR model in Chapter 2 for more information about the components and uncertainties considered in the model). NASA employed conservative uncertainty criteria (97.5th percentile) on cancer mortality, in part to account for unknown non-cancer risks, such as cardiovascular risks that were not considered in the model. These risks are currently considered separately in other standards.

In practice, REID values approach 1 percent for many astronauts that have flown on the International Space Station or the Russian space station Mir (Cucinotta et al., 2008; see Figure 3-1).[4] As currently calculated, the career exposure limit for a 55-year-old male astronaut is 400 mSv, and for a 35-year-old female astronaut it is 120 mSv over the course of her career.

Considering 3 Percent REID

NASA's limit of 3 percent REID was taken as a starting point for this committee's work as it was not part of the study task to consider NASA's underlying risk model or the use of any particular REID limit.

While 3 percent REID has been used by NASA since the 1989 NCRP report, the committee discussed that it may be time for NASA to reconsider the level of REID on which to base the standard. The initial occupation

[3] This NCRP report is in progress and the committee has not had access to the results. For more information, see https://ncrponline.org/program-areas/sc-1-27-evaluation-of-sex-specific-differences-in-lung-cancer-radiation-risks-and-recommendations-for-use-in-transfer-and-projection-models.

[4] Though the career exposure limit is 3 percent REID, NASA currently uses the "administrative limit" of 1 percent REID to meet the 3 percent standard at a 95 percent confidence interval (Semones, 2021).

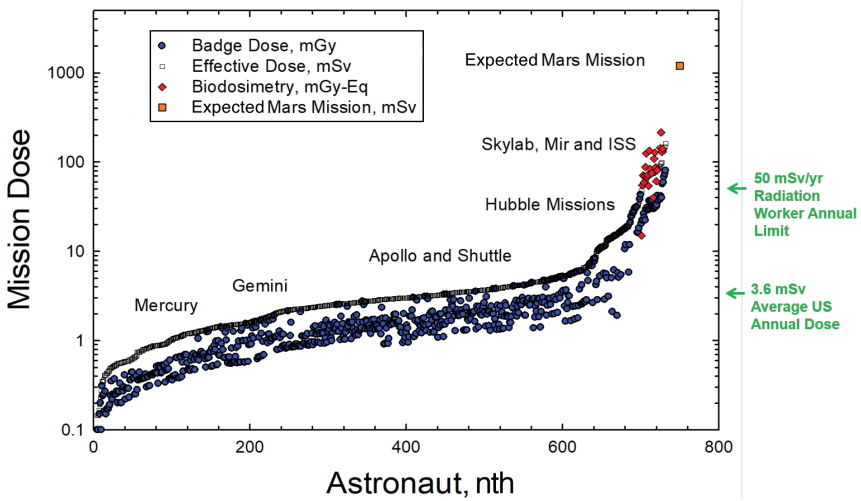

FIGURE 3-1 Summary of mission personnel dosimetry for astronauts on all past NASA space missions through 2007, including Mercury, Gemini, Apollo, Skylab, Apollo-Soyuz, Space Shuttle, NASA-Mir, and the International Space Station, plus estimate of effective dose for an astronaut on a Mars mission, with radiation worker annual limit and average U.S. annual dose noted for context. Summary of results for doses comes from thermoluminescent dosimeters worn by astronauts, biodosimetry, and estimates of effective doses for all NASA missions to date and includes data from astronauts who have flown more than once in space, with the maximum being seven times by two astronauts.
SOURCES: Adapted from Cucinotta et al., 2008; Huff et al., 2016; and Semones, 2021. © 2021 Radiation Research Society.

hazards that were used to decide on 3 percent have changed and are constantly evolving. Indeed, NCRP Report No. 132 (NCRP, 2000) noted that the use of comparisons to fatalities in the "less-safe" industries, such as mining and agriculture, in the 1989 NCRP report was no longer viable due to the large improvements made in ground-based occupational safety.

The 3 percent REID also exceeds the current level of risk in other high-hazard occupations in the United States such as mining or construction and could be due for reconsideration by NASA and other external experts. Though not directly comparable, risk of fatal occupational injury is more than an order of magnitude lower for hazardous occupations than a 3 percent REID (BLS, 2019). As discussed earlier in this report, NASA is unique in its mission of space exploration and discovery. Another unique feature setting the agency apart from traditional terrestrial employers subject to federal occupational safety regulations is that NASA is self-regulating and

uses its own frameworks to set protective standards in order to minimize, manage, and effectively communicate risks of space travel to astronauts. Views also differ on the appropriateness of comparing NASA to terrestrial occupational standards given the different nature of work, the work environment, and relationship between employer and employee.

In summary, the committee believes an important, near term opportunity exists for NASA to conduct an independent analysis of the validity of a 3 percent REID.

COMMITTEE'S ANALYSIS OF NASA'S PROPOSED SPACE RADIATION EXPOSURE HEALTH STANDARD

NASA requested that this committee review and assess NASA's proposed process and strategies for managing the risk of cancer due to exposure to space radiation (i.e., NASA's proposed changes to the space radiation health standard). As described in Chapter 1, NASA requested that this committee consider the components of the standard proposed to be changed using a dose-based standard, applying the same dose-based standard to male and female astronauts, and basing the standard on the 35-year-old female reference base. The committee was not asked to create a new standard nor evaluate NASA's stochastic cancer model underlying the space radiation health standard.

The committee's main analysis appears in this section. It includes scientific and ethical considerations related to the components that make up the proposed revised standard as well as the implications of their relationship and combination as part of a new health standard.

Considering the Interconnected Components of the Proposed Standard

REID informs or serves as the basis for the three components of the proposed revised radiation standard. The components are interconnected but each raises ethics and policy issues separately and when combined into the proposed standard.

1. Commitment to a single standard for male and female astronauts;
2. Selection of the age and sex category on which to base the standard; and
3. Choices made in calculating dose threshold. That is, setting the permissible exposure standard based on the mean, median, 95 percent or 75 percent confidence level of REID.

Notably, a commitment to a single standard requires that standard to have a reference point and justification for that choice, so 1 and 2 are linked

to each other more closely than to 3. All three components taken together determine the acceptable dose to adopt for the standard. For example, applying a single standard to male and female astronauts does not directly result in an increased allowable exposure. It is the decisions about selection of the age and sex on which to base the standard and choices made in using the 3 percent REID to determine the level of acceptable risk that determine whether dose exposure limits would be increased or decreased compared to the current standard. The combination of choosing to calculate the exposure threshold based on 35-year-old females or other age/sex category, and using the mean, median, 95 percent or 75 percent confidence level will in combination have the effect of changing the acceptable dose limit when calculated based on 3 percent REID. While each component of the standard needs to be individually justified, it is not possible to reach complete conclusion about the reasonableness or justifiability of the standard overall based exclusively on consideration of only the individual components. Thus, caution is warranted when basing policy decisions on each component in isolation from the resulting combination.

Commitment to a Single Standard for Male and Female Astronauts

In a 2014 report, the Institute of Medicine recommended that NASA should implement an ethics framework and its concomitant responsibilities as part of the agency's policies and procedures. The report included a recommendation to "provide equality of opportunity for participation in long duration and exploration spaceflights to the fullest extent possible." For this 2020–2021 study committee's consideration, NASA has proposed a revised radiation standard that is responsive to the 2014 committee's recommendation by proposing a single radiation standard that applies to all astronauts independent of sex and age. Such a single standard would provide equality of opportunity, at least to the extent that it avoids radiation exposure standards that differ by sex and result in differential opportunities for participation in crewed spaceflights.

From an ethics perspective, by instituting a single standard NASA would be changing policy in ways that reflect considerations of the principle of justice and its application. First, and as noted above, a single standard would create equality of opportunity for the members of the NASA Astronaut Corps, reflecting justice as fairness. Second, with its consequence of creating greater inclusion of female astronauts, a single standard would respect compensatory justice by rectifying the past limits on women's participation and underrepresentation in spaceflight. Third, by moving toward more balanced inclusion of males and females in spaceflight, a single standard would respect distributive justice through more equitable distribution of the risks of spaceflight which were disproportionately borne by male

astronauts as well as creating equitable distribution of the benefits of participating in crewed missions (IOM, 2014).

The decision to apply a single dose-based limit to all astronauts, regardless of sex and age, also aligns NASA with the majority of its international space agency partners. It is also the case that terrestrial occupational health radiation dose-limiting standards apply irrespective of gender. NASA moving to a single standard is consistent with standard occupational health practice, although there are notable differences between NASA's other proposed changes to the radiation health standard and occupational health practice. For example, the standard for occupational dose limits for terrestrial workers includes both an annual dose limit and a lifetime dose limit. Historically, NASA's dose limits for short-term missions within LEO are several times higher than annual occupational dose limits for terrestrial workers because NASA's limits are intended to prevent acute risks that might disrupt missions, while annual dose limits for terrestrial workers are intended to control the accumulation of career doses (Cucinotta, 2010).

Selection of the Age and Sex Category on Which to Base the Standard

NASA is proposing that the universal dose-based standard be determined based on the mean REID using a 35-year-old female as the reference. NASA indicates this is the "most protective" approach because this age group is projected to be at the highest risk. Therefore, setting the standard based on the 35-year-old female would be the most protective for any given age and sex. Compared to the option of calculating the REID based on sex-averaged for non-sex organs or the average for lung and non-sex organs, calculating the REID using a 35-year-old female is a better option because it is more straightforward and more protective based on current science. On one hand, this approach sets a single, clear and consistent dose limit for all astronauts; but on the other hand it may result in a more restrictive limit than a more individualized approach would allow.

It is reasonable for NASA, in its role as a government agency asking astronauts to accept risk in the interest of society, to adopt an approach that provides the highest level of protection to those at greatest risk of radiation exposure-based harms, acting on the ethics principle of non-maleficence (preventing or removing harm to others). It is also the case that the upcoming NCRP SC 1-27[5] report will provide more information on the differences in lung cancer between males and females based on the latest epidemiological data.

[5] At the time of the publication of this report, the NCRP Committee SC 1-27 on Evaluation of Sex-Specific Differences in Lung Cancer Radiation Risks and Recommendations for Use in Transfer and Protection Models was working on a report with recommendations for NASA.

Choices Made in Calculating Dose Threshold

NASA proposes to utilize the mean value for REID and resulting exposure threshold calculations. NASA's decision to use the mean REID would be a change from its current standard, which is based on the 97.5th percentile of REID. Other options that NASA considered include using the median, 75 percent or 95 percent. Among the considerations that suggest the approach of evaluating the risk at the mean rather than out in the tails of the uncertainty distribution are that the mean, while still imperfect, is representative of expected exposures, more stable and consistent than a quantile, easier to understand by a wider audience, and could provide a better basis for decision making.

As is well recognized by NASA, estimation of REID associated with exposure to space radiation involves multiple sources of uncertainty. The mean of the REID distribution generated from NASA ensemble modeling is estimated with lower uncertainty, compared with the currently used 97.5th percentile of this distribution (Simonsen and Slaba, 2020).

Using the mean will warrant focused attention on communicating with astronauts about the uncertainties surrounding the exposure limit. Using the risk distribution (including description of the tails) and confidence levels in communicating with astronauts, policy makers, and the public, is warranted. The committee provides this rationale in more detail in Chapters 2 and 4.

The committee notes that NASA's proposal to set the permissible dose based on the mean allows for greater dose than the current standard while continuing to use 3 percent REID. This use of the mean results in acceptance of a higher level of risk under the revised standard, compared to use of the 97.5th percentile. This higher probability of harm seems to conflict with an ethics commitment to protection from harm, minimization of risk, and NASA's requirement to ensure astronaut safety by keeping exposures as low as reasonably achievable. The committee recognizes that NASA is engaging in policy decisions and standard setting to protect crews to the greatest extent possible to limit mission risk as well as long-term risk to astronaut health and wellbeing as they consider long duration missions. Revised calculations for dose threshold within the limits imposed by 3 percent REID may be acceptable with appropriate justification.

Combined Implications of NASA's Proposed Radiation Health Standard

In NASA's proposed radiation health standard, career thresholds are driven by mean REID calculations for a 35-year-old female and would be applied to all astronauts, regardless of sex and age. The effective dose equivalent to 3 percent REID, for a 35-year-old female, is ~600 mSv (although

NASA notes that values presented are approximate, +/– 10 percent, and will be verified prior to establishing a new standard). Compared with the existing standard, this proposed standard will increase the allowable exposure for a 35-year-old female by a factor of ~3 and for a 55-year-old male by a factor of ~1.5. Future modifications to this standard could be warranted if, for example, improved models suggest that 3 percent REID is associated with a different dose, or if a different REID cutoff is justified as more appropriate, or if NASA determines that the 3 percent REID is inadequately protective. See Table 3-2 for examples of the effect of modifying certain variables of the ensemble model on the dose limit output.

To reiterate, the three components, or decisions, embedded in NASA's proposed updates to the radiation health standard do not exist in isolation—each component, or decision, interacts with the others such that changing one component results in changes to the overall standard. For example, if NASA had utilized a 35-year-old female as the basis for the new standard, but derived the dose from 3 percent REID by the current methodology of 97.5 percent confidence level, there would be no change to the allowable exposure for a 35-year-old female, but the allowable dose for a 55-year-old male would decrease. Alternatively, if NASA adopted a 1 percent mean REID, the allowable dose would be reduced for all astronauts.

Ethical Considerations

As described in Chapter 1, the committee reviewed documents from NASA presenting the proposed updates to the standard, discussed the proposed updates with NASA leaders in public sessions, and received updated versions of the proposed standard following each of the two public sessions. The committee also considered the scientific literature and reports from NASA or other expert panels on the issue of space radiation. NASA did not provide the committee with a formal ethics analysis for each component of the proposed standard or for the overall standard but did, in public session, discuss the importance of the principles of fairness and autonomy. Furthermore, ethical analysis of the proposed standard does not appear in

TABLE 3-2 Effect of Modifying Variables of the Ensemble Model on the Dose Limit Output

Modification	Effect on Dose Limit
3 percent REID → 1 percent REID	Decrease
35-year-old female → sex-averaged	Increase
97.5 percent confidence level → mean	Increase

the Statement of Task for this study but consideration of bioethics issues was requested as part of a presentation by NASA officials during a public session meeting.

This committee notes that among the consequences of the proposed single standard are that (1) the revised standard creates equality of opportunity by applying the same dose limits to all astronauts without reference to age or sex; (2) some astronauts (primarily women) would be exposed to greater doses of radiation and therefore greater risk than would have been the case with current criteria-based standards adjusted for sex and age, creating a more risky work environment for some; and (3) a single standard with dose limits based on risk to 35-year-old females comes at the expense of potential greater allowable exposures for some older and male astronauts which could be seen as an unfair restriction of opportunity for them. Taken together, the proposed standard creates equality of opportunity for spaceflight with the trade-offs of somewhat higher allowable exposure to radiation for a subset of astronauts (primarily women) and limiting exposures below otherwise acceptable doses for others (primarily older men).

Such an approach can be defended on ethics grounds, but doing so requires weighting some ethics-related commitments more heavily than others in support of the revised standard—equality of opportunity over more individualized risk assessment, and equality of opportunity over commitments to limiting risk (at least for some astronauts). It will be important for NASA to offer explicit ethics justifications for the approach adopted and the resulting standard, to be shared with astronauts and their families, as well as made publicly accessible.

Summary

A single radiation standard for male and female astronauts requires a single dose threshold to be applied. If a single standard is required by NASA, three options exist: (1) use the most protective threshold (e.g., based on risk to 35-year-old females), (2) use the least protective threshold, or (3) choose some value between the most and least protective standard. Under this logic, the most defensible approach is what NASA has proposed (i.e., to use, within the context of the 3 percent REID that this committee has considered as a fixed starting point, the most protective threshold in setting a single, universal standard for male and female astronauts). If 3 percent REID remains the basis for NASA's risk management process, the resulting standard increases the allowable exposure to radiation and risk of cancer for almost all astronauts. If NASA wanted to use the mean and reference base of a 35-year-old female to set the standard and ensure the standard was more protective than the current standard, the option would be to use a lower mean REID (e.g., 1 percent REID instead of 3 percent REID).

It is also the case that the space travel work environment has changed. A human has not traveled beyond LEO since the end of the Apollo program and it has been NASA's intent to re-evaluate the standard prior to new long-duration missions farther afield. Astronauts are also a unique population operating in a uniquely hazardous environment. Radiation carcinogenesis is one important risk but there are many others that NASA considers in the context of a mission.

The risks of space travel are born by a small group (astronauts) but the benefits are for all of society. This imbalance imparts unique responsibilities for NASA to provide protection, as much as possible, for astronauts to limit mission disruption during flight, throughout their careers, and after leaving the agency.

The committee makes the following recommendations regarding NASA's proposed space radiation health standard:

Recommendation 1: NASA should proceed with the proposed approaches to revising the space radiation health standard. As proposed by NASA, the agency should:

- **Apply a single space radiation standard to all astronauts;**
- **Utilize the most protective approach in setting the space radiation standard;**
- **Set the standard as a dose limit; and**
- **Utilize the mean value of the risk distribution based on 3 percent risk of exposure-induced death.**

In implementing this recommendation, NASA should make explicit the agency's own ethical and policy analysis justifying the revisions to the proposed standard.

Recommendation 2: In the near future, NASA should re-examine whether to use risk of exposure-induced death (REID) or other metrics, or a combination of metrics, in setting the dose-based space radiation health standard. NASA should conduct an independent analysis of the validity of 3 percent REID and make explicit the agency's justification for the metrics they choose.

The committee notes that in the rationale section of the proposed radiation exposure standard (see Box 3-1), it says, "Any total exposure (which includes the past exposures plus projected exposure) that exceeds the limit would require a waiver by the agency prior to the mission." Furthermore, the committee notes that NASA has published in numerous papers that astronauts on a Mars mission will be expected to exceed the career limit

of ~600 mSv effective dose (see Figure 3-1 and Table 3-3). The committee recognizes that to complete a crewed mission, especially long-duration missions to other planets, there are a multitude of risks that the astronauts and mission support staff have to address.

The committee reached the following conclusion regarding NASA's proposed space radiation health standard:

> *Conclusion I: The committee concludes that astronauts who travel on long-duration spaceflight missions are likely to be exposed to radiation levels that exceed the proposed new space radiation standard of an effective dose of 600 mSv. For example, a mission to Mars is likely to exceed the exposure standard by up to 150 percent. Unless technological advancements and engineering controls provide improved radiation shielding or other protections to astronauts, for a mission to Mars to proceed, NASA would need to seek waivers to the radiation health standard both for the mission and for each astronaut.*

TABLE 3-3 Projected Radiation Risks for Astronauts on Lunar and Mars Missions

			Fatal risk, % (95% CI)	
	Absorbed Dose (Gy)[a]	Effective Dose (Sv)	Men (age 40 years)	Women (age 40 years)
Lunar mission (180 days)	0.06	0.17	0.68% (0.20–2.4)	0.82% (0.24–3.0)
Mars orbit (600 days)	0.37	1.03	4.0% (1.0–13.5)	4.9% (1.4–16.2)
Mars exploration (1,000 days)	0.42	1.07	4.2% (1.3–13.6)	5.1% (1.6–16.4)

NOTES: Calculations are at solar minimum, where GCR dose is highest behind a 5 g/cm^2 aluminium shield. CI = confidence interval; GCR = galactic cosmic rays; Gy = grey; Sv = sievert. Intervals are obtained by varying the input parameters of the NSCR NASA risk model according to "parameter uncertainty distributions" determined by NASA based on expert judgment.

[a] Mean for tissues known to be sensitive to radiation and at risk of cancer, including lung, colon, stomach, bladder, bone marrow, and breast and ovaries in women. Competing causes of death are included in calculations because they decrease risk probabilities if high (i.e., >5 percent).

SOURCE: Adapted from Cucinotta and Durante, 2006.

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4

Communicating About Radiation-Induced Cancer Risks

As part of this study's Statement of Task (see Box 1-2 in Chapter 1), the National Aeronautics and Space Administration (NASA) requested the committee to consider, "how to express what is needed in the form of a radiation risk management process or approach NASA could apply to determine astronaut eligibility for crewed missions." This chapter focuses on this aspect of the study task and specifically on communicating with astronauts about the risks associated with exposure to space radiation.

As NASA works to manage radiation-exposure health risks, it will be important for the agency to continue to adhere to the radiation safety principle of keeping radiation exposures as low as reasonably achievable (ALARA), employ the ethical principles of beneficence and non-maleficence in decision making, and communicate effectively about radiation risk to astronauts in a manner that respects the ethical principles of autonomy and justice (IOM, 2014; NCRP, 2014). A key component of risk management is evidence-based, thorough, and effective communication of the risks. NASA communications concerning radiation exposure are aimed at astronauts as well as NASA employees and contractors responsible for eliminating, minimizing, or mitigating these risks. Policy makers, other federal agencies, and commercial spaceflight companies are also audiences for NASA's risk communication products.

This chapter provides a framework for how NASA can best communicate space radiation risks to astronauts. First, the chapter introduces the field of science communication (Fischhoff and Scheufele, 2013, 2014, 2019; NASEM, 2017), and then it identifies the risk communication needs of astronauts. When NASA presented to the committee its proposed revisions

to the space radiation standard, it also presented a visual representation of the radiation risk profile ("risk bands," see Figure 4-1), which the agency is considering using as a system for communicating occupational radiation-induced health risk assessments to astronauts. The committee closely reviewed this visual aid and, in this chapter, presents its conclusions and recommendations on the benefits and deficiencies of this aid.

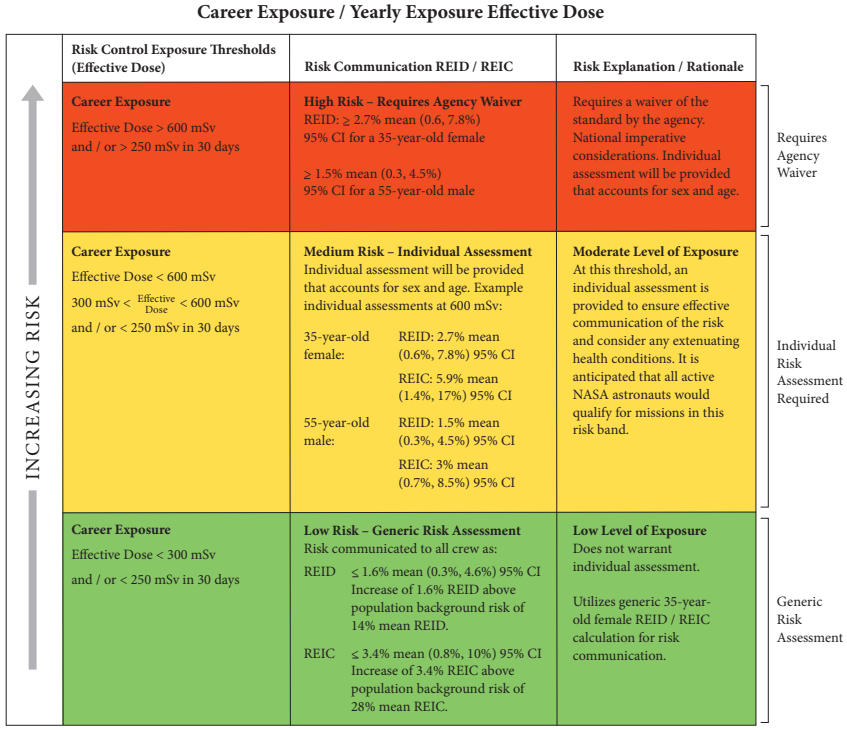

FIGURE 4-1 NASA's proposed system for communicating its proposed space permissible exposure limit for spaceflight radiation exposure standard.
NOTES: If NASA chooses to use this system for communicating risk, the following text should be revised. In the green band "14% mean REID" should be revised to read "14% mean lifetime risk of death from cancer." Similarly, "28% mean REIC" should be revised to "28% mean lifetime risk of being diagnosed with cancer." These distinctions are important to communicating the meaning of REID and REIC. Confidence intervals are obtained by varying the input parameters of the NSCR NASA risk model according to "parameter uncertainty distributions" determined by NASA based on expert judgment. REIC = risk of exposure-induced cancer; REID = risk of exposure-induced death.
SOURCE: White paper provided by Dave Francisco to the committee, February 12, 2021.

NASA'S AIMS WHEN COMMUNICATING CANCER RISK

The first step in communicating risk is to have a clear understanding of the goals of the communication. NASA communications about the cancer risk from radiation exposure during specific space missions and over the course of an astronaut's career appear to have several aims:

- Enable astronauts to make their own health protective decisions;
- Provide the rationale for flight assignment determinations;
- Help astronauts plan their careers; and
- Protect astronaut health and space mission safety and viability.

Achieving these risk communication aims requires an understanding of the risks and the standard themselves, as well as comprehension of how astronauts understand and interpret the formal and informal communications about them. Achieving these aims is complicated by the dynamic nature of the risk communication situation, including but not limited to the evolution of radiation risk sciences, changes in the nature of space missions, diversification of the NASA Astronaut Corps, and the evolution of occupational exposure standards for terrestrial employees, which NASA may reference in developing risk management strategies.

RISK COMMUNICATION RECIPIENTS AND THEIR NEEDS

Health communication can be classified into three categories that differ in the degree of customization and audience segmentation (Hawkins et al., 2008): generic, targeted, and tailored. A generic health message, or a one-size-fits-all approach, provides information within a single communication without taking into account the characteristics of the audience. Targeted messages aim to reach a specific subgroup often based on sociodemographic characteristics such as gender and age. While targeted messages rely on such individual factors, targeting generally does not take into account aspects including cognitive and behavioral factors that can influence health decisions. Tailored messages "intend to reach a specific person based on characteristics that are unique to that person, related to the outcome of interest, and derived from an individual assessment" (Kreuter et al., 2013). Tailored messages are more likely to be read and remembered (Brug et al., 1998; Skinner et al., 1994), perceived to be personally relevant (Noar et al., 2009), and are more effective compared to non-tailored approaches (Noar et al., 2007; Richards et al., 2007; Rimer and Glassman, 1999; Sohl and Moyer, 2007). A systematic literature review of interventions designed to provide tailored information on cancer risk and screening methods showed that cancer information tailored

to individuals' risk factors increased realistic risk perception compared to generic information (Albada et al., 2009).

Depending on its communication goals, NASA may wish to develop generic space radiation risk messages for public audiences, in addition to the targeted risk messages it uses to communicate the space radiation standard to NASA astronauts as a group and the tailored messages it uses for individual astronauts.

Risk Communication Needs for NASA Astronauts

In its discussion of why NASA is proposing to use a space permissible exposure limit standard based on an effective dose of 600 mSv as its new risk management standard, NASA noted that dose is more familiar to astronauts than risk (e.g., risk of exposure-induced death [REID]). Similarly, NASA suggested that the use of "traffic light" color bands to represent the three-stage risk profile would be familiar to astronauts, given the widespread use of color-coded risk matrices at NASA. Familiarity can be an important determinant of communication effectiveness, but it is not the only factor (Keller, 2011). Spaceflight radiation risk communication needs are best assessed relative to the decisions that will be made in response to the communication. To the best of the committee's understanding, a systematic evaluation of astronauts' risk communication needs has not yet been conducted.

The first step in risk communication design in this context is to determine what information astronauts need. Astronauts have prior training and significant expertise that is likely to influence their risk communication needs, which may include training in probability and statistics, as well as in radiation and its biological effects. It is also likely that there is variation among astronauts in expertise and interest regarding radiation-induced cancer risk. In addition, among astronauts, there are variations in decision contexts such as concerns about reproductive health that could influence individual astronaut decision risk communication needs.

Demographics and sociocultural differences may also influence perceptions of risk communications. While many studies have found that these types of variables (age, gender, race, political orientation) account for little variance, some studies do find effects. This might be because certain groups perceive they are at risk of higher rates of exposure or because some groups have lower institutional trust in a particular context (Griffin et al., 2004). Risk message recipients filter messages through their own values and beliefs (Balog-Way et al., 2020). For example, motivated reasoning, where individuals interpret information in a way that is consistent with their predetermined opinions, may explain challenges to designing effective communications, particularly in the context of uncertainty.

Risk Communication Needs for Other Audiences

While NASA astronauts are the primary audience for communication of radiation exposure risks, other communication recipients may include NASA program managers, engineers, and designers, as well as policy makers, other federal agencies, commercial spaceflight companies, and various interested publics. Each of these groups makes decisions that might be informed by the proposed new standard and associated risk communications.

Audiences outside of NASA may not have the same technical background or personal characteristics as NASA personnel, and thus they are likely to interpret and react differently to figures, data, and information about radiation-induced cancer risks. Numeracy and other individual characteristics affect the interpretation of graphical or visual information to communicate risk (Hess et al., 2011; Kreuzmair et al., 2016; Okan et al., 2016; Yang et al., 2021). Expertise also influences how information is processed and used in risk decision contexts; therefore, risk communication needs will vary depending on the specific expertise of the risk communication recipient (Cokely et al., 2018; Perko, 2014).

CONSIDERING NASA'S PROPOSED RISK COMMUNICATION TOOL FOR THE SPACE RADIATION STANDARD

In public meetings, NASA presented this committee with a figure that presents the proposed space permissible exposure limit, as seen in Figure 4-1.[1] The committee understands that this visual aid is intended as NASA's primary risk communication system for the updated space radiation standard. It is composed of three bands, colored in green, yellow, and red as a "traffic light" to represent increasing risk. Each band contains three cells, outlining the exposure thresholds, REID and the risk of exposure-induced cancer (REIC), and the explanation or rationale for each band. The matrix contains both numerical information (e.g., REID and REIC) and evaluative information (e.g., high, medium, low) to communicate the risk. It also includes risk management information, such as the corresponding mission determination for specific audiences (e.g., "all active NASA astronauts would qualify for missions in this band" or whether a waiver would be required for a given mission).

The effects of risk communications can be difficult to predict (Roth et al., 1990; van der Bles et al., 2019). Instead, risk communication methods

[1] NASA presented two versions of this figure to the committee. The first version is available in NASA's January white paper and the modified, second version, which will be referenced through the remainder of this report, is shown in Figure 4-1. NASA's white papers may be requested by contacting the National Academies' Public Access Records Office (PARO@nas.edu).

can be evaluated empirically (Fischhoff et al., 2011; NASEM, 2017; NRC, 1989; Spiegelhalter, 2017). Evaluating risk communications and risk messages first requires knowing or assuming the purposes of the communication (Fischhoff et al., 2011; NASEM, 2017; NRC, 1989). Once the goals are determined, attributes or characteristics of risk communications are evaluated based on empirical evidence gathered from the intended recipients or a representative sample thereof. Lacking such evidence, the committee comments on the elements and attributes of Figure 4-1 based on risk communication literature. The committee adapts the framework proposed by van der Bles et al. (2019) for communicating epistemic uncertainty. This framework assesses the source of the message, the content of the message, the format of the communication, and the anticipated effects of the communication on recipients.

Source of the Message

Presentations and materials provided to the committee by NASA show that both formal and informal communications with astronauts about radiation risks come from multiple sources including the Space Radiation Analysis Group at NASA, the Human System Risk Board, flight surgeons, and others. NASA shared several examples of risk communication materials with the committee, some of which have been used in briefings to the astronaut office or for individual astronauts (e.g., Astronaut Radiation Risk Reports; Semones, 2021). The typical process for astronauts to learn about radiation risk includes briefings by the NASA Radiation Health Officer, annual individual meetings with flight surgeons, as well as, additional meetings with flight surgeons pre- and postflight.

While the committee understood from NASA's public presentations that formal NASA communications are trusted by astronauts, no systematic evidence was presented on this point. Trust in the message source and messenger influences whether a risk message recipient interprets the message as expected, ignores the message, or responds in an opposite way, as in the case of risk communications that backfire (Cairns et al., 2013; McComas, 2006). NASA may consider developing templates to guide meetings between flight surgeons and astronauts, as this may have the benefit of standardizing what information is communicated to astronauts, regardless of the individual characteristics of the messenger. Astronauts may also see flight surgeons as gatekeepers, which could change how astronauts perceive the information they receive and conversely, what information they share.

In addition to meetings where information on space radiation is presented by NASA's Office of the Chief Health and Medical Officer or flight surgeons, it could be valuable to allow astronauts to access on their own

information on cancer risks associated with space radiation. Providing astronauts access to a searchable database or repository of scientific literature used by NASA in developing the space radiation standard and other resources from the radiation science literature could reduce any barriers—real or perceived—astronauts might face in developing their own understanding of space radiation risks. Some astronauts may prefer to explore the relevant research on their own, either instead of or in conjunction with briefings and one-on-one meetings with NASA flight surgeons.

Content of the Risk Communication Message

Individualized Risk Communication

For the purpose of this report, the committee defines *individualized risk communication* as the process of tailoring information based on an individual's specific risk factors for a health condition (e.g., age, sex, family history, prior exposures) (Edwards et al., 2013). As discussed earlier in this chapter, tailored communications are generally found to be more effective than general communications (Albada et al., 2009), and this would seem to be particularly the case in considering how best to communicate with individual astronauts.

NASA proposes a generic risk assessment in the green risk band (exposures below ~300 mSv) and communicating REID and REIC for a 35-year-old female to all astronauts. NASA proposes individual risk assessments using sex and age with consideration of extenuating health conditions for the yellow risk band (exposures between ~300 and ~600 mSv) and the red risk band (exposures exceeding the ~600 mSv limit in the standard) (see Figure 4-1). For astronauts with a career exposure above ~600 mSv, a waiver would be required to fly additional missions. NASA's proposed individual risk assessment is differentiated from the general assessment only by taking into account sex and age. An individual astronaut who wishes to interpret his or her own spaceflight-attributable cancer radiation risks from a proposed mission might need not only specific information about dose and dose rate, but also information about the influence of nonmodifiable individual factors such as genetics and modifiable factors such as lifestyle and environmental factors that interact with spaceflight radiation, all of which contribute to their baseline cancer risk. An individual assessment may also include information about screening and early detection of cancers. NASA may consider exploring future opportunities to enhance the individual risk assessment.

While the Genetic Information Nondiscrimination Act (GINA) precludes the use of personal genetic information in NASA risk management (see Locke and Weil, 2016, for further discussion on this topic), NASA

could consider providing easy access to summary information regarding what is known about the genetic factors that might interact with spaceflight radiation exposures to influence long-term health outcomes for astronauts, as well as the influence of other lifestyle and environmental factors. Best practices indicate the importance of addressing relevant prior beliefs (Morgan et al., 2002; NASEM, 2017), and explicitly discussing uncertainties (Fischhoff, 2012; Fischhoff and Davis, 2014; Manski, 2019; van der Bles et al., 2020), although this poses challenges (NASEM, 2017; Politi et al., 2007; van der Bles et al., 2019).

Putting Risk in Context

Best practices in risk communication suggest communicating both absolute and relative risk to inform risk management decisions (Spiegelhalter, 2017). It is key, however, to also communicate a baseline for relative risks. Figure 4-1 includes REIC, REID, 30-day dose rate, and career effective dose limit. Furthermore, REIC and REID are also communicated as increases above population background cancer risk, for which absolute risk (point) estimates are provided, although it is unclear from Figure 4-1 what the reference population is. Evidence-based communication practices highlight the importance of representing risks in multiple ways (Fischhoff, 2012). For instance, complementing REID with estimates of years of life-loss for deaths that occur may help astronauts contextualize REID in relation to other mortality risks (Cucinotta, 2010). There is evidence that health consequences are easier to imagine and to be remembered when they are presented as years of life loss or gained vs. increase or decreases in disease risk (Galesic et al., 2011).

Figure 4-1 also uses evaluative language by characterizing the risk bands as "low," "medium," or "high." Interpretations and evaluations of technical risk quantities such as REIC, REID, and effective dose can be strongly influenced by this sort of evaluative information (Budescu et al., 2014). It is unclear if the evaluative judgments in Figure 4-1 are intended to correspond to the absolute or relative risks in each band. For example, if a terrestrial worker was exposed to a hazard with a 2.7 percent REID, that would be more than an order of magnitude greater than the level determined by the U.S. Supreme Court to be acceptable for industrial workers.[2]

To help empower astronauts to understand the full picture of their cancer radiation risks, the background cancer risks in the population and risks from occupational radiation exposures can also be communicated in the context of factors that might influence the astronaut's cancer risk (e.g., family history, lifestyle factors) and in the context of other sources of

[2] 29 U.S.C. 655(6)(b)(5).

mortality risk on space missions. Additionally, as the absolute and relative risks can change over time (e.g., chronic versus acute risks), it is helpful if the time interval is explicitly communicated.

NASA also needs to be prepared to answer questions from astronauts on their radiation risk profile, which includes current and past occupational exposures as well as other radiation doses received from medical diagnostic and therapeutic procedures, naturally occurring radioactivity in the environment, and other sources. While these discussions are important to allow astronauts to make informed decisions about missions and understand radiation risks, the committee cautions that communication about non-occupational exposures—in particular, medical exposures—needs to be done with great care. Specifically, NASA needs to communicate to astronauts how exposures other than those received as part of the astronaut's career and space missions are recorded and managed by the agency although they do not contribute toward the astronauts' permissible career dose (NCRP, 2014). Furthermore, NASA needs to make clear that decisions regarding medical diagnostic and therapeutic procedures that involve ionizing radiation are made by qualified medical professionals based on the principles of justification and optimization (ICRP, 2007a).

Format of the Communication

Appropriately designed visual aids can improve both risk understanding and health-relevant decision making (Garcia-Retamero and Cokely, 2017), but they do not always do so (Ancker et al., 2006).

Communicating Uncertainty

The sources of uncertainty in NASA's cancer risk model are discussed at length in Chapter 2. This section will focus on strategies to communicate uncertainties and adequately incorporate uncertainties into NASA's risk communication strategies. In many cases, it is valuable to represent uncertainty in multiple ways to support the understanding of a diverse audience.

Figure 4-1 presents 95 percent confidence intervals for REIC and REID. Even if astronauts have a clear understanding of the relationships between dose and REIC and REID, the presentation format may influence risk perceptions in unintended ways. Confidence intervals can be misinterpreted due to misunderstanding of what they mean, because of motivated reasoning (Dieckman et al., 2015; Viscusi et al., 1991), or because of the misinterpretation of a visual representation of the interval (Savelli and Joslyn, 2013). These misinterpretations can lead to unanticipated effects of the communication (Johnson and Slovic, 1998). Risk communication research suggests that decision makers are sensitive to the ambiguity (or range of

uncertainty) associated with a numerical forecast, although specific effects have proven difficult to predict (van der Bles et al., 2019). In some cases, decision makers may discount information with high ambiguity information to focus on more precise, although potentially less relevant, information (Hsee, 1995). In other contexts, it is valuable to use numerical, rather than only verbal, descriptions of uncertainty to improve understanding (Budescu et al., 2009; Dieckmann et al., 2010).

Effects of communicating the uncertainty around risks (also called ambiguity) are thus a function of the recipient's risk attitudes, numeracy, and the format of the uncertainty communication (Han et al., 2011). Graphical presentations such as gradient bands, probability density functions, or cumulative distribution functions to represent the central tendency and associated uncertainty in estimated risk appear to help convey the actual estimated distribution of probability for the risk estimates (Ibrekk and Morgan, 1987; van der Bles et al., 2019).

Figure 4-1 currently does not distinguish sources of uncertainty, nor does it directly acknowledge risk assessment model limitations. The extent to which this does or should influence interpretations of Figure 4-1 is not clear, as risk communication research is inconclusive on this topic (Budescu and Wallsten, 1995; Budescu et al., 2009; Padilla et al., 2020; Teigen and Løhre, 2017; van der Bles et al., 2019). However, directly acknowledging measurement and model limitations may facilitate conversations with members of the NASA Astronaut Corps that acknowledge that the quality of evidence could be improved, which could in turn support shared decision making and increase trust and transparency.

While evidence suggests that multiple forms of communicating uncertainty may be beneficial, caution is warranted. Evidence-based practice also recommends simplifying and highlighting the essential information (Zikmund-Fisher et al., 2010). In the absence of evidence-based evaluations of NASA's specific communications practices and materials, it is unclear how to best strike the balance between enough information and too much information, especially with regard to the communication of uncertainty.

Risk Matrices and Traffic Light Color Coding

As described previously, Figure 4-1 is a matrix containing three bands colored in green, yellow, and red as a "traffic light" to represent increasing risk. Each band contains numerical and evaluative information on the risk, as well as risk management information relevant to mission assignments. Although matrices can be helpful in tracking and prioritizing risks, they pose several communication challenges. The categorization of risk consequences is subjective, as it reflects a specific risk attitude, and therefore it

is best practice to be transparent about how risk categorization decisions are made (Cox, 2008).

Colors can be helpful in risk communication (Hill et al., 2010; Severtson et al., 2009; Sutton et al., 2021). Traffic light color-coded communications are used in numerous contexts to communicate risks, including health risks (Neuner et al., 2011). For example, when used in nutrition labeling (Emrich et al., 2017), the traffic light has the advantage of being familiar to lay audiences and consequently can be more effective than numeric labels at influencing food purchases (Trudel et al., 2015; Zhang et al., 2020). The use of traffic light color coding may be particularly familiar to astronauts, because NASA uses this system to visualize other risks (Dillon et al., 2018, 2019).

In the context of radiation, colors represent approximate relative magnitude of risk; that is, they inherently provide evaluative descriptions of each band as "low," "medium," or "high." In the case of radiation, stochastic health risks from radiation exposure increases continually with increased exposure, rather than in a stepwise fashion with distinct cutoffs or endpoints for risk levels. Therefore, categorizing radiation risks into traffic light color-coded bands may not accurately represent the risk. Additionally, the traffic light color-coded system could be intended to convey information on decision making: green means go, yellow slow, and red stop. In the case of Figure 4-1, it is not clear that distinct risk management decisions correspond to each band. It is particularly unclear if the red band means stop, because the waiver process is mentioned within the red band (see further discussion on the waiver below).

Shortcomings in the use of color-coded risk matrices at NASA have previously been identified. A study that assessed risks reported for NASA 21 Goddard Space Flight Center from the Cross Cutting Risk framework database from July 2015 to 2017 found that among 666 unique reported technical and programmatic risks, only 5 percent were categorized as red, 51 percent were yellow, and 44 percent were green (Dillon et al., 2018), consistent with extensive research showing tendencies for subjectively judged frequencies of risks to be compressed (overestimated for low probability risks, underestimated for high probability risks) (Fischhoff, 2015).

The committee reached the following conclusion:

Conclusion II: NASA has proposed to use a traffic light color-coded system to categorize and communicate space radiation risks. Without empirically testing the traffic light color-coded system, there is insufficient information to determine whether it is an effective way for NASA to communicate the space radiation risks to astronauts.

Anticipated Effects of the Communication

Ideally, any proposed communication tool or message should be designed based on stated communication goals, the evidence from prior research regarding how best to achieve those goals with the targeted audience, and at least exploratory (i.e., formative) empirical evaluations of the message or tool with representatives from the targeted audience. Anecdotal evidence was provided to the committee regarding astronaut radiation risk communications needs and experiences, but the committee was not given any systematic empirical evidence of risk communication effectiveness to review. NASA astronauts are heterogeneous and singularly dissimilar to general audiences (e.g., with regard to expertise and decision contexts), which further increases the difficulty of predicting the likely effects of specific risk communication tools, such as Figure 4-1, on NASA astronauts with regard to specific communication aims. While recognizing these challenges, the committee recommends modifying Figure 4-1 in light of current understanding of anticipated risk communication effects and ethical considerations (e.g., autonomy) as shown in Figure 4-2.

The committee reached the following conclusion:

Conclusion III: The committee reaches the conclusion that there are two concerns with the proposed traffic light system for communicating the space radiation health standard dose-based thresholds:

- *At doses below the standard (i.e., in the green and yellow bands), there is insufficient clarity and detail about associated cancer risks.*
- *At doses above the standard (i.e., in the red band), inclusion of the waiver process suggests that an exception to the standard is built into the standard and its application.*

The committee makes the following recommendation:

Recommendation 3: To inform astronauts about their radiation risk, NASA should provide all astronauts with an individual radiation risk assessment and revise the risk communication system (i.e., the traffic light) for the updated space radiation standard to do the following:

- **Assess and communicate the radiation risk at an individual level (as opposed to generic risk assessments) for all astronauts independent of the actual or projected radiation exposure and risk.**
- **Communicate the mean value of the risk estimate associated with an astronaut's radiation exposure.**

INCREASING RISK

Effective-Dose Thresholds	REID and REIC Values	Risk Communication and Impact on Ability to Fly
Career Exposure: ≥ 600 mSv BFO limit: > 250 mSV in 30 days	**Dose ≥ 600 mSv – Dose Exceeds Standard** Individual assessment will be provided that accounts for sex and age. Include example individual assessments; REID and REIC values to be supplied by NASA.	Individual risk assessment will be communicated with the astronaut. An active NASA astronaut in this risk band **would not qualify** for missions.[a]
Career Exposure: ≥ 300 mSv but < 600 mSv BFO limit: < 250 mSV in 30 days	**Dose 300 to < 600 mSv – Permissible Dose Below the Standard** Individual assessment will be provided that accounts for sex and age. Example individual assessment at 600 mSV: **35-year-old female:** REID 2.7% at the mean (0.6%, 7.8%) 95% CI REIC 5.9% at the mean (1.4%, 17%) 95% CI **55-year-old male:** REID 1.5% at the mean (0.3%, 4.5%) 95% CI REIC 3% at the mean (0.7%, 8.5%) 95% CI	Individual risk assessment will be communicated with the astronaut. An active NASA astronaut in this risk band **would qualify** for missions.
Career Exposure: < 300 mSv BFO limit: < 250 mSv in 30 days	**Dose below 300 mSv – Permissible Dose Below the Standard** Individual assessment will be provided that accounts for sex and age. Include example individual assessments at 300 mSv; REID and REIC values to be supplied by NASA.	Individual assessment will be communicated with the astronaut. An active NASA astronaut in this risk band **would qualify** for missions.

FIGURE 4-2 Proposed modifications to NASA's communication tool: a modified tool for communicating the occupational, radiation-induced health risk assessment of astronauts.
NOTES: Limits encompass cancer, cardiovascular, and central nervous system. Cancer is the constraining factor. BFO = blood forming organs.
[a] Exposures ≥ 600 mSv would require a waiver of the standard by the agency based on considerations of national imperative, how essential the mission is, and individual risk considerations.
SOURCE: Created by the committee based on NASA's proposed visual aid.

- **Communicate the uncertainties for the risk distribution using both uncertainty intervals and limits, and visual representations of the risk distribution such as probability density curves, histograms, or heat maps.**
- **Address specific questions and concerns that individual astronauts may have regarding their overall health risks following communication of their actual or projected radiation dose, and help them place radiation risks into perspective compared to other mission risks.**

The committee understands NASA may want to continue to use the traffic light color-coded method of communication because it is familiar to astronauts and is similar to risk matrices used to communicate other human health risks. If the traffic light communication system is used to convey radiation cancer risk then the committee proposes modifications to Figure 4-1 (NASA's diagram), which are shown in Figure 4-2. Specific updates include

1. Remove the mention of the waiver from the red band.
2. Explicitly label the red band as exceeding the standard.
3. Replace evaluative descriptions of each band (low, medium, and high) with more appropriate risk management terms describing each band in the context of the standard, such as *acceptable dose* and *dose exceeds standard*.
4. Include information on whether or not an astronaut qualifies for missions in each band.

The committee would like to note that the effectiveness of the modified matrix also needs to be tested.

The committee makes the following recommendation:

Recommendation 4: NASA should communicate a comprehensive picture of an individual astronaut's cancer risks due to radiation exposure, beyond the information contained in the traffic light system. To do so, NASA should do the following:

- **Respond to questions from astronauts regarding their total radiation exposure, and help astronauts put their radiation-induced cancer risk in context.**
- **Continue to discuss any changes in radiation risks as part of routine health briefings for the astronaut office, crews, and individual astronauts.**
- **Provide astronauts with an up-to-date resource on their radiation risks that they can access outside of formal meetings with NASA's Office of the Chief Health and Medical Officer.**
- **Provide astronauts with easy access to summary information regarding what is known about the cancer risk factors that might interact with radiation exposures to influence long-term health outcomes for astronauts.**

RISK COMMUNICATION AND NASA'S WAIVER PROCESS

Protection of the health and safety of astronauts is handled differently than for any other profession. Workers in terrestrial professions are primarily protected by health and safety standards and regulations established by the Occupational Safety and Health Administration (OSHA). However, the OSHA ground-based radiation standards do not apply to astronauts engaged in spaceflight. Instead NASA is required to "establish supplemental standards appropriate for space missions" (Locke, 2016). For astronauts, NASA's Health and Medical Technical Authority (HMTA) establishes and implements the agency's own occupational exposure limits and other health standards, often relying on external scientific advice and expertise.

The mission of HMTA focuses on both the health and safety of astronauts and the viability of agency missions. To do this, HMTA standards, such as fitness for duty standards, are applied to individual astronauts to both protect the astronauts and also to assure they can perform at a level needed for any specific mission. NASA also establishes space permissible exposure limits (SPELs), which are quantifiable limits of exposure to a component of the environment during spaceflight over a given length of time, such as limits on lifetime radiation exposure (NASA, 2014). NASA's exposure limits, like those of other agencies and organizations, consider the possibility or probability of adverse outcomes from hazards.

Exposure-related risk deemed acceptable by NASA is not specifically stated but it is implied by NASA SPELs and permissible outcome limits. NASA permissible outcome limits are described as the "acceptable maximum decrement or change in a physiological or behavioral parameter, during or after a spaceflight mission, as the result of exposure to the space environment" (NASA, 2014, p. 19).

Occupational exposure limits by OSHA and NASA, as well as those recommended by other agencies and nongovernmental organizations, are generally based on the best available scientific information when they are established. As a rule, there is a process for adjusting standards based on new or improved scientific information.

NASA generally addresses the need to meet a specific standard by implementing what is known as a hierarchy of controls, a well-established set of practices. For example, if the risk results from the use of a particular substance such as benzene or asbestos, NASA may choose to protect all employees by eliminating the use of the hazardous material and substituting a less hazardous alternative. When a chronic disease may result from cumulative exposure to a hazardous substance over time, NASA may choose to reduce the level of exposure to all employees through improved engineering and design, when and where it is feasible to do so. Exposure for any individual can also be reduced through "administrative controls," such as

job assignments that take into consideration past accumulation of exposure and thus risk. An individual may be required to wear protective equipment designed to reduce risk associated with specific job duties.

If hazards associated with a particular potential work activity cannot be controlled or mitigated adequately using available technology, the employer may decide to postpone or abandon the potential work activity until they or others develop the technology needed to control the risk to the desired level.

However, space exploration missions may face challenges to risk mitigation that are not typically found in terrestrial high-hazard work. Terrestrial workers in high-risk jobs may choose to end their exposures by leaving their job. This is likely not the case for astronauts, particularly those on long duration missions beyond low Earth orbit. An astronaut's commitment to any particular mission is generally irrevocable once in space. There may be missions that the agency believes are so time sensitive and have sufficient urgency that there is justification for exceeding the established standard for all astronauts. In this instance, unlike employers subject to OSHA standards, NASA may seek to obtain permission for a mission waiver that would permit the agency to subject all volunteers for that mission to an unusual level of risk that would be unacceptable in less time-sensitive and critical missions.

Waivers for specific missions and potentially for individual participation in any given mission was considered in depth by the Institute of Medicine's Committee on Ethics Principles and Guidelines for Health Standards for Long Duration and Exploration Spaceflights (IOM, 2014). That committee recommended that NASA follow a three-level, ethics-based decision framework when considering a waiver to an existing standard or standards. The threshold consideration would be to consider and explicitly make a determination as to whether "any missions that are unlikely to meet current health standards are ethically acceptable" and if so, what "specific conditions must be fulfilled" to approve the waiver (IOM, 2014, p. 144). The 2014 committee expected NASA would make this general determination to establish and articulate criteria independent of any specific mission and that these criteria would be known both to the NASA Astronaut Corps and the general public. Once the criteria were established, the 2014 committee recommended that NASA consider "whether a specific mission is ethically acceptable" by determining whether the particular mission meets the mission-independent criteria established and communicated by NASA (IOM, 2014, p. 144). If NASA decides the specific contemplated mission meets these criteria, the agency would then be in a position to consider individual astronaut participation and crew composition. This consideration would include the skills and expertise needed for the mission, as well as astronauts' individual health and risk considerations. Astronauts would be making these decisions alongside NASA at this stage (IOM, 2014).

The waiver process recommended previously is consistent with the process of "justification" described by the International Commission on Radiological Protection (ICRP, 2007). It notes that certain necessary occupational activities may result in uncontrolled exposures that exceed established limits. The ICRP says that these exposures need to be "justified" by a process that often includes public consultation:

> The responsibility for judging the justification usually falls on governments or national authorities to ensure an overall benefit in the broadest sense to society and thus not necessarily to each individual. However, input to the justification decision may include many aspects that could be informed by users or other organizations or persons outside of government. As such, justification decisions will often be informed by a process of public consultation. (ICRP, 2007a)

NASA has not established an upper limit for its proposed waiver process. The main purpose for an upper dose limit to the waiver is to provide additional protection to astronauts from the expected adverse health effects of high radiation doses. High radiation doses carry high risks for cancer induction in the future and could induce tissue reactions (deterministic effects) (ICRP, 2007b). For example, on board a spacecraft, shielding and operational dosimetry systems are used effectively to mitigate exposure to an SPE. However, it is difficult to predict when an SPE will occur and how intense the radiation will be. If astronauts are performing an extravehicular activity in space or on a planetary surface when an SPE occurs, they could be in serious jeopardy. While an upper limit for the waiver is appropriate, the committee does not see it as appropriate to recommend to NASA what an upper limit should be.

The committee's view is that the process of issuing a waiver needs to be separate from the process of setting, adhering to, and communicating the radiation health standard. As such, providing a recommendation on the radiation dose limit for the waiver is outside this committee's task, which focuses on the assessment of the proposed revised radiation standard and effective risk management and communication. Establishing a universal upper limit to the waiver independent of the mission could lessen the value of setting and adhering to the radiation health standard, which in turn creates communication challenges on what the actual occupational health limit is. The goals of the missions that would require a waiver to individual astronauts could include advancing science and technology, space exploration, or national imperative. Therefore, the specific need to carry out a mission could differ in significance and urgency. NASA needs to maintain authority over the decision to carry out a mission as well as over the decision to issue a waiver to its astronauts following an established process.

The fact that NASA serves as both employer and the organization that establishes and assures compliance with its own health standards confers particular ethical responsibilities and opens the agency to a high level of public scrutiny. The previous committee report (IOM, 2014) described the ethical principles serving as the foundation for this recommended stepwise process.

The committee reached the following conclusion regarding NASA's waiver process:

Conclusion IV: The committee recognizes that NASA's inclusion of the waiver in its space radiation risk management process may be necessary to maintain the flexibility for the agency to pursue missions in which astronauts are exposed to radiation doses that exceed its standard. The committee concludes there is a need for an explicit and public framework for how NASA will consider both mission and individual waivers.

The committee makes the following recommendation:

Recommendation 5: NASA should develop a protocol for waiver of the proposed space radiation standard that is judicious, transparent, and informed by ethics. To avoid the perception that an exception to the standard is built into the space radiation standard itself, NASA should follow the ethics decision framework in developing a waiver protocol and it should provide supporting analysis and explanation justifying any waiver to the standard.

RISK COMMUNICATION RESEARCH OPPORTUNITIES FOR NASA

Given the unique needs and characteristics of spaceflight programs and astronaut populations, NASA would benefit from engaging in risk communication evaluation and research. This would support evidence-based decision making about the use of specific metrics and visualizations. There is also an opportunity for NASA to contribute to important but under-researched questions in risk communication that would benefit other NASA programs and the field more broadly, such as communicating deep uncertainty. It is difficult to predict the effect of risk communications and empirical evidence is needed to determine if a particular communication has the intended effect. There is little existing risk communication research focused on astronauts or on communicating space radiation risk.

The discussion in this chapter highlights numerous opportunities to conduct risk communication research on NASA's communications strategies and materials. It would be valuable to study the "red/yellow/green" tool

reviewed by this committee, strategies or templates used by flight surgeons in pre- and post-mission consultations, other communications materials and strategies used by NASA, as well as any tools or materials NASA might develop for astronauts to use at their own discretion for individualized radiation risk modeling or assessment. The published literature cited in this chapter include many examples of empirical studies that illustrate viable approaches for designing and evaluating risk communications and methodological advances in risk communication research. One challenge in this instance is that the active NASA Astronaut Corps is a small population that could easily be overtaxed by risk communication studies. It would be valuable to characterize other populations and determine the extent to which their risk perceptions can and cannot be generalized to astronauts. Retired astronauts or astronauts in training may be a suitable population, as well as radiation professionals who have similar levels of expertise and numeracy.

The committee makes the following recommendation:

Recommendation 6: NASA should conduct research to develop evidence-based risk communication and the agency should develop a radiation risk communication research agenda to fill knowledge gaps such as (1) what information astronauts want; (2) how astronauts process risk information; and (3) who/what are the most effective sources of information for astronauts. In addition, NASA should carry out research to examine and improve the effectiveness of its current and proposed risk communication strategies and materials.

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Appendix A

Study Methods

This appendix includes public meeting agendas, and a list of materials supplied to the committee by NASA. The information-gathering sessions included public meetings and webinars held by the committee from January 2021 to April 2021, and they are listed in chronological order.

PUBLIC MEETING AGENDAS

January 25 and 26, 2021

DAY 1: Monday, January 25, 2021

11:00 AM **Welcome and Opening Remarks to Public Audience**
Hedvig "Hedi" Hricak, Memorial Sloan Kettering Cancer Center, Committee Chair

11:15 **Session 1: Statement of Work**
J. D. Polk, Chief Health and Medical Officer, National Aeronautics and Space Administration (NASA)

- Charge to the committee (what is included and excluded)
- Description of the NASA strategies the committee is being asked to consider
- Why NASA is considering an update to the radiation standard

11:35 **Discussion with Committee**
Moderator: Hedi Hricak, Memorial Sloan Kettering Cancer Center, Committee Chair

12:00 PM **Session 2: Background on NASA Radiation Standard**
Edward Semones, Space Radiation Analysis Group, NASA Johnson Space Center
Lisa Simonsen, Radiation Technology Integration, NASA HQ
- Space radiation overview, history, NASA Space Cancer Risk (NSCR) model, implementation
- International partner standards

12:45 **Discussion with Committee**
Moderator: Julian Preston, U.S. Environmental Protection Agency, Committee Vice Chair

1:30 **Break**

1:45 **Session 3: Health and Medical Risk Characterization at NASA**
Erik Antonsen, Assistant Director for Human Systems Risk Management, NASA Johnson Space Center
- Risk characterization
- Comparison of radiation risks to health and medical risk
- Radiation working group discussion points

2:10 **Discussion with Committee**
Moderator: Hedi Hricak, Memorial Sloan Kettering Cancer Center, Committee Chair

2:50 **Closing Remarks**
Hedi Hricak, Memorial Sloan Kettering Cancer Center, Committee Chair

3:00 **Adjourn Day 1**

DAY 2: Tuesday, January 26, 2021

11:00 AM **Welcome and Opening Remarks to Public Audience**
Hedvig "Hedi" Hricak, Memorial Sloan Kettering Cancer Center, Committee Chair

11:15 **Session 4: Sex Difference Considerations**
S. Robin Elgart, Space Radiation Element Scientist, NASA Johnson Space Center
Marisa Covington, Bioethics Director, NASA HQ
- Human research program radiation overview
- Focus on studies related to sex differences/cancer incidence
- Bioethics considerations on sex differences

11:35 **Discussion with Committee**
Moderator: Hedi Hricak, Memorial Sloan Kettering Cancer Center, Committee Chair

12:00 PM **Session 5: Cancer Incidence Within the Astronaut Corps**
Mary Van Baalen, Lead, Lifetime Surveillance for Astronaut Health, NASA Johnson Space Center
- Assessment of crew cancer incidence/exposure
- Comparison to similar populations

12:20 **Discussion with Committee**
Moderator: Julian Preston, U.S. Environmental Protection Agency, Committee Vice Chair

1:00 **Break**

1:15 **Session 6: Astronaut Office Perspective**
Serena Aunon-Chancellor, Astronaut
- Crew perspective

1:30 **Discussion with Committee**
Moderator: Hedi Hricak, Memorial Sloan Kettering Cancer Center, Committee Chair

2:00 **Session 7: NASA Proposed Standards and Summary**
David Francisco, Technical Fellow for Human Spaceflight Standards, NASA HQ
J. D. Polk, Chief Health and Medical Officer, NASA HQ
Edward Semones, Space Radiation Analysis Group, NASA Johnson Space Center
- Factors considered for modified standard: confidence level, sex/age differences, dose based, bands, effective risk informing
- Proposed standards for consideration
- Summary

2:20 **Discussion with Committee**
Moderator: Julian Preston, U.S. Environmental Protection Agency, Committee Vice Chair

2:50 **Closing Remarks**
Hedi Hricak, Memorial Sloan Kettering Cancer Center, Committee Chair

3:00 **Adjourn Meeting**

Monday, February 22, 2021

12:00 PM **Convening Open Session and Welcome**
Hedvig "Hedi" Hricak, Memorial Sloan Kettering Cancer Center, Committee Chair

12:05 **NASA Overview**
- Options for updating the standard
- Description of the components of the model for calculating REID

J. D. Polk, Chief Health and Medical Officer, NASA
David Francisco, Technical Fellow for Human Spaceflight Standards, NASA HQ
Edward Semones, Space Radiation Analysis Group, NASA Johnson Space Center

12:30 **Discussion with Committee**
Moderator: Hedi Hricak, Memorial Sloan Kettering Cancer Center, Committee Chair

1:30 **Adjourn Open Session**

Wednesday, April 14, 2021

1:00 PM **Convening Public Webinar and Welcome**
Hedvig "Hedi" Hricak, Memorial Sloan Kettering Cancer Center, Committee Chair
Gayle Woloschak, Northwestern University, Committee Member

1:05 **Overview of the International Commission on Radiological Protection's (ICRP's) Task Group 115 Motivation, Agenda, and Future Plans**
Werner Rühm, Helmholtz Zentrum München, Germany, Task Group 115 Chair

2:20 **Overview of International Space Agencies Assessment of Dose and Risk for Astronauts**
Marco Durante, GSI Helmholtz Center, Germany, Task Group 115 Member

1:40 **Discussion with Committee and ICRP's Task Group 115 Members**
Gayle Woloschak, Northwestern University, Committee Member

ICRP discussants include

- *Chunsheng Li, Health Canada, Canada; TG115 member*
- *Ulrich Schraube, ESA, Germany; TG115 member*
- *Vyacheslav Shursahkov, RSA, Russian Federation; TG115 member*
- *Leena Tomi, CSA, Canada; TG115 member*
- *Alexander Ulanowski, IAEA, Austria; TG115 member*
- *Jing Chen, Health Canada, Canada*
- *Chris Clement, ICRP Scientific Secretary*
- *Mikhail Dobynde, Institute of Biomedical Problems, RAS*
- *Samy El-Jaby, Canadian Nuclear Laboratory, Canada*
- *Mark Shavers, ISMT, USA*
- *Guangming Zhou, Suzhou University, China*

2:30 **Adjourn Open Session**

OVERVIEW OF DOCUMENTS PROVIDED BY NASA

The documents below were provided or submitted by NASA to the committee during the course of the study. Copies of the documents can either be found on the NASA website[1] or are deposited in the study's public access file.[2]

[1] These materials are available on nasa.gov. Links to specific NASA webpages are noted in footnotes.

[2] Copies of documents in the public access file may be requested by contacting the National Academies' Public Access Records Office (PARO@nas.edu).

Materials Developed by NASA for the Committee

- **Processes and Strategies Being Considered for Revising the NASA Space Permissible Exposure Limit for Spaceflight Radiation Exposure Standard, December 3, 2020**[2]
  NASA provided an example of a modified standard that NASA is considering, as well as background information for the committee, including the specific factors NASA is considering in modifying the standard, why NASA is considering a change to the standard, and the existing NASA Space Permissible Exposure Limit for Spaceflight Radiation Exposure Standard, as well as background on the space radiation environment, international partner standards, and NASA standards.
- **Background Information, January 21, 2021, White Paper**[2]
  NASA provided updated background information for the committee, including the specific factors NASA is considering in modifying the standard, why NASA is considering a change to the standard, and the proposed update to the NASA Space Permissible Exposure Limit for Spaceflight Radiation Exposure Standard, as well as background on the space radiation environment, international partner standards, and NASA standards.
- **Proposed Standard Overview, Alternate Options, and Clarifications, February 2021, Revision A**[2]
  NASA provided clarifying material and an updated white paper based on questions and comments from the committee at the public meeting on January 25 and 26, 2021. The material provides more detail, comparison, explanation, context, and additional options for the NASA proposed update to the Space Permissible Exposure Limit for Spaceflight Radiation Exposure Standard for cancer mortality.
- **Questions and Answers Directed to NASA from the Committee, February 21, 2021**[2]
  NASA provided answers to specific committee questions regarding the cancer risk model via email.
- **Proposed Standard Overview, Alternate Options, and Clarifications, March 2021, Revision A**[2]
  NASA provided clarifying material and an updated white paper in response to additional questions posed by the committee at the February 2021 public session. The material provides more information on the proposed standard language, median versus mean, sex-averaged versus female-only calculations, risk communication, and the standards update process.

Supporting Materials Sent to the Committee by NASA

- **Space Radiation Cancer Risk Projections and Uncertainties—2012**[1,3]
  Report that documents NASA's responses to the recommendations from the National Research Council's (NRC's) Space Science Board of the National Academy of Sciences review of the NASA Model 2010, published in March 2012. This includes several updates of the NSCR-2010 model and discussion of points of clarification.
- **Report on Virtual Radiation Risk Panel, September 24, 2020**[2]
  This report, prepared by Erik Antonsen, summarizes the results of an advisory panel of clinicians from reputable and leading academic centers who are well versed in cancer and other radiation health effects to individually advise Human System Risk Board on radiation risk characterization and the Health and Medical Technical Authority on how the standard can be aligned and viewed in context with the other clinical risks. The panel was held on August 21, 2020.
- **Ensemble Methodologies for Astronaut Cancer Risk Assessment in the Face of Large Uncertainties, October 2020**[1,4]
  Provides an overview of a new approach to NASA space radiation risk modeling that has successfully extended the current NASA probabilistic cancer risk model to an ensemble framework able to consider submodel parameter uncertainty (e.g., uncertainty in a radiation quality parameter) as well as model-form uncertainty associated with differing theoretical or empirical formalisms (e.g., combined dose-rate and radiation quality effects).
- **Design for Ionizing Radiation Protection NASA-STD-3001 Technical Brief, October 15, 2020**[1,5]
  During any mission, astronauts face threats of ionizing radiation from a variety of sources. Standards outlined in NASA-STD-3001 state that crews are not to be exposed to radiation that increases their risk of radiation-related mortality by 3 percent. Design choices and shielding strategies can be implemented to reduce the threat posed by radiation and ensure crew safety and health.
- **Mission-Associated Summary of Health (M.A.S.H.) for Jane Astronaut Mars Expeditions 100**[2]
  Example MASH document that provides a summary of test results and "details" pages containing test descriptions, the rationale for

[3] See https://spaceradiation.jsc.nasa.gov/irModels/TP-2013-217375.pdf.

[4] See https://ntrs.nasa.gov/api/citations/20205008710/downloads/NASA-TP-20205008710.pdf.

[5] See https://www.nasa.gov/sites/default/files/atoms/files/radiation_protection_technical_brief_ochmo_021420.pdf.

each MED-B, the preferred testing schedules, actual test dates, and select results for astronauts.

- **Office of the Chief Health and Medical Officer Human Spaceflight Standards Newsletter, March 2021**[2]
  March 2021 newsletter to all astronauts that provides updates on human spaceflight standards.

Table A-1 starts on the next page.

TABLE A-1 Summary of Evidence on Sex-Specific Radiation Risk Estimates of Lung Cancer Mortality from Population Studies of Radiation Exposure

Type of Exposure	Studies	References	Mean Dose to the Lungs, Gy[a]
High-dose rate (acute exposures delivered over a short period of time)			
Low- to medium-dose	A-bomb	Ozasa et al., 2012[1]	F/M: 0.2 (colon, whole cohort)
High-dose	Studies of RT for cancer and benign diseases	Hodgkin lymphoma: Gilbert et al., 2003[2]	F/M: 25 (dose to specific site where LC was diagnosed)
		Peptic ulcer: Little et al., 2013,[3] Carr et al., 2002[4]	F/M: 1.8 (for the left lung) 0.6 (for the right lung)
Low-dose rate (protracted exposures)			
Low-dose	Occupational exposures	15-country study: Cardis et al., 2007[5] – nuclear industry workers	F/M: 0.0194 Sv (average cumulative recorded whole-body external dose for the whole cohort)
		UK NRRW: Muirhead et al., 2009[6] – radiation workers	F/M: 0.0249 Sv (mean lifetime recorded whole-body external dose for the pooled cohort)
		Rocketdyne workers: Boice et al., 2011[7] – radiation workers	F/M: 0.019 Sv (mean combined dose to the lung from external and internal radiation)

Number of Subjects	Number of Lung Cancer Deaths/Cases	Excess Relative Risk per gray (ERR/Gy) (95% CI) for lung cancer[a,b,c]
F: 50,924 M: 35,687	F: 657 M: 901	F: 1.10 (0.68, 1.60) M: 0.40 (0.17, 0.67)
Full study population: F: 132 M: 388 Exposed: F: 110 M: 307	Full study population: F: 44 M: 129 Exposed: F: 39 M: 107	F: 0.044 (–0.009, 0.53) M: 0.18 (0.063, 0.52)
Full cohort: F: 788 M: 2,812 Exposed: F: 351 M: 1,389	Full cohort: F/M: 193	Full cohort: F/M: 0.559 (0.221, 1.021) Exposed: F/M: 1.724 (0.053, 417.1)
F/M: 407,391 F: 40,739 M: 366,652	F: 65 M: 1,392	ERR/Sv F/M: 1.86 (90% CI 0.49, 3.63) F: –1.04 (90% CI <0, 11.1) M: 1.88 (90% CI 0.50, 3.66)
F/M: 174,541 (<10% F)	F/M: 2,230 (trachea, bronchus, lung)	ERR/Sv F/M: 0.106 (–0.43, 0.79) (trachea, bronchus, lung)
F: 466 M: 5,335	F/M: 214	F/M: RR/100 mGy = 1.01 (0.89, 1.16)

continued

TABLE A-1 Continued

Type of Exposure	Studies	References	Mean Dose to the Lungs, Gy[a]
Low-dose (continued)	Occupational exposures (continued)	Mayak: Gilbert et al., 2013[8] – workers of the plutonium production facility	Plutonium dose among exposed: whole cohort: 0.115 F: 0.165 M: 0.093 External dose among exposed: whole cohort: 0.397 F: 0.335 M: 0.418
		Fernald: Silver et al., 2013[9] – uranium processing workers	Mean cumulative dose to lung (μGy) Females Caucasian Hourly: 67.9 Salaried: 296 Females non-Caucasian Hourly: 34.5 Salaried: 154 Males Caucasian Hourly: 1,552 Salaried: 388 Males non-Caucasian Hourly: 965 Salaried: 138
		Mound Nuclear Facility: Boice et al., 2014[10] – workers in the nuclear weapons production facility	F/M: 0.1 Sv (full cohort combined dose to the lung from internal and external radiation)

Number of Subjects	Number of Lung Cancer Deaths/Cases	Excess Relative Risk per gray (ERR/Gy) (95% CI) for lung cancer[a,b,c]
Full cohort: F: 3,703 M: 10,918 Positive plutonium dose: F: 1,971 M: 4,569	Full cohort: F: 40 M: 446	Plutonium lung dose: F, age 60: 24 (11, 56) M, age 60: 7.4 (5.0, 11) External lung dose: F/M: 0.13 (–0.04, 0.38)
Overall: F: 952 M: 5,451 Females Caucasian Hourly: 153 Salaried: 731 Females non-Caucasian Hourly: 30 Salaried: 38 Males Caucasian Hourly: 3,440 Salaried: 1,771 Males non-Caucasian Hourly: 193 Salaried: 47	F: Hourly: 5 Salaried: 17 M: Hourly: 223 Salaried: 52 (trachea, bronchus, lung)	External dose: M: ERR/100 mGy = 0.17 (–0.18, 0.68) Organ dose: M: ERR/100 μGy = 0.0021 (–0.00062, 0.0064) Radon decay products: M: ERR/10 WLM = –0.0061 (–0.013, 0.0046)
Full cohort: F: 1,806 M: 5,463 Exposed: F: 973 M: 4,004	Full cohort: F/M: 310 Exposed: F/M: 204	F/M RR at 100 mSv: 1.00 (0.97, 1.04)

continued

TABLE A-1 Continued

Type of Exposure	Studies	References	Mean Dose to the Lungs, Gy[a]
Low-dose (continued)	Occupational exposures (continued)	Mayak and Sellafield pooled analysis: Gillies et al., 2017[11] – workers of plutonium production facilities	F/M plutonium dose: Mayak: 0.1756 Sellafield: 0.0055 F/M gamma exposure: Mayak: 0.455 Sellafield: 0.0725
		UK NRRW: Haylock et al., 2018[12] – radiation workers	Total: 0.0253 Sv F: 0.0056 Sv M: 0.0275 Sv (mean lifetime recorded whole-body external dose for the pooled cohort)
		INWORKS: Richardson et al., 2018[13] – nuclear workers	Organ-specific cumulative external dose: F: 0.0048 M: 0.0228
		Industrial radiographers: Boice et al., 2019[14]	External radiation and iridium-192 and cobalt-60 dose: F: 0.002 M: 0.012
		Mound: Boice et al., 2019[14] – workers in the nuclear weapons production facility	Full cohort combined dose to the lung from internal and external radiation: F: 0.0249 M: 0.1129
		Nuclear power plant: Boice et al., 2019[14]	Full cohort combined dose to the lung from internal and external radiation: F: 0.0179 M: 0.0413
		NPP + IR: Boice et al., 2019[14]	Full cohort combined dose to the lung from internal and external radiation: F: 0.0061 M: 0.0278

Number of Subjects	Number of Lung Cancer Deaths/Cases	Excess Relative Risk per gray (ERR/Gy) (95% CI) for lung cancer[a,b,c]
F: 8,540 M: 37,277	F: 95 M: 1,100	Mayak, plutonium lung dose: F, at age 60: 11.62 (90% CI 6.93, 18.78) Mayak/Sellafield, plutonium lung dose: M, at age 60: 4.73 (90% CI 3.53, 6.18) Mayak/Sellafield, external lung dose: F/M, all ages: 0.37 (90% CI 0.22, 0.55)
F: 16,437 M: 150,566	F/M: 3,058	ERR/Sv F/M: 0.028 (–0.44, 0.63) (lung, trachea, bronchus)
F: 40,035 M: 268,262	F/M: 5,802	F/M: Maximum likelihood: 0.51 (90% CI 0.00, 1.09) F/M: Hierarchical Bayes: 0.56 (90% CI 0.08, 1.02)
F: 12,933 M: 110,577	F: 55 M: 2,060	ERR/100 mGy F: –0.33 (–0.45, 0.21) M: 0.09 (0.02, 0.16)
F: 971 M: 3,983	F: 21 M: 182	ERR/100 mGy F: –0.01 (–0.07, 0.07) M: 0.01 (–0.02, 0.04)
F: 4,420 M: 130,773	F: 48 M: 3,337	ERR/100 mGy F: 0.80 (–0.96, 2.56) M: –0.05 (–0.10, 0.01)
F: 17,353 M: 241,350	F: 103 M: 5,397	ERR/100 mGy F: 0.16 (–0.49, 0.81) M: 0.01 (–0.04, 0.06)

continued

TABLE A-1 Continued

Type of Exposure	Studies	References	Mean Dose to the Lungs, Gy[a]
Low-dose (continued)	Occupational exposures (continued)	U.S. radiation technologists: Velazquez-Kronen, 2020[15]	Full cohort cumulative dose to the lung from external exposure: F: 0.024 M: 0.026
Medium-dose	Radiation diagnostic exposures	Massachusetts TB fluoroscopy: Davis et al., 1989[16]	F/M: 0.84 (total lung tissue dose among exposed)
		Canadian TB fluoroscopy: Howe, 1995[17]	F/M: 1.02 Sv (total lung tissue dose among exposed)
		Canadian TB fluoroscopy: Boice et al., 2019[14]	Total lung tissue dose among exposed: F: 1.072 M: 1.038

Abbreviations: CI = confidence interval; ERR/Gy = excess relative risk per gray; ERR/Sv = excess relative risk per sievert; F = female; F/M = combined estimate for females and males; Gy = gray; IR = industrial radiographer; LC = lung cancer; M = male; NPP = nuclear power plant; RR/100 mGy = relative risk per 100 milligray; SMR = standardized mortality ratio; Sv = sievert; TB = tuberculosis.

[a] In this table, we chose to present the results as they appeared in original publications. While the majority of studies used absorbed doses to the lungs (in gray [Gy] or mGy), some used effective doses expressed in sievert (Sievert) and averaged over entire body. All estimates presented are in Gy, unless otherwise noted.

[b] All estimates presented are ERR/Gy, unless otherwise noted.

[c] ERR/Gy is a measure of effect per unit of radiation dose. While relative risks (RRs) are traditionally used to express risks in exposure categories compared to a reference category, excess RRs are frequently used in radiation epidemiology to express excess risks (risks above 1.0) per unit of dose (1 Gy is traditionally used as a reference category). In models with a linear relationship between exposure and outcome, an estimate of RR with a reference category of 1 Gy is equivalent to a RR/Gy = ERR/Gy + 1.0. For example, an ERR/Gy = 1.88 from Cardis et al., 2007, could be expressed as RR at 1 Gy = 1.88 + 1.00 = 2.88 (women exposed to a dose of 1 Gy have 2.88 times higher risks of lung cancer compared to women with no radiation exposure [dose = 0]). ERR/100 mGy could be expressed as ERR/Gy as follows: ERR/Gy = ERR/100 mGy * 10. For example, an ERR/100 mGy = 0.09 from Boice et al., 2019, could be expressed as ERR/Gy = 0.9.

Number of Subjects	Number of Lung Cancer Deaths/Cases	Excess Relative Risk per gray (ERR/Gy) (95% CI) for lung cancer[a,b,c]
F: 80,180 M: 25,888	F: 711 M: 379	ERR/100 mGy F: 0.06 (<0–0.23) M: –0.14 (<0–0.09)
F: 6,513 M: 6,872	Exposed: F: 19 M: 50 Unexposed: F: 22 M: 104	Exposed: F: SMR = 0.8 M: SMR = 0.8 Unexposed: F: SMR = 1.0 M: SMR = 1.4
F: 31,917 M: 32,255	F: 266 M: 912	ERR/Sv: F: –0.08 (–0.10, 0.07) M: 0.02 (–0.01, 0.11)
F: 31,787 M: 31,920	F: 266 M: 912	ERR/100 mGy F: –0.007 (–0.015, 0.002) M: 0.002 (–0.003, 0.008)

Table A-1 References

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Appendix B

Biographical Sketches of Committee Members and Staff

COMMITTEE MEMBERS

Hedvig "Hedi" Hricak, M.D., Ph.D. (*Chair*), is the chair of the Department of Radiology at the Memorial Sloan Kettering Cancer Center, a member of the Molecular Pharmacology and Chemistry Program at the Sloan Kettering Institute; and a professor at the Gerstner Sloan Kettering Graduate School of Biomedical Sciences in New York City. She has served on a number of national advisory boards and councils, including the National Institutes of Health's Board of Scientific Counselors, the Scientific Advisory Board of the National Cancer Institute, the Advisory Council of the National Institute of Biomedical Imaging and Bioengineering, and the National Academies of Sciences, Engineering, and Medicine's Nuclear and Radiation Studies Board. She has served as the chair, the co-chair, or a member on a number of National Academies studies. She is a member of the National Academy of Medicine (NAM) and a "foreign" member of both the Russian Academy of Sciences and the Croatian Academy of Sciences and Arts. For her efforts to promote national and international education and collaboration in oncologic imaging and low-dose radiation safety from diagnostic imaging exposures, she has won numerous awards, including the David Rall Medal for Distinguished Leadership from the NAM, five gold medals, and honorary memberships or fellowships in 22 international radiological societies. She holds an honorary doctorate from the Ludwig Maximilian University in Munich, Germany, and Toulouse III Paul Sabatier University in Toulouse, France

R. Julian Preston, Ph.D. (*Vice Chair*), is currently a special government employee (expert) with the Radiation Protection Division of the U.S. Environmental Protection Agency (EPA). He was previously the associate director for health for the National Health and Environmental Effects Research Laboratory of EPA. He also served as the director of the Environmental Carcinogenesis Division at EPA and as the senior science adviser at the Chemical Industry Institute of Toxicology. He has been employed at the Biology Division of the Oak Ridge National Laboratory and has served as the associate director for the Oak Ridge–University of Tennessee Graduate School for Biomedical Sciences. Dr. Preston's research and current activities have focused on the mechanisms of radiation and chemical carcinogenesis and the approaches for incorporating these types of data into cancer risk assessments. Dr. Preston currently serves on two National Council on Radiation Protection and Measurements committees and is a member of the National Academies of Sciences, Engineering, and Medicine's Nuclear and Radiation Studies Board and was recently a member of the Office of Science and Technology Policy's Committee on Low Dose Radiation Research. Dr. Preston was the chair of Committee 1 of the International Commission on Radiological Protection (ICRP), a member of the ICRP Main Commission, and the representative and a member of the U.S. delegation to the United Nations Scientific Committee on the Effects of Atomic Radiation. He served as the chair for the National Research Council's Committee to Assess the Scientific Information for the Radiation Exposure Screening and Education Program and on the Task Group on the Biological Effects of Space Radiation. He is an associate editor of *Environmental and Molecular Mutagenesis* and *Chemico-Biological Interactions*. Dr. Preston has had more than 200 peer-reviewed papers and chapters published. He received his B.A. and M.A. from Peterhouse, Cambridge University, England, in genetics and his Ph.D. from Reading University, England, in radiation genetics.

Amy Berrington de González, D.Phil., is the branch chief and a senior investigator in the Radiation Epidemiology Branch at the National Cancer Institute. She is an internationally recognized cancer epidemiologist who has made important contributions to the understanding of cancer risks from medical radiation exposures. Dr. Berrington de González is the principal investigator (PI) of the U.S. Pediatric Proton Therapy Cohort, the Kaiser Breast Cancer Survivors Study, and co-PI of the UK Pediatric CT scans cohort, which was the first epidemiological study to support a direct link between CT scans and subsequent cancer risk. Dr. Berrington de González is currently a member of the National Academies of Sciences, Engineering, and Medicine's Nuclear and Radiation Studies Board and has participated in numerous national and international radiation and cancer advisory committees. She is an elected member of the American Epidemiological Society

and served on the editorial board for the *American Journal of Epidemiology*. Before joining the National Cancer Institute, she held faculty positions at Oxford University and Johns Hopkins University. Dr. Berrington de González is also the senior advisor for strategic activities in the Division of Cancer Epidemiology & Genetics. In this role, she provides advice to the director on the division research portfolio and works with the deputy director to oversee strategic planning.

Ann Bostrom, Ph.D., is the Weyerhaeuser Endowed Professor of Environmental Policy at the Daniel J. Evans School of Public Policy and Governance at the University of Washington. From 1999 to 2001, she was the program director at the National Science Foundation for the Decision, Risk, and Management Science program. She researches risk perception, risk communication, and decision making under uncertainty, with a focus on mental models of hazardous processes. Her current research projects include interview, survey, and experimental research on perceptions, communication, and decision making about climate change, earthquake early warning, and extreme weather forecasts and warnings. Dr. Bostrom earned her Ph.D. in policy analysis from Carnegie Mellon University, her M.B.A. from Western Washington University, and her B.A. in English from the University of Washington.

Casey Canfield, Ph.D., is an assistant professor in engineering management and systems engineering at the Missouri University of Science and Technology. Her research is focused on quantifying the human part of complex systems to improve decision making, particularly in the context of energy, governance, and health care. She has a Ph.D. in engineering and public policy from Carnegie Mellon University, where she published research on behavioral interventions and risk management in the context of energy and cybersecurity. After completing her Ph.D., she spent 1.5 years as a science and technology policy fellow in the U.S. Department of Energy's Solar Energy Technologies Office.

Harry M. Cullings, Ph.D., was the chief of the Statistics Department at the Radiation Effects Research Foundation (RERF) in Hiroshima and Nagasaki, Japan, until 2018 and is now a consultant to RERF. He has been conducting research at RERF since 1999. RERF is a public interest foundation funded by the Japanese Ministry of Health, Labour and Welfare and the U.S. Department of Energy (DOE). Dr. Cullings holds a B.S. in fundamental sciences from Lehigh University and an M.S. in medical physics and Ph.D. in analytical health sciences (biometrics) from the University of Colorado Health Sciences Center in Denver, Colorado. He completed a postdoctoral fellowship in radiation sciences funded by DOE

at the University of Pittsburgh. The emphasis of Dr. Cullings's research is on radiation dosimetry and other aspects of radiation epidemiology, including dosimetric uncertainty and applications of spatial statistics. Dr. Cullings has published numerous reports, papers in scientific journals, and book chapters on subjects related to radiation dosimetry and radiation health effects research. He served as a member of the Joint U.S.-Japan Working Group on the Reassessment of Atomic-bomb Dosimetry, which created the Dosimetry System 2002 that is currently in use at RERF. Dr. Cullings's research has been funded strictly through RERF, in part through a DOE award to the National Academy of Sciences. Dr. Cullings has received no external research funding from government agencies, private companies, or foundations.

Lawrence T. Dauer, Ph.D., DABHP, FHPS, is an attending physicist in the Departments of Medical Physics and Radiology at the Memorial Sloan Kettering Cancer Center and is their corporate radiation safety officer. He has spent more than 35 years in the field of radiation protection and health physics, including programs for the nuclear energy and industrial sectors as well as operations and research in medical health physics. His research focuses on low-dose radiation epidemiology and dosimetry, as well as improving radiation protection practices and communication avenues to reduce the risk of exposure to ionizing radiation and facilitate beneficial clinical applications. He is currently a council member and previous board member of the National Council on Radiation Protection and Measurements (NCRP). He is currently serving NCRP as the scientific director for the Million Person Study of Low-Level and Low-Dose-Rate Effects. He served 7 years on the International Commission on Radiological Protection Committee 3, Radiation Protection in Medicine, and has served on several committees for the Health Physics Society (HPS), the Greater New York Chapter of HPS, the Radiological and Medical Physics Society, the American Association of Physicists in Medicine, the American College of Radiology, the Society for Interventional Radiology, and the Radiation Research societies. He received the Elda E. Anderson and fellow awards from HPS.

Bernard A. Harris, Jr., M.D., M.B.A, F.A.C.P., is currently the chief executive officer (CEO) and the managing partner of Vesalius Ventures, a venture capital firm that supports and invests in early to mid-stage health care technologies and companies. Dr. Harris also serves as the CEO of the National Math & Science Initiative and leads the organization's efforts to improve teacher effectiveness and student achievement in communities across the country. He has been involved in math and science education for more than 25 years through his philanthropy efforts through the Harris

Institute & Foundation. Dr. Harris was at the National Aeronautics and Space Administration (NASA) for 10 years, where he conducted research in musculoskeletal physiology and disuse osteoporosis. Dr. Harris is also a former astronaut who flew on the Space Station in 1991 and 1995 for a total of 18 days in Earth orbit. Dr. Harris earned a B.S. in biology from the University of Houston, a master of medical science from the University of Texas Medical Branch at Galveston, an M.B.A. from the University of Houston, and an M.D. from the Texas Tech University School of Medicine. He completed a residency in internal medicine at the Mayo Clinic, a National Research Council Fellowship in endocrinology at the NASA Ames Research Center, and trained as a flight surgeon at the Aerospace School of Medicine at Brooks Air Force Base. He is also a licensed private pilot and certified scuba diver. He is the recipient of numerous awards, including nine honorary doctorates, the NASA Spaceflight Medal, the NASA Award of Merit, a fellow of the American College of Physicians, and was the recipient of the 2000 Horatio Alger Award.

Alejandra Hurtado de Mendoza, Ph.D., is an assistant professor at the Cancer Prevention and Control Program at the Georgetown Lombardi Comprehensive Cancer Center. She is a bilingual social psychologist with an interdisciplinary training in anthropology and communication, culture, and technology. She aims to combine interdisciplinary approaches in social psychology, behavioral science, and communication to develop and evaluate interventions that address stark disparities in the uptake of genetic risk assessment in high-risk underserved groups. Her research focuses on translational genomics with underserved populations. She is the principal investigator of a 5-year multi-site grant to test the effect of a culturally targeted narrative video on genetic counseling and testing uptake in Latina women at risk of hereditary breast and ovarian cancer. She is also co-leading an NINR R21 grant to adapt an Intelligent Tutoring System intervention (BRCA-Gist) to enhance the use of genetic counseling services in at-risk Latina and African American women. In her Career Award (KL2) she adapted an evidence-based telephone counseling intervention to broaden the reach and accessibility to genetic counseling for at-risk Latina women.

Jeffrey Kahn, Ph.D., M.P.H., is the Andreas C. Dracopoulos Director of the Johns Hopkins Berman Institute of Bioethics, a position he assumed in July 2016. From 2011, he has been the inaugural Robert Henry Levi and Ryda Hecht Levi Professor of Bioethics and Public Policy. He is also a professor in the Department of Health Policy and Management at the Johns Hopkins Bloomberg School of Public Health. He works in a variety of areas of bioethics, exploring the intersection of ethics and health/science policy, including human and animal research ethics, public health, and

ethical issues in emerging biomedical technologies. Dr. Kahn has served on numerous governmental and international advisory panels, including most recently on the International Commission on the Clinical Use of Heritable Human Genome Editing. He is currently the chair of National Academies of Sciences, Engineering, and Medicine's Board on Health Sciences Policy; the chair of the National Academies' Committee on Aerospace Medicine and Medicine of Extreme Environments; and has previously chaired its Committee on the Use of Chimpanzees in Biomedical and Behavioral Research (2011); the Committee on Ethics Principles and Guidelines for Health Standards for Long Duration and Exploration Spaceflights (2014); and the Committee on the Ethical, Social, and Policy Considerations of Mitochondrial Replacement Techniques (2016). He is currently a member of the National Academy of Medicine Council.

Guillermina Lozano, Ph.D., is a geneticist recognized for her studies of the p53 tumor suppressor pathway, from characterizing p53 as a transcriptional activator to characterizing the physiological importance of Mdm2 and Mdm4 proteins as inhibitors of p53, and the consequences of p53 mutations on tumor development. Dr. Lozano completed undergraduate studies in biology and mathematics at Pan American University (now known as the University of Texas Rio Grande Valley). She completed graduate studies at Rutgers University and the University of Medicine and Dentistry of New Jersey, and a postdoctoral fellowship at Princeton University. She was hired as an instructor at The University of Texas MD Anderson Cancer Center in 1987 and is now the chair of the Department of Genetics. She was elected a fellow of the American Association for the Advancement of Science. She received the Minorities in Cancer Research Jane Cooke Wright Lectureship and the Women in Cancer Research Charlotte Friend Lectureship awards, both from the American Association for Cancer Research. Dr. Lozano is also the recipient of distinguished alumni awards from both her undergraduate and graduate alma maters. She is a member of the National Academy of Sciences and the National Academy of Medicine.

Giovanni Parmigiani, Ph.D., is a professor in the Department of Data Sciences at the Dana-Farber Cancer Institute and a professor of biostatistics at the Harvard T.H. Chan School of Public Health as well as the associate director for population sciences at the Dana-Farber/Harvard Cancer Center. He received his undergraduate degree in economics and social sciences at Università L. Bocconi and a master's degree and Ph.D. in statistics from Carnegie Mellon University. He has held faculty positions at Carnegie Mellon University, Duke University, and Johns Hopkins University. His work creates statistical tools for understanding cancer data, with particular focus on cancer risk in genetic epidemiology and genomics contexts.

He pioneered the use of machine learning in the assessment of risk from inherited susceptibility to cancer, developing risk assessment tools that have been in use for more than two decades. He also played a key role in early studies of somatic mutations in cancer. He is the recipient of several awards including mentoring awards at Johns Hopkins University, Harvard University, and the Dana-Farber Institute.

Robert L. Satcher, Ph.D., M.D., is an associate professor in the Department of Orthopaedic Oncology at The University of Texas MD Anderson Cancer Center (MDACC) in Houston, Texas. He specializes in the treatment of skeletal metastatic disease, soft tissue sarcoma, technology applications for improving surgical outcomes, teleoncology, and intraoperative navigation. Dr. Satcher is a former astronaut, having served as a mission specialist who visited the International Space Station. Dr. Satcher is leading institutional efforts to establish the clinical enterprise for virtual care at MDACC. Additionally, his work with MDACC's Global Oncology enterprise is focused on building relationships with international health care partners that will lead to the construction of a Cancer Center in sub-Saharan Africa. Dr. Satcher co-founded the eHealth Research Institute, a collaborative endeavor among Rice University, the National Space Biomedical Research Institute, and MDACC to bring together physicians with academic and industry researchers to improve access to specialized health care using the latest in research and technology. Dr. Satcher is a member of numerous professional organizations, including the American Academy of Orthopaedic Surgery, the Musculoskeletal Tumor Society, the National Comprehensive Cancer Network, the American Telemedicine Association, the American Association of Cancer Research, Doctors United in Medical Missions, and the Orthopaedic Research Society.

Carol Scott-Conner, M.D., Ph.D., M.B.A., is a professor emeritus of surgery at the University of Iowa Carver College of Medicine. She received her B.S. in electrical engineering from the Massachusetts Institute of Technology in 1969 and her M.D. from the New York University (NYU) School of Medicine in 1976. She remained at NYU to complete a 5-year general surgical residency in 1981. She was appointed the head of the Department of Surgery at the University of Iowa in 1995. She is the author or co-author of nine major surgical texts and a book of short stories. Her other works have included numerous papers, chapters, and presentations on a wide range of surgical topics.

Igor Shuryak, M.D., Ph.D., is an assistant professor in the Center for Radiological Research in the Department of Radiation Oncology at the Columbia University Medical Center. His research interests focus on mechanistic

mathematical modeling of the effects of ionizing radiation on living organisms. They include modeling of radiation-induced carcinogenesis at both low and high doses (e.g., second cancers induced by radiotherapy for primary malignancies), cancer therapy (e.g., tumor control and normal tissue complications), non-targeted ("bystander") effects of radiation (e.g., for densely ionizing radiation exposures such as those occurring on manned space missions), and mechanisms of resistance to ionizing radiation in human and nonhuman cells. Dr. Shuryak's training and experience have been interdisciplinary, starting with biology (B.A. from Columbia University) and medicine (M.D. from the State University of New York Downstate College of Medicine). He received a Ph.D. with distinction from the Department of Environmental Health Sciences (Columbia University Mailman School of Public Health) for work on combining both short- and long-term time scales in mechanistic modeling of radiation-induced carcinogenesis.

Gregory R. Wagner, M.D., is an adjunct professor of environmental health at the Harvard T.H. Chan School of Public Health. At Harvard, he teaches about the science behind occupational and environmental policies and regulations and the process of improving health protections at work. He also chairs the Policy Working Group for the Harvard Center for Work, Health, and Wellbeing. Dr. Wagner previously served as the senior advisor to the director of the National Institute for Occupational Safety and Health of the Centers for Disease Control and Prevention. From 2009 to early 2012, he served as the deputy assistant secretary of labor for mine safety and health, leading efforts to develop and enforce regulations protecting the health and safety of U.S. miners. He has worked closely with both the World Health Organization and the International Labour Organization to stimulate and support international efforts to better recognize and prevent diseases from work and improve screening and surveillance practices. Board certified in internal medicine and public (occupational) health, Dr. Wagner has practiced rural primary care medicine and taught both medicine and public health.

Gayle E. Woloschak, Ph.D., D.Min., is currently a professor of radiation oncology at Northwestern University in Chicago and an adjunct professor of religion and science at the Lutheran School of Theology Chicago and at the Pittsburgh Theological Seminary. She holds a Ph.D. in biomedical sciences from the University of Toledo (Medical College of Ohio), and a D.Min. in Eastern Christian studies from the Pittsburgh Theological Seminary. Her laboratory interests include molecular biology, radiation biology, and nano-biotechnology, and her science–religion fields include biological evolution, stem cell research, and ecology.

Lydia B. Zablotska, M.D., Ph.D., M.P.A., is a professor in the Department of Epidemiology and Biostatistics and the Salvatore Pablo Lucia Chair in Preventive Medicine in the School of Medicine at the University of California, San Francisco (UCSF), where she serves as the leader of the occupational and environmental epidemiology area of concentration. Dr. Zablotska is a physician and an epidemiologist with extensive training and publications in radiation epidemiology, biostatistics, and risk modeling. Her research activities have focused primarily on the examination of risks of radiation exposures in various occupational and environmental settings. Dr. Zablotska's work has clarified our understanding of the effects of occupational radiation exposures on health risks of nuclear power industry workers and workers of the uranium fuel production cycle in various occupational cohorts from the United States and Canada. Dr. Zablotska serves as a director of epidemiology, biostatistics, and population health education in the medical school curriculum at UCSF and has received multiple institutional and national teaching and mentoring awards. She is the inaugural councilor for epidemiology at the Executive Council of the Radiation Research Society.

NATIONAL ACADEMIES STAFF

Rebecca English, M.P.H. (*Study Director*), is a senior program officer in the Board on Health Sciences Policy. She is the staff director for the National Aeronautics and Space Administration–sponsored Standing Committee on Aerospace Medicine and the Medicine of Extreme Environments. Ms. English has directed, co-directed, and staffed a number of projects at the National Academies of Sciences, Engineering, and Medicine, including, most recently, *Necessity, Use, and Care of Laboratory Dogs at the U.S. Department of Veterans Affairs* (2020); *Temporomandibular Disorders: From Research Discoveries to Clinical Treatment* (2020); *Physician-Assisted Death: Scanning the Landscape: Proceedings of a Workshop* (2018); and *Mitochondrial Replacement Techniques: Ethical, Social, and Policy Considerations* (2016). She has also staffed the Forum on Drug Discovery, Development, and Translation in various capacities since 2009 and worked 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 then for the National Active and Retired Federal Employees Association. She holds an M.P.H. from the University of Michigan, Ann Arbor, and a B.A. from the University of Notre Dame with a major in political science.

Ourania (Rania) Kosti, Ph.D., is a senior program officer at the Nuclear and Radiation Studies Board (NRSB) of the National Academies of Sciences,

Engineering, and Medicine. Dr. Kosti's interests within the NRSB focus on radiation health effects, and she is the principal investigator for the National Academies' Radiation Effects Research Foundation Program that supports studies of the atomic bomb survivors in Japan. Prior to her current appointment, she was a postdoctoral fellow at the Lombardi Comprehensive Cancer Center at Georgetown University Hospital in Washington, DC, where she conducted research on biomarker development for early cancer detection using case-control epidemiological study designs. She focused primarily on prostate, breast, and liver cancers and trying to identify those individuals who are at high risk of developing malignancies. Dr. Kosti also trained at the National Cancer Institute (2005–2007). She received a B.S. in biochemistry from the University of Surrey, United Kingdom, an M.S. in molecular medicine from the University College London, and a Ph.D. in molecular endocrinology from St. Bartholomew's Hospital in London, United Kingdom.

Leah Cairns, Ph.D., is a program officer in the Board on Health Sciences Policy. Her primary interests include health policy and biomedical research. Prior to joining the National Academies of Sciences, Engineering, and Medicine she served as an American Association for the Advancement of Science Science and Technology Policy fellow working as legislative staff for a member of Congress focusing on health policy and appropriations. Dr. Cairns also previously served as a Christine Mirzayan Science & Technology Policy Fellow at the National Academies in the Policy and Global Affairs division. Dr. Cairns received her Ph.D. in biophysics from the Johns Hopkins University School of Medicine and a B.A. in biochemistry and molecular biology from Hamilton College.

Claire Giammaria, M.P.H., is an associate program officer in the Board on Health Sciences Policy for the Health and Medicine Division of the National Academies of Sciences, Engineering, and Medicine. Prior to coming to the National Academies, Ms. Giammaria was the research associate for the Technology and Liberty Project at the American Civil Liberties Union where she primarily worked on genetics, health care, and privacy issues. She has an M.P.H. from the University of Michigan where she studied public health policy and concentrated in public health genetics. Ms. Giammaria received her B.A. from Grinnell College where she majored in biology.

Ruth Cooper is a research associate in the Board on Health Care Services at the National Academies of Sciences, Engineering, and Medicine. She has worked on several National Academies projects, including studies on cancer and disability and evidence-based opioid prescribing and workshops on

organ transplant and disability, companion animals as sentinels for environmental exposures, and diagnostic excellence in cardiac events. She has also assisted with numerous National Cancer Policy Forum workshops ranging from topics like the cancer workforce to health literacy. Prior to joining the National Academies, Ms. Cooper spent 1 year volunteering at Open Arms Home for Children in South Africa. In addition to her experience in health policy, Ms. Cooper also has experience in Arctic science policy, having interned at the U.S. Arctic Research Commission, and has participated in three Arctic field cruises. She holds a B.A. from the University of Notre Dame in neuroscience and behavior with a minor in Mediterranean Middle Eastern studies, and is currently pursuing her master's degree in international science and technology policy at The George Washington University.

Cyndi Trang is the manager of internal communications and program support in the Health and Medicine Division of the National Academies of Sciences, Engineering, and Medicine. Prior to this role, Ms. Trang was a research associate in the Board on Health Care Services. She has worked on several National Academies projects, including studies on sickle cell disease, evidence-based opioid prescribing, and primary care implementation and workshops on veterans' health access and diagnostic excellence in sepsis. She has also assisted with numerous National Cancer Policy Forum workshops ranging from such topics as cancer care in low-resource areas to patient navigation in cancer care. Prior to joining the National Academies, Ms. Trang was a cancer research fellow at the National Cancer Institute, where she worked in the Gene Regulation and Chromosome Biology Laboratory. In addition to her experience in public health policy and laboratory research, Ms. Trang also has experience in the medical field as a former chief scribe at Novant Health. She graduated as an Honors Program Scholar from Marymount University. She is currently pursuing her master's degree in patient safety and health care quality at Johns Hopkins University.

Kendall Logan is a senior program assistant for the Health and Medicine Division's (HMD's) Board on Health Sciences Policy. She joined the National Academies of Sciences, Engineering, and Medicine in 2018 and staffed two consensus studies: *Social Isolation and Loneliness in Older Adults: Opportunities for the Health Care System* and *Temporomandibular Disorders: Priorities for Research and Care*. She also supports the standing committee on Medical and Epidemiological Aspects of Air Pollution on U.S. Government Employees and Their Families. Ms. Logan received her B.A. in anthropology with a public health minor from Haverford College and is currently pursuing an M.P.H. from Columbia University.

Michael K. Zierler, Ph.D., is the founder and the co-owner of RedOx Scientific Editing, a small shop that provides developmental editing and related editorial and writing services. He has an undergraduate degree in biology from Brown University and a Ph.D. in biology from Johns Hopkins University, where he worked on the regulation of gene expression in eukaryotes, stockpiling of DNA polymerases during embryogenesis, and intramolecular movements in hemoglobin studied using hydrogen exchange. Prior to graduate school, he worked for a cardiothoracic surgeon at the West Roxbury Veterans Affairs Medical Center, doing research in the laboratory and the operating room on monitoring and improving the physiology of the heart during open heart surgery using mass spectrometry and a miniaturized pH electrode. After graduate school, he completed a postdoctoral position at SUNY Stony Brook helping to identify the molecular components of the *Salmonella* injectisome, a bacterial invasion system. He has taught biological sciences at the high school and college level. He has also served as the deputy mayor and the chair of the planning board in his hometown of New Paltz, New York.

Sharyl Nass, Ph.D., serves as senior director of the Board on Health Care Services and the director of the National Cancer Policy Forum (NCPF) at the National Academies of Sciences, Engineering, and Medicine. The National Academies provide independent, objective analysis and advice to the nation to solve complex problems and inform public policy decisions related to science, technology, and medicine. To enable the best possible care for all patients, the board undertakes scholarly analysis of the organization, financing, effectiveness, workforce, and delivery of health care, with emphasis on quality, cost, and accessibility. NCPF examines policy issues pertaining to the entire continuum of cancer research and care. For more than two decades, Dr. Nass has worked on a broad range of health and science policy topics that includes the quality and safety of health care and clinical trials, developing technologies for precision medicine, and strategies for large-scale biomedical science. She has a Ph.D. in cell biology from Georgetown University and undertook postdoctoral training at the Johns Hopkins University School of Medicine, as well as a research fellowship at the Max Planck Institute in Germany. She also holds a B.S. and an M.S. from the University of Wisconsin–Madison. She has been the recipient of the Cecil Medal for Excellence in Health Policy Research, a Distinguished Service Award from the National Academies, and the Institute of Medicine staff team achievement award (as team leader).

Andrew M. Pope, Ph.D., is the senior director of the Board on Health Sciences Policy. He has a Ph.D. in physiology and biochemistry from the University of Maryland and has been a member of the National Academies

of Sciences, Engineering, and Medicine staff since 1982 and the Health and Medicine Division (HMD) staff since 1989. His primary interests are science policy, biomedical ethics, and environmental and occupational influences on human health. During his tenure at the National Academies, Dr. Pope has directed numerous studies on topics that range from injury control, disability prevention, biologic markers to the protection of human subjects of research, National Institutes of Health priority-setting processes, organ procurement and transplantation policy, and the role of science and technology in countering terrorism. Since 1998, Dr. Pope has served as the director of the Board on Health Sciences Policy, which oversees and guides a program of activities that is intended to encourage and sustain the continuous vigor of the basic biomedical and clinical research enterprises needed to ensure and improve the health and resilience of the public. Ongoing activities include Forums on Neuroscience and Nervous System Disorders; Genomics; Drug Discovery, Development, and Translation; and Medical and Public Health Preparedness for Catastrophic Events. Dr. Pope is the recipient of HMD's Cecil Award and the National Academy of Sciences' President's Special Achievement Award.