The Lifetime Surveillance of Astronaut Health

NEWSLETTER

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Editor's Note

BY **RONNIE RAFANAN**

Welcome to the October 2023 issue of the Lifetime Surveillance of Astronaut Health (LSAH) Newsletter! This issue will showcase our Space Radiation Analysis Group (SRAG), highlighting their contributions towards keeping our astronauts safe during spaceflight.

Also, be sure to check out the *Clinic Corner* with Dr. Tim LaVan, LSAH's annual *Publications Corner*, as well as the *Formers Corner* where we share images and captions submitted by you and your fellow crewmates.

Enjoy!

SPACE MEDICINE OPERATIONS DIVISION

In this Issue…

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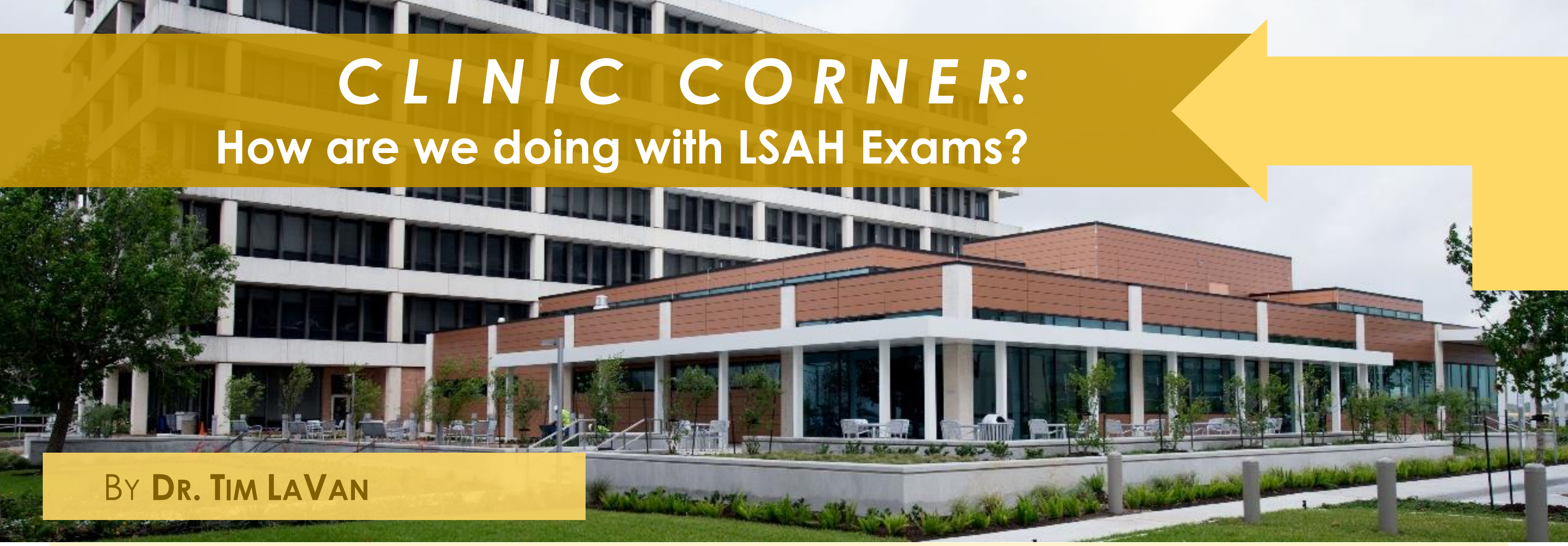
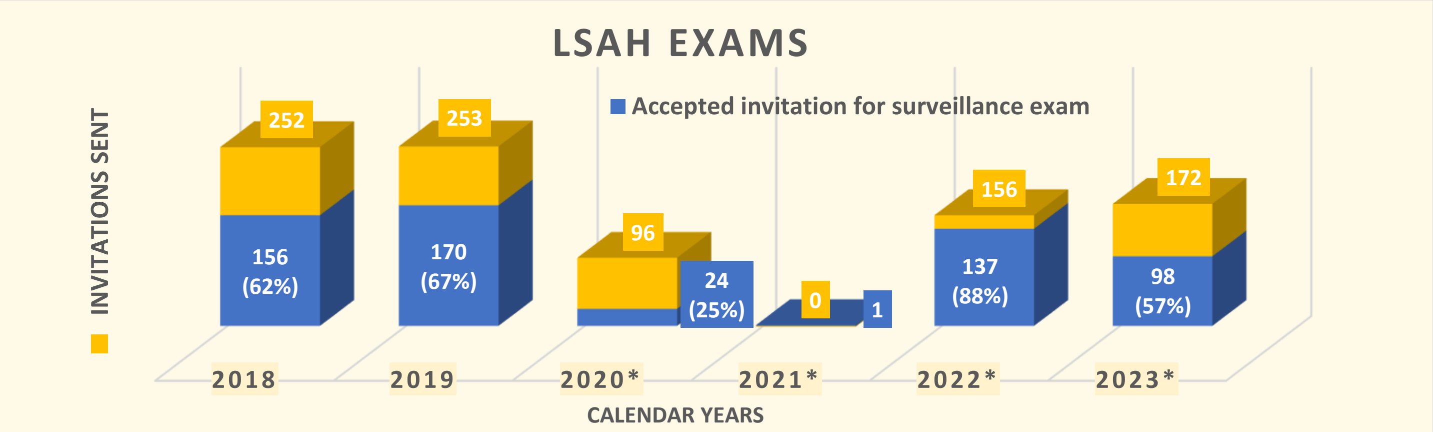
In this Issue… *(Cont'd)*



CLINIC CORNER:
How are we doing with LSAH Exams?

By **Dr. Tim LaVan**

We just took a look at what percentage of former astronauts accepted the invitation to come to Houston for the annual surveillance exam. I thought I would share the rates over the last five years.



- * 2020 Exams stopped in March, but invitations went out for birthdays through May
- * 2021 No invites due to COVID; one exam performed for certification
- * 2022 Invites started for June birthdays with catch-up/appointments accepted in April & May
- * 2023 Through the end of September

In the years prior to COVID, we would routinely see about two thirds of the invitations accepted. 2022 was a banner year due to the “reopening” and catch-up exams. 2023 looks more like a return to the steady state, as we often see a rush of physicals toward the end of the year (around the time of the reunion). While we do not press retired astronauts about reasons for declining, informally, our schedulers have heard the barriers include difficulties with travel due to advancing age, ongoing concern with travel due to continued risk of COVID, and a preference to see their primary care physician (PCP). We certainly understand these concerns but would still like to encourage former astronauts to seriously consider coming in for our comprehensive exam. If an in-person exam is not feasible, I’d like to remind everyone that we have an option to complete the exam virtually, with labs performed locally and a face-to-face interview with one of our physicians via video teleconference. For those who choose to stay with their PCP, we ask that you please consider notifying JSC Clinic when you have had your annual exam and provide permission to obtain the results so we may include them in the database. The more data we have, the better we are able to characterize the long-term effects of spaceflight. Looking forward to seeing everyone at JSC this year and standing by to support however we can!

If you are interested in scheduling a virtual surveillance encounter, please feel free to call the FMC and we will help you get it set up. **Flight Medicine Clinic (FMC): (281)483-7999**

Introduction: Space Radiation Analysis Group (SRAG)

Space Radiation Health and Protection is the practice of supporting all aspects of radiation safety for spaceflight inhabitants. The principal group within Medical Operations at JSC that provides mission support is the Space Radiation Analysis Group (SRAG). SRAG is responsible for ensuring that the radiation exposure received by astronauts remains below established exposure limits. Main SRAG duties are briefly summarized below.

To support crew radiation safety in space, SRAG maintains 24/7 support for Mission Control to inform/advise crew surgeons and flight directors of the radiation environment and protocols for operationally mitigating in-mission crew exposures. Real-time monitoring using particle detectors and dosimeters onboard the ISS along with other space assets are used to characterize the radiation environment. Individual Crew Active Dosimeters are worn by crew members to ensure accurate measurement of radiation doses for use in astronaut cancer risk assessments. SRAG maintains the current career radiation exposure database for all astronauts and provides radiation systems and environments overview training for the crew, flight directors, surgeons, BMEs, and other members of the flight control team. SRAG also provides NASA Standards update recommendations and is responsible for their operational implementation. Non-ionizing radiation (NIR) risk assessment and subject matter expertise are also provided by SRAG.

To perform radiation risk assessment of crew members, SRAG developed and implemented the RAE (Risk Assessment Environment), a relational database used to calculate astronaut stochastic radiation risk. Models of the relevant flight vehicles are used to determine how cosmic radiation is modified by spacecraft shielding, and SRAG's RAE uses a combination of particle transport simulations and statistical modeling techniques to compute cancer risk probabilities for crew members. The cancer risk probabilities (risk of exposure-induced death [REID] and risk of exposure-induced cancer [REIC]) are informed by human epidemiological data and US background cancer rates. Each year, an individualized report of radiation exposure from space missions and from other exposure sources (medical diagnostic and biomedical research studies), as well as the cancer risk probabilities from radiation exposure during space missions, is generated by SRAG and provided to each crew member through the flight surgeon. After a mission, space radiation environment models are combined with the models of radiation shielding and in-flight measurements from the crew-worn dosimeter and vehicle area monitors to determine the radiation exposure during the entire mission. SRAG also provides pre-flight and extra-vehicular activity (EVA) crew exposure projections.

The following newsletter articles elaborate on the historical perspective of space radiation dosimetry and risk assessment, updates to the NASA radiation standard and partner agency standards/limits, US background cancer rates in risk estimation, and NIR support portions of SRAG portfolio.

SRAG DEFINITIONS AND ACRONYMS

Absorbed Dose *– energy deposited to matter per unit mass by ionizing radiation*

Effective Dose *– a quantity related to the risk of a radiation-induced cancer that accounts for the absorbed dose to all organs of the body, the relative harm caused by incoming radiation types, and the sensitivities of each organ to radiation exposure*

Gray-Equivalent Dose *– a measure of the potential for early-onset or late-occurring harmful non-cancer effects in specific organs and tissues (skin, eye lenses, bone marrow, circulatory system), used to design missions and limit the possibility of harm from intense exposures such as may occur during an energetic solar particle event or in other extreme conditions*

REID *–* ***R****isk of* ***E****xposure-****I****nduced* ***D****eath: probability of dying from a radiation-exposure-induced cancer over a lifetime, calculated for individuals in a cohort of the same age, sex, smoking status, and exposure conditions*

REIC *–* ***R****isk of* ***E****xposure-****I****nduced* ***C****ancer: probability of cancer incidence from radiation exposure over a lifetime, calculated for individuals in a cohort of the same age, sex, smoking status, and exposure conditions*

SPEL *–* ***S****pace* ***P****ermissible* ***E****xposure* ***L****imit: a quantifiable limit of allowable radiation exposure over a certain period of time, e.g., the 600 mSv career effective dose limit for NASA astronauts*

ALARA *–* ***A****s* ***L****ow* ***A****s* ***R****easonably* ***A****chievable: a guiding principle of radiation protection related to the idea that any amount of radiation exposure can be harmful; a cost-benefit analysis should take place in any scenario where humans or animals are subject to exposure*

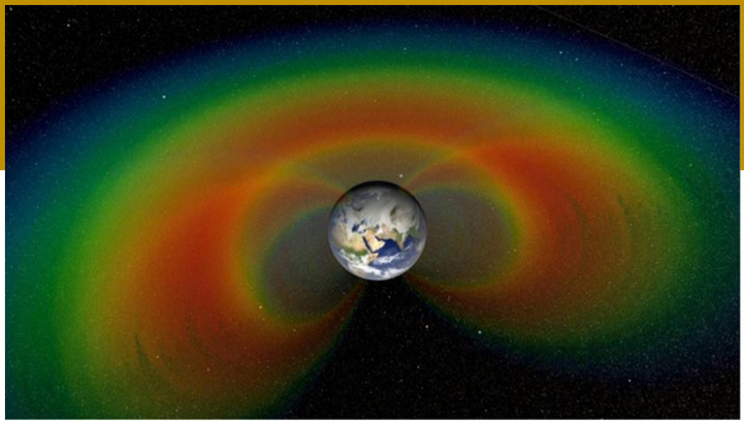
SPE *–* ***S****olar* ***P****article* ***E****vent: an ejection of energetic particles (mostly protons) near the surface of the Sun due to some disturbance on its surface, like a solar flare, or a coronal mass ejection*

GCR *–* ***G****alactic* ***C****osmic* ***R****ays: collection of energetic heavy charged particles that originate from outside the solar system and constantly bombard all of space*

The new NASA Space Radiation Health Standard:

Protecting Crew Members Beyond Low Earth Orbit (BLEO) Exploratory Missions

By **Janapriya (JP) Saha, PhD**



An artist's concept of the Van Allen belts with a cutaway section of the two giant donuts of radiation that surround Earth. Credit: NASA Goddard Space Flight Center/Scientific Visualization Studio

SPACE RADIATION ENVIRONMENT

In space, ionizing radiation is ubiquitous, thus an unavoidable hazard. Astronauts are exposed to high energy protons and heavy ions from galactic cosmic rays (GCR) that cannot be shielded, trapped protons and electrons in low-Earth orbit (LEO), and infrequent solar particle events (SPEs) comprised largely of medium energy protons, which can be easily shielded. In LEO, the Earth's magnetosphere provides some protection by trapping the high energy radiation particles and forms two belts of radiation, known as the Van Allen Belts, surrounding the Earth like enormous donuts (illustrated above).

IONIZING RADIATION DOSE

The amount of ionizing radiation to which a person is exposed is quantified as dose and can be expressed either as a measurable, physical quantity as absorbed dose (milligray or mGy) or calculated as effective dose for radiation protection purposes. Effective dose is a calculated value, measured in millisieverts (mSv), that considers the absorbed dose to all organs of the body, how harmful the radiation is, and the sensitivities of each organ to radiation. For radiation protection purposes, as low as reasonably achievable (ALARA) is a principle used to optimize the radiation dose. Using ALARA and Space Permissible Exposure Limits (SPELs)/dose limits, NASA manages radiation exposures to crew members and ensures compliance with exposure limits for individual astronauts through all phases of spaceflight. From a quantitative point of view, while the average radiation background on Earth is about 2.4 mSv/year[1], astronauts on the International Space Station (ISS) receive doses in the order of 0.5 mSv/day[2]. Due to the lack of protection from Earth's magnetic field, higher doses, on the order of 1 mSv/day or more, are projected for Beyond low-Earth orbit (BLEO), such as for Artemis (lunar) and Mars missions. However, on the lunar surface, the dose is projected to be on the order of 0.5 mSv/day (the moon provides some protection). To measure absorbed dose in space, astronauts wear an "active" personal dosimeter that provides real-time dose telemetry. In addition, several strategically placed area monitors throughout the ISS and spacecraft provide time-resolved absorbed dose measurements. These measurements are utilized to determine the total dose a crewmember received and for assessing the increased cancer risk.

CANCER RISK ASSESSMENT

Risk of cancer from ionizing radiation exposure is one of the health-related risks for astronauts. To calculate the probability of dying from radiation-induced cancer, also called Risk of Exposure-Induced Death (REID), the NASA Space Cancer Risk Model (NSCR-2012)[3] is operationally applied. The NSCR model uses the tissue-specific cancer incidence analyses of human epidemiology data, primarily from the Japanese atomic bomb survivor cohort, and the cancer and survival rates in the U.S. population adjusted to a population of never-smokers to provide age- and sex-specific excess cancer rates.

THE PREVIOUS NASA RADIATION STANDARD

Until recently, NASA estimated the career Space Permissible Exposure Limit (SPEL) based on the National Council on Radiation Protection and Measurements (NCRP) recommendation of limiting occupational radiation exposure to 3% lifetime excess risk of cancer death. This recommendation was based on large uncertainties in estimating health risks from space radiation exposure due to lack of appropriate data from a relatively small cohort of astronauts. NASA adopted sex- and age-dependent career limits based on 3% REID at the 95% upper confidence level (CL), which effectively limited the REID to 1%. REID estimates the probability an individual will die from cancer associated with the radiation exposure. For example, a 1% REID implies that within a cohort of 100 astronauts, one is likely to die of radiation-induced cancer due to the space radiation exposure. Since the previous standard was age-and sex dependent, it favored males and older astronauts who are at lower cancer risk from radiation exposure based on epidemiological evidence. Females, on the other hand, are considered more radiosensitive, largely driven by lung cancer data from the Japanese Life Span Study (LSS) data. However, when evidence from other more recent epidemiological cohorts is taken into consideration, the increased radiation sensitivity for female lung cancer is less definitive[4]. With additional data available for review, the Artemis mission on the horizon, and other future deep space explorations including a mission to Mars in the planning and development stages, there was a need to reassess the NASA radiation standard, designed primarily for LEO missions. In 2020, NASA initiated a study to seek recommendations from an ad hoc committee of the National Academies of Sciences, Engineering, and Medicine (NASEM) on updating the radiation standard for exploration missions beyond LEO[5].

THE NEW RADIATION STANDARD

2017 Astronaut Class Selfie

While personalized age- and sex-dependent REID calculations will continue to be calculated for all active astronauts and missions for a well-rounded risk assessment, the SPEL requirement was recently redefined based on NASEM committee recommendations to limit all crew to an effective dose, replacing REID as the limit metric. The newly defined radiation limit of 600 mSv targets a 3% increase in mean cancer REID for a 35-year-old female. NASA considers this age group and sex to be "at the highest risk" of cancer-induced mortality from space radiation based on epidemiological evidence. NASA revised the Agency Standard that limits radiation exposures to astronauts for all NASA programs for human spaceflight (NASA-STD-3001, 2022/23). In addition to the new effective dose-based career radiation exposure limit, additional limits were introduced to address specific sources of mission exposures: SPEs and nuclear technologies. The new risk standard states, "*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.*" In addition to cancer SPEL, limits are used to avoid clinically significant deterministic or non-cancer effects to the skin, lens of the eye, central nervous system (CNS), and the circulatory system, which have remained unchanged at this time.

BENEFITS OF UPDATING THE RADIATION STANDARD

The 600 mSv limit brings NASA to a standard closer to that of our international partners and is on the order of risk of nominal lifestyle choices (such as inactivity, weight, and diet) of the American population. Different space agencies use different approaches and dose limits to protect their crew from radiation exposure in space (discussed in detail in the article "*Career Limits on Radiation Exposure of Astronauts for ISS Partner Agencies* by Dr. Mark Shavers" of this newsletter). Even at 600 mSv, NASA's new radiation standard is more conservative than other international partners' but would bring it closer to their age- and sex-independent effective dose limits. The new standard will also provide women of all ages more opportunities to fly longer duration missions than was previously possible. In addition, communicating risk to flight surgeons and crew members is simpler and more effective via a "more familiar" dose-based metric compared to the complex concept of excess risk or REID.

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Space Radiation Cancer Risk Across Two Decades:

Impacts of Background Cancer Rates on Lifetime Risk

By **Lori Chappell, MS**

Cancer is the second leading cause of death in the United States. Decades of research have been devoted to cancer prevention and treatment to reduce the cancer death rate. Early detection and reducing risk factors can be important for cancer prevention. Smoking is one of the most well-documented behaviors that increases cancer risk [6]. The decrease in cancer death rates observed over the last two decades in the United States can be linked to the reduction in smoking rates [1].

Radiation is another well-documented risk factor for cancer. Since radiation exposure is unavoidable in the space environment, NASA has devoted much research into understanding and modeling the radiation cancer risk from such exposure. Personalized astronaut radiation risk assessments are performed for every space shuttle, ISS, and projected mission, using the NASA Space Cancer Risk Model (NSCR) [2,3]. The metric risk of exposure induced death (REID) quantifies the probability of dying from a radiation-induced cancer over a lifetime. Ideally the probability of dying from radiation-induced cancers will decrease as early detection and treatments lower the death rate for all cancers.

Background cancer rates are linked to both major excess risk model types that contribute to NSCR. The excess relative risk model directly models the excess risk as proportional to the background cancer rates. The excess absolute risk model estimates excess incidence for cancer independent of background rates but is scaled to death rates using more recent U.S. cancer statistics. REID trends over the last two decades due to changes in background cancer rates can be estimated within NSCR using cancer death rates from 1999 to 2019 [4,5]. To try to reduce confounding from smoking, the U.S. average background cancer rates are adjusted to a never-smoked (NS) population.

The ten leading sites for cancer deaths for males in the U.S. population are the lung and bronchus, prostate, colon and rectum, pancreas, liver and intrahepatic bile duct, leukemia, esophagus, urinary bladder, Non-Hodgkin lymphoma, and the brain and other parts of the central nervous system. The ten leading sites for cancer deaths for females in the U.S. population are the lung and bronchus, breast, colon and rectum, pancreas, ovary, uterine corpus, liver and intrahepatic bile duct, leukemia, Non-Hodgkin lymphoma, and the brain and other parts of the central nervous system [1]. Many of these cancer sites have risk models available in NSCR. The trends in cancer death rates at age 70 by the leading sites with risk models available are shown in figure 1 for males and figure 2 for females.

FIGURE 1

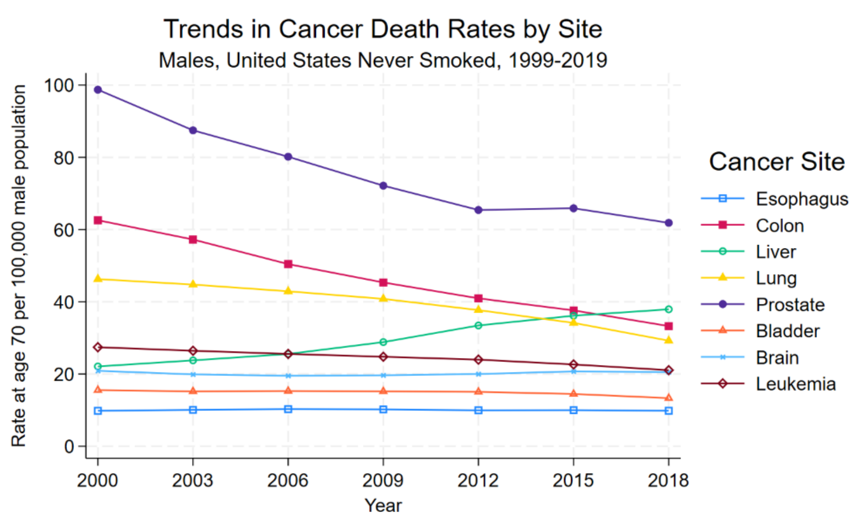
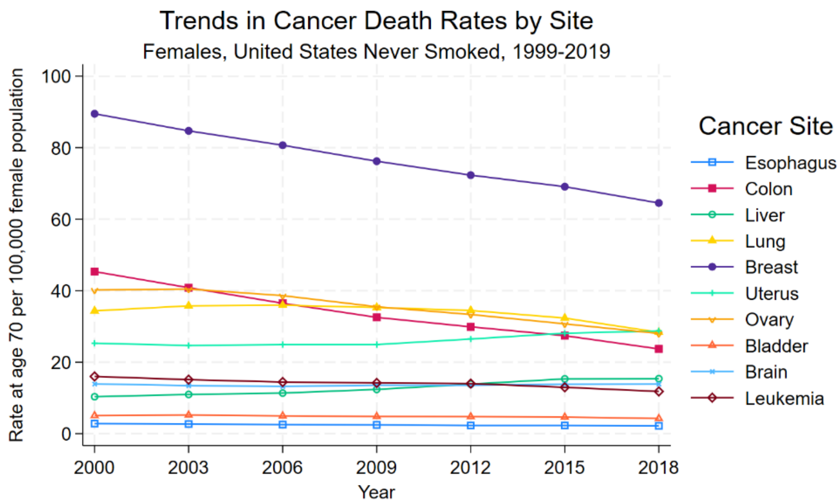


FIGURE 2



The corresponding trends in REID for a 35-year-old astronaut on a 1-year ISS mission during solar minimum (NASA effective dose = 253 mSv) are shown in figure 3 for males and figure 4 for females.

FIGURE 3

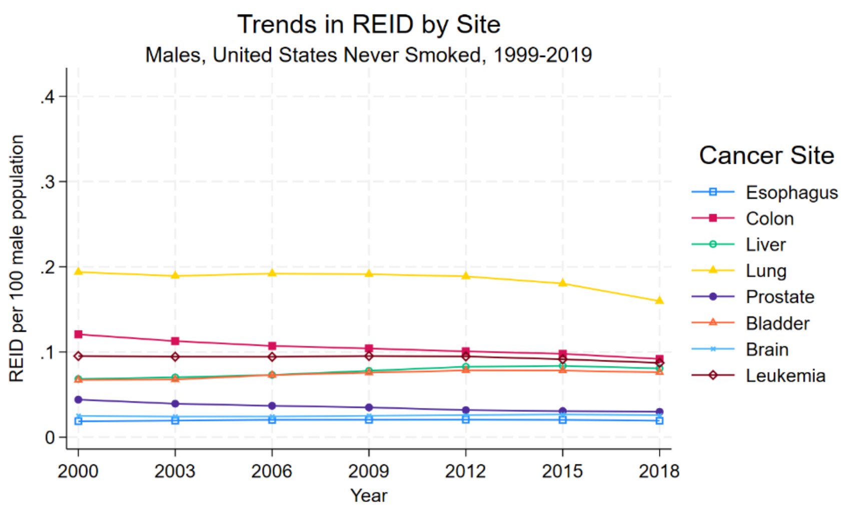
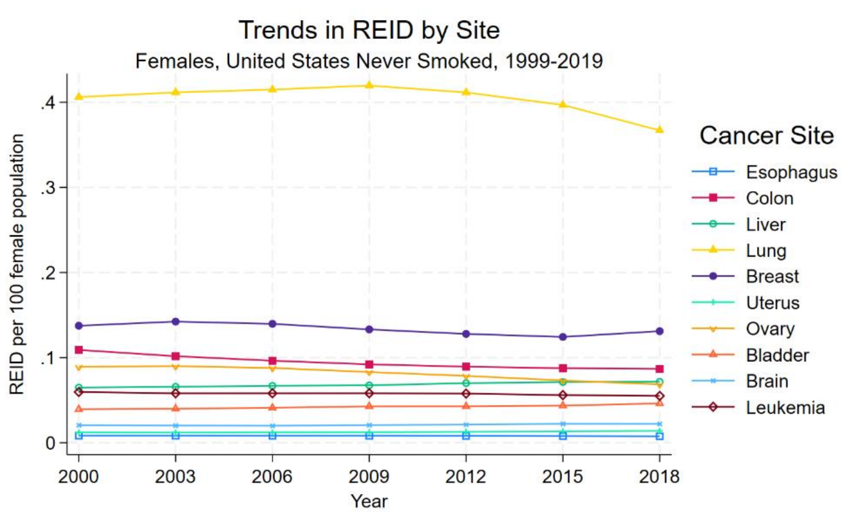


FIGURE 4



Decreasing cancer death rates are visible for the lung, colon, breast, prostate, and ovary cancers, which have the highest death rates in the U.S. population. These improvements are also reflected in the REID estimates for lung, colon, and prostate cancers. The improvement is not seen in breast cancer because only an excess additive risk model is applied to breast cancer. When the REIDs for all the cancer sites are combined, the total REID has decreased by approximately 10% over the two-decade time period. One notable exception to the decreasing death rate trend is observed for liver cancer. Liver cancer incidence is rapidly increasing in the United States due to lifestyle factors such as excess body weight, diabetes, hepatitis infections, and alcohol consumption [1].

While there have only been marginal improvements in REID over the past two decades, initiatives such as the Cancer Moonshot aim to reduce the cancer death rate by half over the next two decades [7]. NASA plans to support four of the five major Cancer Moonshot priorities to help achieve this mission: close the screening gap, understand and address environmental and toxic exposures, decrease the impact of preventable cancers, and drive innovation from discovery to patients. The Human Research Program Space Radiation Element has a robust research strategy that focuses on understanding the impact of unavoidable environmental stressors to establish data-driven models of radiation risk that leverage bioinformatics and computational modeling to translate results and develop practical mitigation strategies to reduce associated health outcomes. Specifically, the strategy will invest in current and emerging early screening technologies providing robust long-term health surveillance and countermeasure implementation for improvement of cancer outcomes. The background cancer rates will continue to be monitored so that improvements can be incorporated into NSCR as soon as they are observable in the cancer statistics.

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Apollo vs. Artemis:

A Dosimetric Comparison of the Crewed Lunar Space Programs

By **Luke Stegeman**

NASA's Artemis program seeks to return humans to the Moon for the first time since 1972 (Apollo 17) and establish a sustainable long-term presence in preparation for missions to Mars. Space radiation exposure is one factor among several that has historically limited long-term human spaceflight beyond low-Earth orbit (LEO). The radiation environment beyond LEO carries enhanced long-term carcinogenic and acute health risks to Moon-bound astronauts. Beyond LEO, Earth's magnetic field weakens to the point where it no longer protects astronauts from incident galactic cosmic rays (GCRs)—low flux, high energy, heavy charged particles that come from outside the solar system—let alone any energetic particles that originate from the Sun in the form of solar particle events (SPEs) or radiation trapped in the outer Van Allen belt. Figure 1 depicts a few distinct radiation environments encountered on a hypothetical mission to the Moon. All these radiation sources contribute to an astronaut's cumulative exposure.

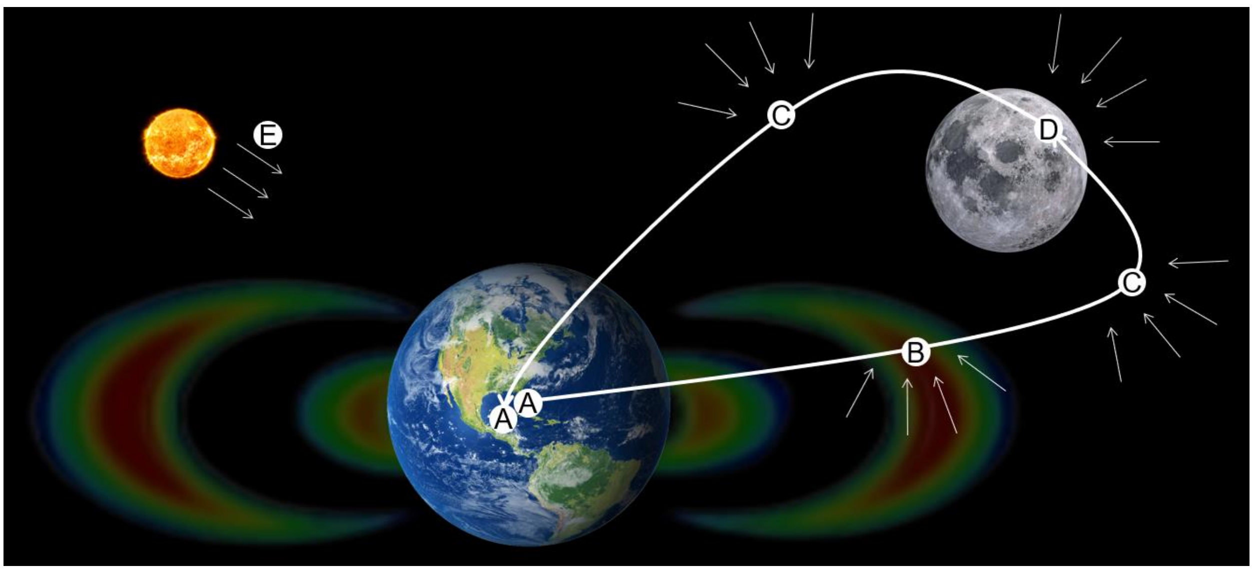

Figure 1: Space radiation environments encountered on the way to the Moon, including the LEO environment (A), the Van Allen Belts (B), cis-lunar space (C), the lunar surface (D), and solar radiation (E). Locations (C) and (D) are subject to consistent GCR irradiation and carry the risk of encountering difficult-to-predict SPEs from the Sun.

Astronauts' radiation exposures are tracked to ensure that astronauts do not exceed the NASA-established 600 mSv career effective dose limit [1]. The effective dose is a quantity that correlates to the likelihood of developing cancer from ionizing radiation. Lunar missions are inherently riskier than LEO missions, (e.g., International Space Station [ISS] Expeditions), and while the total radiation exposure received by any astronaut is influenced by solar activity, vehicle shielding, and position relative to Earth's magnetic field, it is expected that astronauts participating in lunar missions will experience higher mean effective dose rates than their counterparts on the ISS.

To estimate the radiation-induced risk astronauts will incur on Artemis missions, we examine the dosimetric results of the Apollo missions, the radiation measurements of the Artemis I mission, and the projected dosimetry of the Artemis 2 and 3 missions according to the NASA Space Cancer Risk Model [2]. In lieu of available effective dose data for Apollo missions, averaged absorbed dose rates (in skin) are compared between the Apollo missions and the first three Artemis missions in Table 1 and Figure 2. For reference, the average skin dose rate on the ISS is approximately 0.2 mGy/day [2].

Mission	Flight Path	Duration [days]	Skin Dose [mGy]	Skin Dose Rate [mGy/day]	Departure
Apollo 7	LEO	10.84	1.60	0.15	8/11/1968
Apollo 8	Lunar Orbit	6.13	1.60	0.26	12/21/1968
Apollo 9	LEO	10.04	2.00	0.20	3/3/1969
Apollo 10	Lunar Orbit	8.02	4.80	0.60	5/18/1969
Apollo 11	Lunar Landing	8.14	1.80	0.22	7/16/1969
Apollo 12	Lunar Landing	10.19	5.80	0.57	11/14/1969
Apollo 13	Lunar Orbit	5.95	2.40	0.40	4/11/1970
Apollo 14	Lunar Landing	9.00	11.40	1.27	1/31/1971
Apollo 15	Lunar Landing	12.30	3.00	0.24	7/26/1971
Apollo 16	Lunar Landing	11.08	5.10	0.46	4/16/1972
Apollo 17	Lunar Landing	12.58	5.50	0.44	12/7/1972
Artemis 1*	Lunar Orbit	25.45	10.18*	0.40*	11/16/2022
Artemis 2 (M)**	Lunar Orbit	10	6.97	0.70	Late 2023
Artemis 2 (F)**	Lunar Orbit	10	7.61	0.76	Late 2023
Artemis 3 (M)**	Lunar Landing	30	9.53	0.32	Late 2024
Artemis 3 (F)**	Lunar Landing	30	9.85	0.33	Late 2024
ISS Expedition (180 day)	LEO	180	36.0	0.20	***
ISS Expedition (30 day)	LEO	30	6.0	0.20	***

Table 1: Duration, measured/projected absorbed dose (rate) in skin, and departure dates for all crewed Apollo missions [3] *and first three planned Artemis missions. Typical ISS Expedition skin doses and dose rates are also included for reference.*
**Artemis 1 was uncrewed and shows absorbed dose (rate) in water* [4].
***All Apollo astronauts were male. Projections for Artemis 2 and 3 consider both male (M) and female (F) astronaut phantoms* [2].
****Typical ISS skin doses and dose rates were computed by averaging data from all ISS missions to date.*

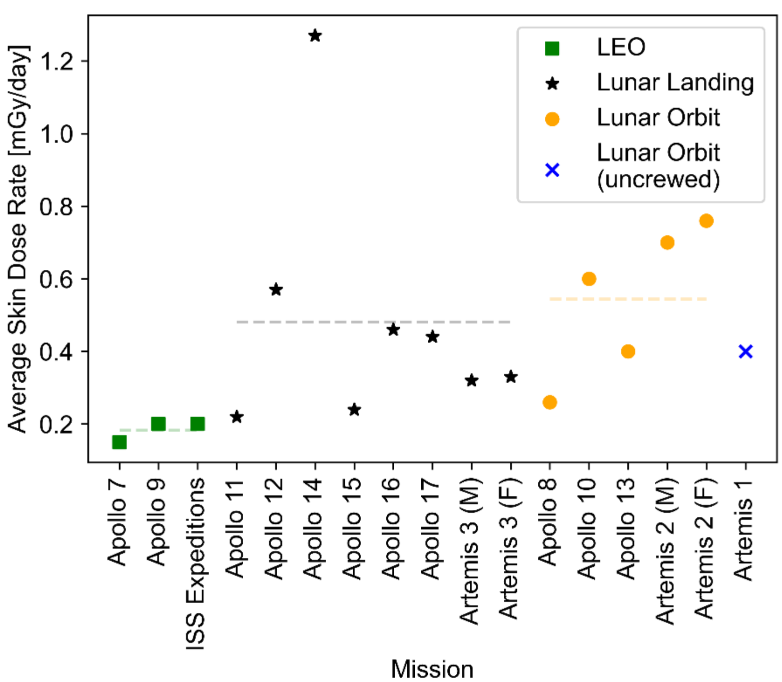

Figure 2: Mean skin dose rates for all crewed Apollo missions and the first three planned Artemis missions grouped by mission type. Mean skin dose rates <u>for each mission type</u> are shown via the dotted line associated with each group. A typical ISS Expedition skin dose rate is also included for reference.

**Artemis 1 was uncrewed and shows absorbed dose rate in water* [4].

***All Apollo astronauts were male. Projections for Artemis 2 and 3 consider both male (M) and female (F) astronaut phantoms* [2].

Table 1 indicates that the magnitude of the skin dose is positively correlated with the mission duration. Figure 2 shows that mission type (i.e., whether the mission remained within LEO, orbited the Moon, or landed on the Moon) greatly influences the mean dose rate for each mission type. Specifically, missions in which astronauts land on the Moon see a decrease in mean dose rate compared to those in which astronauts only orbit the Moon. This occurs because the Moon itself acts as a shield against approximately half of the incoming GCR exposure when astronauts are situated on its surface, lowering the overall dose rate. Increasing the distance between the surface and the spacecraft decreases the solid angle subtended by the Moon with respect to the spacecraft. This solid angle is at maximum on the lunar surface (near 2π steradians). As this solid angle decreases, the fraction of unobstructed space "seen" by the spacecraft increases, which leads to an increase in GCR exposure, thus explaining the increase in dose rate for lunar orbit-only missions.

Based on the results shown in Figure 2, generic dose rates for Artemis 2 are expected to be slightly higher than the mean dose rates of Apollo 8, 10, and 13 (missions in which crews only orbited the Moon). Artemis 2's slightly higher projected mean dose rate compared to other lunar orbit missions is related to how much time is spent in different radiation environments. For example, during the approximate six-day duration of Apollo 8, approximately 20 hours were spent orbiting the Moon (~14% of mission in lunar orbit). Artemis 2 will spend a few days orbiting the Moon, with an estimated total mission duration of 10 days (~30% of mission in lunar orbit). A greater fraction of mission time spent in lunar orbit or cislunar space yields higher doses and higher mean dose rates, explaining why Artemis 2's dose rate is slightly higher than the mean dose rate among other lunar orbit missions. Conversely, the mean dose rate for Artemis 3 is expected to be slightly lower than the mean dose rates of Apollo 11, 12, 14, 15, 16, and 17 (missions in which crews landed on the lunar surface). In this case, because Artemis 3 will spend a long time on the lunar surface relative to previous missions, the mean dose rate for the Artemis 3 mission should be smaller than the mean dose rate among other missions that landed on the lunar surface.

Finally, it should be noted that Artemis 2 and/or 3 may encounter off-nominal space environment conditions which could significantly affect dose rates. For example, Figure 2 shows that Apollo 14 experienced a much higher dose rate than all other missions. This high dose rate is a result of the spacecraft trajectory, which passed through the heart of the trapped radiation belts, and timing, as Apollo 14 happened to take place during a period when the space radiation background environment was more intense than usual. Fluctuations in solar activity could cause less predictable changes to Artemis 2 and 3 projected dose rates.

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Career Limits on Radiation Exposure of Astronauts for ISS Partner Agencies

By **Mark Shavers, PhD**

Using various instruments and crew badge measurements coupled with virtualized "astronaut phantoms" the Space Radiation Analysis Group (SRAG) calculates the types of ionizing radiation passing through each organ and tissue of interest. Radiation risk calculations or "models" are then used to find the likelihood these exposures will cause tumors (cancer incidence) or even death (cancer mortality). Astronauts are provided with a report of the potential for cancer risks. NASA analysts use any new information to develop computational models of other possible effects that may occur in the brain or cardiovascular system.

NASA calculates and reports a quantity called *effective dose*. Simply put, the effective dose is a *calculated* measure of how biologically harmful each type of radiation is and weighted by how much each organ or tissue contributes to development of a potentially lethal cancer when exposed to radiation. Each of the International Space Station (ISS) International Partner Agencies calculates effective dose using their own algorithms or recipes for cancer risk; in some cases, harmful effects other than cancer are folded in as well.

Do we know who will develop a tumor? When or how aggressive will it be? Unfortunately, we are not able to make those predictions. However, information from healthy working-age adults and cohorts of people who have been exposed to radiation allows us to set radiation exposure limits and inform astronauts about the possible health outcomes.

NASA controls cancer risk for ISS and other space missions with a "career limit" for radiation exposure, developed to protect the most radiosensitive NASA astronauts. This limit is formally labelled the "Space Permissible Exposure Limit" and sometimes is informally referred to as the "career radiation limit" or the "cancer risk limit". Risk models tell us that a group of younger female astronauts are at higher cancer risk than older males. Smokers are at higher risk than non-smokers. With that in mind, NASA set the 600 millisievert effective dose limit to ensure that healthy, non-smoking females who are 35 years old when they are exposed to the career limit will (on average) have an increased risk (3 chances in 100) of dying several years to decades after the mission. The formal quantity for the increased risk of cancer mortality is called REID–Risk of Exposure-Induced Death. Using the NASA cancer risk model (NSCR-2012), older female astronauts will have a lower increased cancer risk, while older male astronauts will have an even lower cancer risk. Fortunately, clinical care will "cure" many cancers, and early detection and improved treatment protocols will further improve patient outcomes. To communicate cancer risk more clearly, SRAG also calculates REIC—Risk of Exposure-Induced Cancer—to convey the increased risk of both fatal and non-fatal cancers. For males, cancer in 25 different organs and tissues are considered while 27 are considered for females. Cancer incidence and mortality (REIC and REID) are reported to astronauts each year as part of their annual physical examinations while they are in active duty.

ISS PARTNER AGENCIES' CAREER RADIATION EXPOSURE LIMITS

The Canadian Space Agency (CSA), European Space Agency (ESA), and Russian Federal Space Agency (RSA) each have a career *effective dose* limit of 1000 millisieverts. While the 600 millisievert Space Permissible Exposure Limit (SPEL) set by NASA limits the risk of increased cancer deaths, the international partners consider additional causes of premature death and other health impacts. Russia (RSA) calculates an excess risk of cardiovascular disease in addition to cancer mortality; their effective dose career limit of 1000 millisieverts protects against a total lifetime risk of dying from space mission exposures to no more than ten percent. JAXA maintains an age- and sex-based career exposure limit that increases with the astronaut's age at the time of the mission. Females are limited to 500 millisieverts (age 27) up to 800 millisieverts (ages 47 and higher) and males are limited to 600 millisieverts (age 27) up to 1000 millisieverts (age 47+). Agencies differ, too, in requiring an informed consent process. JAXA, for example, requires informed consent upon selection as an astronaut and upon mission assignment. NASA follows ethics guidelines that require informing astronauts of all known potential mission-related health risks from radiation and other potential hazards.

Exposure Limits

…another lecture.

Astronaut career exposure limits for each ISS Space Agency.

Space Agency	CSA	ESA	JAXA*	NASA@	RSA
Career Limit [Sv]	1	1	0.5-1	0.6	1

*JAXA's career limit is age- and sex-specific, ranging from 0.5 Sv for a female 27y of age at first exposure to 1 Sv for males older than 45 at first exposure.

@The NASA SPEL limits each astronaut to 0.6 Sv, calculated as the mean effective dose to a female. The limit was guided by the calculation of cancer mortality of <3% Risk of exposure-induced death (REID) in a female exposed at 35 years of age.

NASA LIMITS FOR NON-CANCER EFFECTS

NASA uses other metrics to quantify and limit the possibilities of harm other than cancer arising from exposures to ionizing radiations that come from the sun, stars, and any other sources such as nuclear power or propulsion. Astronauts are protected from those "non-cancer effects" by using engineering and design solutions, monitoring of the "space weather", radiation shielding and sheltering, and by carefully controlling mission activities.

Dosimetry and Risk Metrics

Transport → $$D_T = \frac{10^{-8}}{6.24} \sum_{Z,A} \int \phi(Z,A;E) \cdot L(Z,A;E)\, dE;$$ Organ **absorbed dose** from ions Z,A

Dose Equivalent $$H_T = \frac{10^{-8}}{6.24} \sum_{Z,A} \int \phi(Z,A;E) \cdot L \cdot Q\left(\frac{Z^{*2}}{\beta^2}, L, E\right) dE;$$ Q is biological weight **for radiation type**; no dose rate modifier.

Effective Dose $$H_E = \sum_{Tiss} w_T H_T;$$ **Effective Dose** from organ doses, Q, and tissue/organ weighting factors, w_T.

Effective Dose
Limits cancer risk

Risk of Exposure-induced Death in organ, *T* *(REID)*

$$REID_T = \int_{a_{EN}}^{a_{max}} \lambda_{1,T}^{(M)}(a, a_{E1}, H_{1,T}) S_0(a|a_{E_N})\, e^{-\int_{a_{EN}}^{a} \Sigma_T \lambda_{1..N,T}^{(M)}(t, a_{E1}, H_{1,T}, \ldots, a_{EN}, H_{N,T}) dt} da + \int_{a_{EN}}^{a_{max}} \lambda_{2,T}^{(M)}(a, a_{E2}, H_{2,T}) S_0(a|a_{EN})\, e^{-\int_{a_{EN}}^{a} \Sigma_T \lambda_{1..N,T}^{(M)}(t, a_{E1}, H_{1,T}, \ldots, a_{EN}, H_{N,T}) dt} da + \cdots + \int_{a_{EN}}^{a_{max}} \lambda_{N,T}^{(M)}(a, a_{EN}, H_{N,T}) S_0(a|a_{EN})\, e^{-\int_{a_{EN}}^{a} \Sigma_T \lambda_{1..N,T}^{(M)}(t, a_{E1}, H_{1,T}, \ldots, a_{EN}, H_{N,T}) dt} da$$

$$= \int_{a_{EN}}^{a_{max}} \left[\lambda_{1,T}^{(M)}(a, a_{E1}, H_{1,T}) + \lambda_{2,T}^{(M)}(a, a_{E2}, H_{2,T}) + \cdots + \lambda_{N,T}^{(M)}(a, a_{EN}, H_{N,T})\right] \times S_0(a|a_{EN}) \times e^{-\int_{a_{EN}}^{a} \Sigma_T \left[\lambda_{1,T}^{(M)}(t, a_{E1}, H_{1,T}) + \lambda_{2,T}^{(M)}(t, a_{E2}, H_{2,T}) + \cdots + \lambda_{N,T}^{(M)}(t, a_{EN}, H_{N,T})\right] dt} da$$

*NASA dose quantities and risk metrics that are used in cancer risk analysis. By limiting the **effective dose** that each astronaut can received over their career, the increased risk of death caused by the radiation exposures is held to an average of no more than 3 chances out of 100. Here, the REID in a specific organ or tissue "T" is calculated for a number (N) of missions. Additional exposure limits exist to control risks from transient exposures or exposures from nuclear technologies that may occur during a mission.*

Human Space Exploration: Mitigating The Non-ionizing Radiation Risks

By Ramona Gaza, PhD and Sabrina Houston

Figure 1. The International Space Station. Photo Credit: NASA

Human spaceflight exploration poses a multitude of health risks for the astronauts inhabiting the International Space Station (ISS) in low-Earth orbit (LEO). Outside LEO, exploration missions to the Moon and other planets (e.g., Mars) involve progressively enhanced risks due to the dynamic and hazardous space environment, increased distance form Earth, and potentially longer duration missions. Exposure to ionizing and non-ionizing radiation in space is one of the major health risk concerns. The non-ionizing radiation (NIR) sources that are monitored for crew protection include radiofrequency (RF) emitters, natural and artificial incoherent light sources, and lasers.

Through the development, habitation, and research utilization of the ISS, there has been an expansion in the use of stronger lasers, coherent and incoherent light sources, and more powerful antennas to provide increased communication capabilities. Although the NIR safety requirements are based on comprehensive terrestrial regulatory guidelines, the unique challenges associated with spaceflight operations require a proactive, flexible, and highly adaptive risk management approach that is unique compared to more traditional terrestrial NIR safety processes.

The hazard mitigation considerations expand to include the hazard severity as determined by the discipline Subject Matter Experts (SME) and the development of hazard controls and corresponding verification methods by the system/payload provider, all covered through safety documentation records per the established NASA Safety Review Panel (SRP) approval process. Hardware design and controls, health countermeasures, and operational controls are all used as part of the NASA's NIR hazard mitigation strategy.

The SRAG NIR SMEs, as a part of the Human Health and Performance Directorate, are the agency's focal point of expertise for NIR hazard requirements regarding space crew protection and are responsible for ensuring that the NIR exposure received by astronauts in space remains below established safety limits.

LEO programs (e.g., ISS) and beyond LEO exploration programs (e.g., Artemis, Gateway, and HLS) will rely on lasers for a variety of operational and research applications, such as vehicle docking, optical communications Laser Communications Relay Demonstration (LCRD) systems, extravehicular activities (EVA) rover laser for surface studies of planets and celestial bodies, and intravehicular activities (IVA) laser science payloads.

The extravehicular (EV) lasers can pose a hazard to EV crew during spacewalks, the intravehicular (IV) crew through the ISS windows, the visiting vehicle crew approaching to dock with the station, and they can also potentially pose a very small hazard to the uncontrolled general population, primarily through magnifying optics viewing from the ground. Alternatively, since the space station is tracked and targeted by ground lasers extensively for science and research purposes, the ISS crew members are subject to laser exposures from Earth which are strong enough to reach LEO. This can be particularly damaging during aided optics viewing activities since cameras and binoculars are routinely used by crew members for Earth observations.

Figure 2. NIR SMEs (left to right): Dr. Ramona Gaza (lead), Sabrina Houston

Due to the complexity of space environment operations, nominal terrestrial safety practices (e.g., turn laser off for maintenance and troubleshooting; no direct beam viewing for hazardous laser; minimize reflective surfaces) cannot be easily implemented. For example, the ISS crew members need to purposefully observe the visiting vehicle docking through the ISS windows, thus be potentially directly exposed to a strong docking laser. The ISS large solar panels can act as laser reflectors that could affect the EV crew. In addition, there is a potential for unintentional and unquantified risk for external lasers to cause temporary or permanent ocular damage through the ISS windows.

Figure 3. ISS crew during Earth Observation activities. Photo Credit: NASA

Astronauts are exposed to natural incoherent light (e.g., sunlight) during the multiple daily 90-minute orbits through the ISS windows. Some of the module windows offer full protection against sunlight (e.g., Cupola windows with the new scratch panes installed); however, some module windows and hatch windows lack in UV and IR protection (Figure 3).

The ISS crew members are instructed to use NASA developed laser and sunlight protection glasses during all ISS window viewing activities. In addition, the crew must not use binoculars or the camera view finder when the sun is either in the field of view or anticipated to be in the field of view.

The artificial incoherent light exposure limits and the corresponding damage mechanisms are dependent on the emitting wavelength(s). Biological effects due to exceeding light exposure limits range from retinal thermal damage (visible and infrared light) to photochemical effects, including corneal sunburn, macular degeneration, and skin damage (blue and UV light). Examples of sources used for research or operations in space include, but are not limited to, LEDs, lamps, cabin lightning, and display screens. Figure 4 shows an example of ISS research using a strong light source.

Figure 4. ISS crew performing on-board activities in support of the Veggie research project. Photo Credit: NASA https://spaceflight101.com/iss/veggie/

The RF emitters that could potentially harm the EV and IV crew aboard the space station range from large antennas to CubeSats to radiofrequency identifier systems. Some of the biological effects encountered after RF exposure include RF shocks or burns; heating pain or tissue burns; and behavioural disruption, heat exhaustion or heat stroke. Some of the challenges associated with strong emitter in space is not being able to impose keep out zones, a basic RF safety practice for terrestrial applications. One of the acceptable mitigation techniques for crew protection in such cases is the power down of the RF source while the crew members are scheduled to execute daily activities near the RF emitter.

Enabling safe human space exploration to provide protection from non-ionizing radiation hazards is paramount for the agency and all NASA Programs. The Human Health and Performance Directorate will continue evaluation of the NIR hazards to ensure mission success and safe human exploration on ISS, outside low-Earth orbit, in cis-lunar space and on future missions.

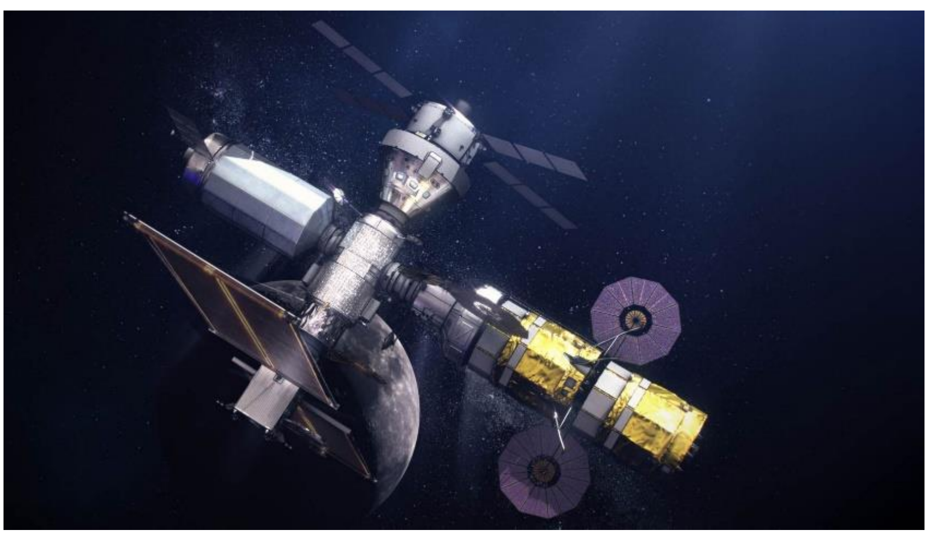

Figure 5. The Artemis Gateway with docked Orion vehicle, artist's impression. Photo Credit: NASA

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Course Lights the Path to

Safer Space Exploration

By **Monica Edwards**

A six-month virtual curriculum, led by scientists at NASA's Human Research Program (HRP), recently completed its inaugural year. Course planners are now preparing for the next class of participants.

This course, called the Space Radiation Didactic Curriculum, is part of the "Space Health Impacts for the NASA Experience" (SHINE) program. SHINE is tailored for graduate students, post-docs, senior research scientists, and principal investigators. The program provides participants with a comprehensive understanding of HRP through a focus on the safety and well-being of astronauts.

Twenty-five participants completed this space radiation course, previously known as the NASA Space Radiation Summer School. Coursework focused on helping participants better understand how spaceflight impacts human health, become familiar with the internal NASA processes that impact risk management, and gain understanding of HRP's grant application process.

SHINE takes a multi-faceted approach to its course load. Participants engage in formal lectures covering fundamental scientific concepts guided by experts in the field. The learning experience is further enriched by interactive "coffee hours", which give participants the opportunity to network with leaders in space radiation research.

"Fostering collaboration in this way strengthens the community of like-minded researchers committed to advancing space health," explained Robin Elgart, lead scientist for HRP's Space Radiation group.

In future versions of the Space Radiation Didactic Curriculum, HRP hopes to offer short practicum sessions at NASA's Space Radiation Laboratory, the agency's premier space radiation analog facility. This hands-on experience will enable participants to delve deeper into space radiation research and its real-world applications.

SHINE organizers also aim to expand curriculum offerings to include a course from each of HRP's four other research groups: Human Health Countermeasures, Exploration Medical Capabilities, Human Factors and Behavior Performance, and Research Operations and Integration.

"Through such expansion, SHINE can help students learn in depth about the five main hazards to humans in space: radiation, isolation and confinement, distance from Earth, changing gravity fields, and closed environments," said Elgart.

SHINE's use of the virtual environment opens doors to a diverse cohort of participants, Elgart notes. Recent participants included citizens from eight different countries, as well as a few students who physically participated from Canada and the United Kingdom. SHINE coordinators eventually seek to host recordings of all lectures online. Until then, researchers interested in course resources can email SHINE coordinators at jsc-hrp-space-radiation-element@mail.nasa.gov.

PUBLICATION CORNER 2023

Attached are publications from August 2022–August 2023 related to LSAH data requests and other papers that may be of interest. For your convenience, each publication has a link to take you directly to the abstract or publication online. For papers not available via open source, the corresponding author may be able to provide you with a copy.

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FORMERS CORNER

> Thanks for the continuing care! Spending much of my retirement time backpacking the New Mexico and Colorado mountains. Summitted Mt. Harvard, 14,421 ft, for my 77th birthday. Geezer Power!

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NASA Astronaut (Ret.), Col., USAF (Ret.)
Professional Speaker
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