# In-Space Assembly of the Gateway-Lunar Surface Development and Protection: Lunar Operations Conceptual Design I.

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**Background:**
NASA plans to build a Lunar Orbital Platform-Gateway (LOP-G) consisting of at least one element of power and propulsion, habitability, logistics and docking possibilities. To be assembled in space (like the International Space Station or ISS), the first module will be a power and propulsion system, using "high power electric propulsion" to maintain the position of the platform in a stable lunar orbit. Assembled first on the ground, both the propulsion and habitation elements it will be launched together with other elements for mostly robotic in-space assembly (ISA). Unlike ISS assembly by astronauts with robotic manipulators, robotic ISA allows for complex structures to be assembled without the need for EVAs. EVA-assembled structures were designed around the limitations of humans in spacesuits and other criteria, such as maximum force applied, time limits, and dexterity requirements. Robotic ISA, on the other hand, requires design for both the structure and the robotic assemblers, the latter being either Stationary, Crawling, or Free-flyers. The robotic system with a stationary base has manipulator(s) rigidly attached to a single location on the base structure and a workspace directly linked to the length of the manipulator (Komendera and Dorsey (2017)). Thrusters are used in unattached Free-flying robotic systems to move the robot body around the workspace, (Wenberg et al. (2017). Crawling robotic systems with more manipulators remain attached at designated footholds to move the robot body along the structure base (Lee et al. (2016).

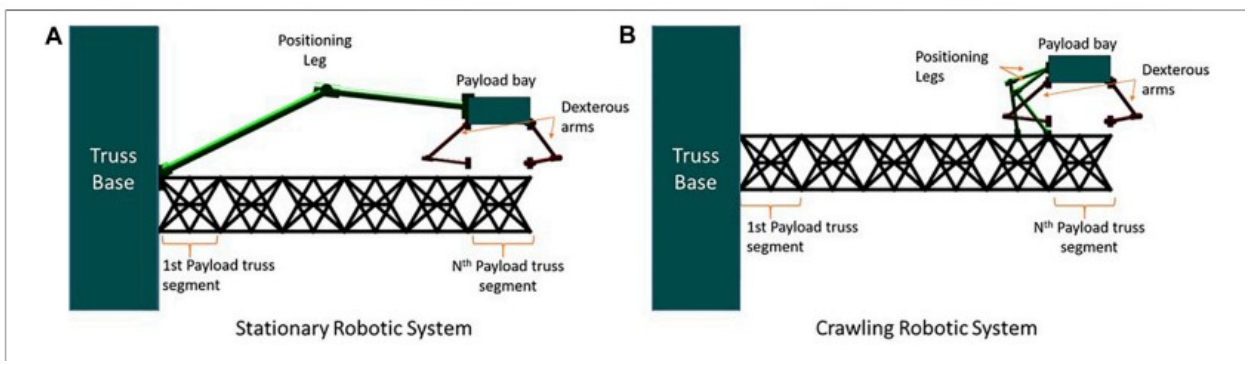



Figure 1 | (A) Stationary robotic system (B) Crawling robotic system.

In-space assembly LOP-G robots will have a 20 m linear truss structure to expand into a 10 and 50 m truss. Both a stationary robot and a mobile robot will crawl along a structure and utilize two planar dexterous manipulators to assemble individual truss pieces into a linear truss [1]. Teleoperating these robots may be controlled from Earth ground station or an orbital platform. LOP-G enables a Gateway installed-complex control station to operate similarly. Such was demonstrated on ISS with ANALOG-1 technology in 12 distinct METERON experiments [2]. Therefore, ESA's ANALOG-1 experiment per lunar surface development may commence with a fleet of a NASA-supported robotic spacecraft touching down on the lunar soil. Masten Space's lander intends to embark on the Moon's South Pole in November 2023, carrying instruments to detect water ice. Astrobotic will deliver NASA's VIPER rover on the Moon's South Pole in November 2024, to explore areas in and around PSRs for over 100 days.

## Introduction:

Comprehensive observations from the CRaTER instrument on the Lunar Reconnaissance Orbiter characterize the radiation environment and space weathering on the Moon [3]. Extreme solar storms occur at random. Many, like the infamous 1859 Carrington event, occurred during seemingly low solar activity. Although extreme events are very rare, making them hard to study. Besides describing and managing TID-induced hazards to lunar operations, single

event upsets (SEU) needs characterization for predictive safety measures. Solar radiation storms occur when a large-scale magnetic eruption, often causing a coronal mass ejection and associated solar flare, accelerates charged particles in the solar atmosphere to very high velocities. The most important particles are protons which can get accelerated to 1/3 the speed of light or 100,000 km/sec [4].

The effects that can be experienced as the result of environmental disturbances that NOAA's Space Weather Prediction Center forecasts, includes geomagnetic storms and solar radiation storms.The solar storm of August 1972 occurred between two Apollo missions. The crewed Apollo 16 had returned to Earth in April and the crewed Apollo 17 was preparing for a moon launch in December. However, an Apollo command module with its aluminum hull would have attenuated the 1972 storm from 400 rem to less than 35 rem at the astronaut's blood-forming organs. Thirty-three years later, the proton storm of January 15-20, 2005, packed more than 100 million electron volts (100MeV) of energy. The sun-lit side of the moon is totally exposed to solar flares. With little warning, a giant sunspot "720" exploded and produced five solar flares, yet the crew in the heavily shielded and magnetosphere-protected ISS were safe, absorbing no more than 1 rem (equivalent to one roentgen, typical of a diagnostic CAT scan). Proton storms generally interfere with communications, impact satellite operations, causing short circuits and computer reboots, as well as penetrate spacesuits and make astronauts feel sick [5].

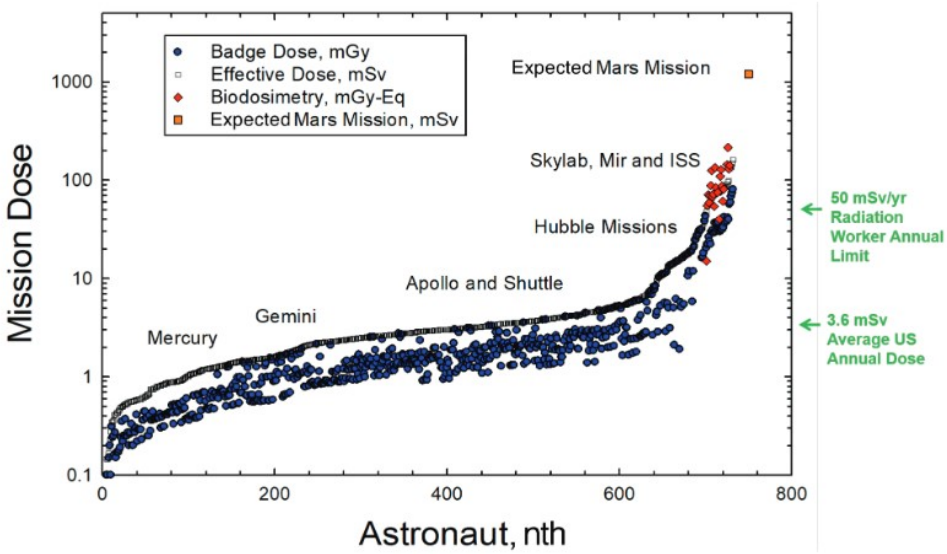



Figure Summary of mission personnel dosimetry for astronauts on all past NASA space missions through 2007.

The following NOAA's space weather scale describes the environmental disturbances for solar radiation storms, listing possible effects at each level. They also show how often such events happen, and give a measure of the intensity of the physical causes.

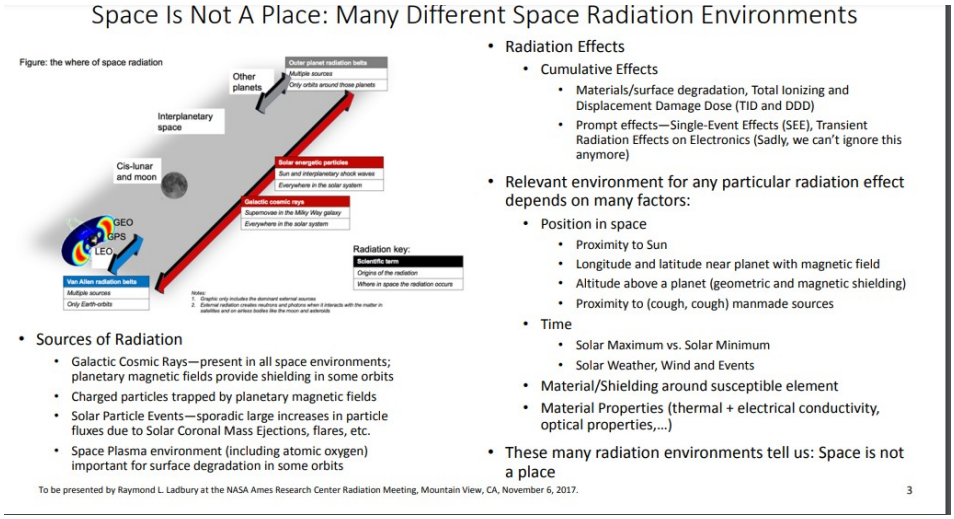
| Solar Radiation Storms | | | Flux level of ≥ 10 MeV particles (ions)* | Number of events when flux level was met** |
|---|---|---|---|---|
| **S 5** | Extreme | Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. ***<br>Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible.<br>Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult. | $10^5$ | Fewer than 1 per cycle |
| **S 4** | Severe | Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***<br>Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded.<br>Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely. | $10^4$ | 3 per cycle |
| **S 3** | Strong | Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.***<br>Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely.<br>Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely. | $10^3$ | 10 per cycle |
| **S 2** | Moderate | Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.***<br>Satellite operations: infrequent single-event upsets possible.<br>Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected. | $10^2$ | 25 per cycle |
| **S1** | Minor | Biological: none.<br>Satellite operations: none.<br>Other systems: minor impacts on HF radio in the polar regions. | 10 | 50 per cycle |

* Flux levels are 5 minute averages. Flux in particles $s^{-1}$ $ster^{-1}$ $cm^{-2}$ Based on this measure, but other physical measures are also considered.
** These events can last more than one day.
*** High energy particle (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

Space weather exposes the hardware-driven mission to vulnerable risks of radiation-induced failures. A robot malfunction or failure causes unforeseen robot stoppage, resulting in economic and production losses. ARTEMIS I mission of 2022 did not carry crew, but two identical manikin torsos wore an Astro-Rad vest equipped with radiation detectors, mapping internal radiation doses to areas of the body [6].

On March 15, 2023, the spacesuit for NASA's Artemis III Moon surface mission was revealed. Created in collaboration with Axiom Space, technological innovations in life support systems, pressure garments, and avionics were applied [7].

In November 2024, a crewed Orion spacecraft will perform a lunar flyby test and return to Earth. When Artemis III and its crew of four arrive in lunar orbit in 2025, a landing vehicle will take two to an awaiting robotic rover VIPER for a 7-day lunar excursion while the other two remain onboard the Gateway. The ridesharing orbital Lunar Flashlight cubesat will help choose Artemis III's landing site by finding and sampling deposits of water ice. Space weather radiation exposes hardware, software, and humanware alike to solar particle events (SPEs) and galactic cosmic radiation (GCR). Consequences of human exposure include carcinogenesis, degenerative tissue risk, acute and late risks to the central nervous system, and acute radiation syndrome (ARS). Therefore, planetary EVAs should be planned around solar activity, but not all SPEs and GCRs are predictable. And so, carcinogenesis risk mitigation is necessary for lunar visit/ habitation, deep space journey/ habitation, and planetary missions. NASEM (National Academies of Sciences, Engineering, and Medicine) reviews processes for long-term risk assessment and management for crewed missions and how to manage uncertainty of space radiation exposure risk assessments. 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 [8].




A study carried out to determine the magnitude and effects of extreme solar particle events on spacecraft design, spacecraft mission planning and human spaceflight is described in [9]. This investigation (termed the Energetic Particle Environment/SEPEM Project) which was implemented for the European Space Agency, was designed to determine, among other things, the radiation effects due to extreme SEPs on the crew of a manned mission of nine months duration at solar maximum and the possible radiation impact of a 'worst-case' extreme SEP. The comparisons show that the spectrum of the SEPEM 95% confidence level event for a mission of 9 months closely resembles that of the October 2003 SEP (which is the largest event in the 10 s of MeV range to be recorded in the past twenty years). In order to estimate the probability that the first modelled SEP (see above) would occur in a 20-year period, a statistical extrapolation was performed, assuming that the duration of a solar cycle is 11 years, with four quiet years offering a negligible probability of the occurrence of a severe SEP as compared with the seven active years). This calculation yielded a 58% probability that at least one such SEP would exceed the measured fluence boundary at any given energy (it is noted that a non-negligible chance that more than one SEP might exceed the given fluence was also recognized [10]. On the assumption that extreme events follow a Poisson distribution, the mean event occurrence corresponding to a 42% chance that no sufficiently large event would take place was determined to be 0.87 for a given time period. As this is of the order of unity, the modelled spectrum was inferred to represent an approximately 1-in-20-year SEP [11].

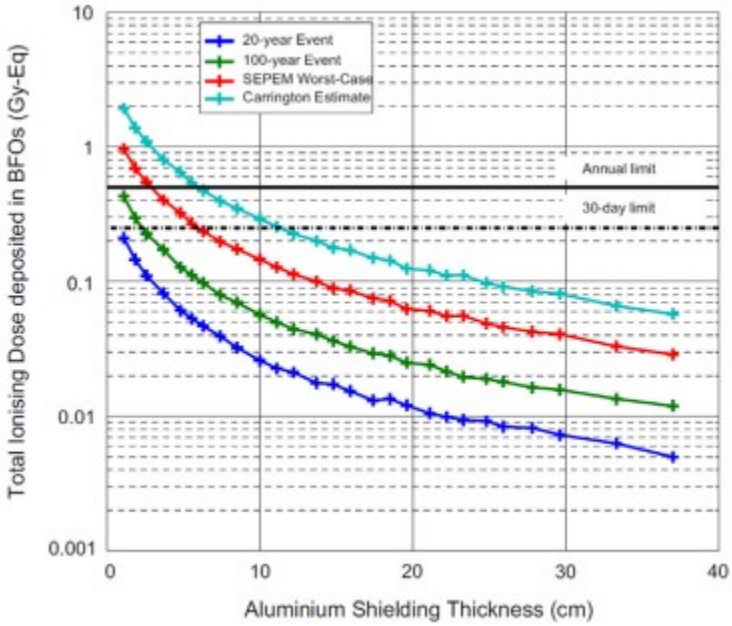
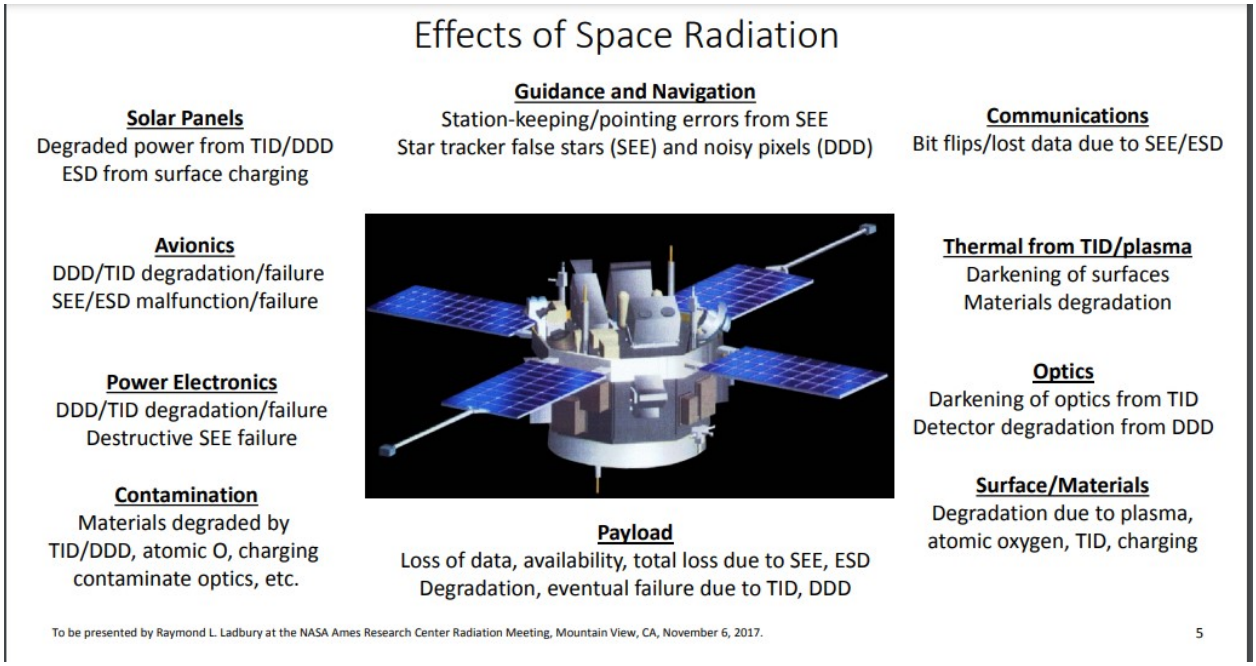


Figure . Total dose deposited (gray –equivalent) in the blood forming organs as a result of encountering each of the four SEPs generated by the SEPEM statistical model, compared with the 30-day and 1-year limits adopted by ESA

The ESA limit (like that adopted by NASA) is based upon a 95% confidence that there is no more than a 3% chance of death in a person's lifetime resulting from the radiation encountered while in space (Risk of Exposure Induced Death/REID). This ESA limit is currently taken to be 1 Sv of dose. On the basis of the results obtained, a minimum of 10 cm Al. equivalent was estimated to provide an appropriate shielding level to protect humans from extreme SEPs. The risks due to GCR were pointed out to be very difficult to shield against although these risks could be reduced by opting to fly the mission at solar maximum [12].

Current spacecraft design is intended to mitigate the cumulative effects of total ionizing dose (TID) through a combination of radiation hardened parts selection and shielding. In particular, the accumulated total dose, over the course of the Europa Clipper Mission, will be attenuated from 2.7 MRad(Si) to 150 kRad(Si) using a protective radiation vault. The shielding vault is designed with ~500 mil aluminum walls to house most of the spacecraft and payload electronics. In addition, a radiation design factor (RDF) of two is applied to the 150 kRad(Si) internal operational environment for the vault electronics [13]. Therefore, given the present shielding design, it is required that electronic components are capable of operating up to a TID level of 300 kRad(Si) at the part location. The RDF of two provides a systematic approach to managing the risk posed by uncertainties in the predicted external radiation environment and subsequent transport models as well as hardware susceptibility. In general, electronics are exposed to ionizing radiation in the space environment at a low dose rate [14]. The total dose for the robotic LRO satellite mission over the first 333 days was only 12.2 Rads behind ˜130 mils of aluminum because of the delayed rise of solar activity in solar cycle 24 and the corresponding lack of intense SEPs. The dose rate in a 50 km lunar orbit was about 30 percent lower than the interplanetary rate, as one would expect from lunar obstruction of the visible sky [15].




NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance space exploration and development. The present state of this effort is documented in NASA's 2020 Technology Taxonomy (Roadmap), an integrated set of seventeen technology area roadmaps. "2020 Technology Taxonomy" is a foundational element of NASA's technology management process. NASA's Mission Directorates (MDs) reference the taxonomy to solicit technology proposals and to inform decisions on NASA's technology policy, prioritization, and strategic investments. Comprised of 17 distinct technical discipline based Taxonomies (TXs), a three-level hierarchy breakdown structure for each technology area is provided. Level 1 represents the technology area. Level 2 is a list of the subareas. And, Level 3 categorizes the types

of technologies within the subareas. Also included is an example technologies section that provides a non-exhaustive sample of relevant technologies.

The 2020 Taxonomy is an update to the 2015 TABS, expanding the total number of technology areas from 14 to 17 areas. The update reflects a shift to a structure that aligns technology areas based on technical disciplines. The updates also include new technologies relevant to NASA, such as cybersecurity and advancements in artificial intelligence.


*Figure 1. The second-level breakdown of the structure used in the 2020 Technology Taxonomy. This document contains details at the third level, with fourth-level technology examples provided in all cases.*

Similarly, "2005 Bioastronautics Roadmap: A Risk Reduction Strategy for Human Space Exploration" documents several key goals for the technologies NASA manages, including new measurement approaches for understanding penetrative space radiation, and validation of radiation shielding designs needed to define risk levels and risk mitigation. The 2005 Roadmap was based on three Reference Missions, including some typical parameters used for

mission planning purposes, including launch dates for the Moon, no later than 2025 (corrected), and for Mars, 2030-2035 (corrected).

| Parameters | Reference Missions | | |
|---|---|---|---|
| | ISS (1-yr) | Moon (30-d) | Mars (30-m) |
| Crew Size | 2+ | 4-6 | 6 |
| Launch Date | NET 2006 | NET 2015, NLT 2020 | NET 2025-2030 |
| Mission Duration | 12 Months | 10-44 Days | 30 Months |
| Outbound Transit | 2 Days | 3-7 Days | 4-6 Months |
| On-Site Duration | 12 Months | 4-30-days | 18 Months |
| Return Transit | 2 Days | 3-7 Days | 4-6 Months |
| Communication lag time | 0 + | 1.3 Seconds+ | 3-20 Minutes+ |
| Hypogravity | 0-G | 1/6-G for up to 30 days | 1/3-G for up to 18 months |
| Internal Environment | 14.7 psi | TBD | TBD |
| EVA | 0-4 per mission | 2-3 week; 4-15/person | 2-3/week; 180/person |

The Roadmap focuses on two types of risks: health and medical risks, and engineering technology and system performance risks. The research and technology questions (R&TQ) in the Roadmap represent issues that must be sufficiently addressed either to resolve questions or retire a risk, or to inform an accepted risk decision. Ensuring the health, safety and performance of those exposed to the space environment requires a research and technology portfolio that spans clinical, basic and applied research and technology development activities, as well as the operational and policy issues related to human spaceflight. The Roadmap will evolve to accommodate new information and technology development, and will enable formal critical path analyses in the future taking into account benefits and costs associated with alternative critical paths and risk reduction options [16]. Question Categories are provided for program assessment purposes. And, Roadmap deliverables are specified to products, identified as desirable outcomes or solutions to the R&TQ.


**Problem:**
Space weather exposes the hardware-driven mission to vulnerable risks of radiation-induced failures. And, it exposes astronauts to health risks, acute as well as progressively clinical. The Apollo Program and the International Space Station Project were primarily human, astronautic-directed. Operations in lunar surface activities and ISS-extravehicular activities directly interfaced astronauts with space weather. Space operations have long leveraged technology "push" with costs and scheduling, but managed risks with safety regimes of probabilistic reliability of operable space assets, sensor-enabled control loops, and barrier-shielding. Twenty years ago, "Bioastronautics Roadmap: A Risk Reduction Strategy for Human Space Exploration" prioritized different technologies underlying

space assets according to their risk to astronaut health and provided investigative questions regarding the risks. Moreover, NASA identified dust as a risk factor for EVA performance and crew health that compromises EVA systems, in addition to deeming space radiation a high priority in protecting astronaut health. The moral issue indicates the apportionment between human EVAs and robotic EVAs.

**Purpose:**
This paper aims to conceptualize an integrated radiation-hardened framework as a mitigating approach to risk management of vulnerable operations in a harsh and unfamiliar lunar climate characterized as space weather. The current design for a radiation tolerant spacecraft is intended to mitigate the cumulative effects of total ionizing dose (TID) in a radiation environment through a combination of radiation hardened parts selection and shielding.

**Methods and Results (TBD):**
NASA engages in a multitude of technology development activities to enable NASA missions by broadening knowledge of and capabilities in aeronautics, science, and space. To manage and communicate the extensive and diverse technology portfolio, NASA uses a technology taxonomy that identifies, organizes, and communicates the technology areas that NASA advances in order to achieve future space missions and aeronautics activities. The 2005 Bioastronautics Roadmap: A Risk Reduction Strategy for Human Space Exploration was evaluated for astronaut risk areas suggesting prioritization of technology areas listed in the 2020 NASA Technology Taxonomy (Roadmap) with sometimes technological readiness level (TRL) < 5. This study aims to describe a current integrated framework, wherein under current R& D literature review, mitigates health risks in lunar operations due to the lunar environmental hazards..

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