National Aeronautics and Space Administration

A Holistic, Collaborative, System of Systems Approach For Viable Radiation Mitigation Solutions

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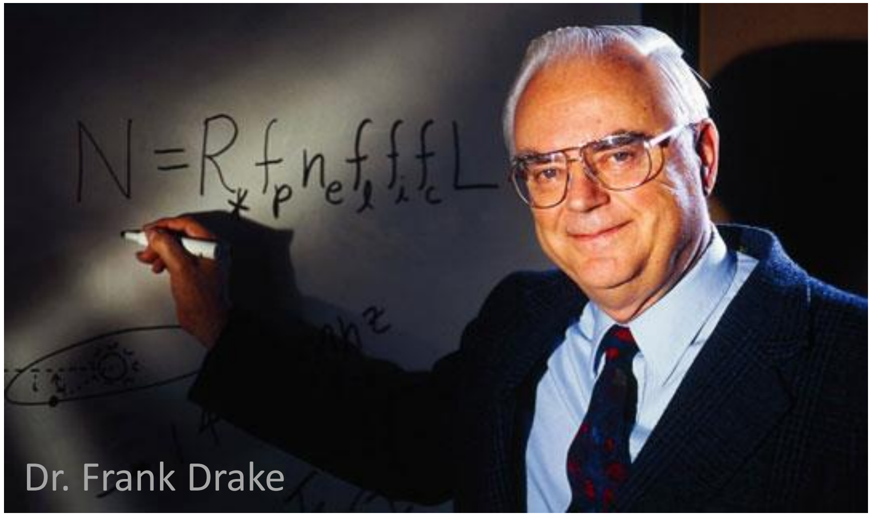
Life Amongst the Stars: The Drake Equation

"What do we need to know about to discover life in space?"

How can we estimate the number of technological civilizations that might exist among the stars?

$$N = R^{*} \cdot f_{p} \cdot n_{e} \cdot f_{l} \cdot f_{i} \cdot f_{c} \cdot L$$



N	The number of civilizations in The Milky Way Galaxy whose electromagnetic emissions are detectable
R^{*}	The rate of formation of stars suitable for the development of intelligent
f_{p}	The fraction of those stars with planetary systems
n_{e}	The number of planets, per solar system, with an environment suitable for life
f_{l}	The fraction of suitable planets on which life actually appears
f_{i}	The fraction of life bearing planets on which intelligent life emerges
f_{c}	The fraction of civilizations that develop a technology that releases detectable signs of their existence into space
L	The length of time such civilizations release detectable signals into space

What does the Drake Equation Inform Us of?

- It has no unique solution
- The equation helps bound the terms
- It specifies contributing factors to a complex query
- There is a relationship between the factors
- No one factor is the sole contributor to the solution
- The equation “stimulates intellectual curiosity”

A Snag with Our Present Approach

- Today's operational "solutions" for HEO-related radiation mitigation
  - Crew Selection
  - Prediction models
  - Distributed dosimeters within the spacecraft
  - Projected biological countermeasures
  - Shielding
  - Orion: duck and cover with available logistics and movable mass
- "Requirement" for cis-lunar vehicle under formulation
  - plans do not include dedicated radiation protection
  - Supplemental radiation protection via internal arrangement
  - "Mission profiles and agreements on acceptable radiation exposure risk determine the amount of radiation protection required"
  - In-situ detectors

Ethical Solution

When a Health/Medical Standard can’t be met…

- Liberalize existing health/medical standards

ARBITRARY

- Establish more permissive health/medical standards for long duration and exploration class missions

UNJUSTIFIED

- Grant an exception to existing health and medical standards under very limited circumstances

ETHICAL

A Snag with Our Present Approach

- Some would say these are sufficient; and has been reported and repeated by some as "we have no showstoppers" for deep space and Mars travel
- But yet, a tension is apparent between statistical treatment, observation, forecasts, and design conceptualization and requirements
  - Accuracy and precision of our models
  - Risk and uncertainty

Sample Caveats

"Confidence level depends on exposure type (GCR, SPE, etc.)"

"Gray Equivalent quantity is used to limit non-cancer effects and is largely unknown for cardiovascular and CNS effects"

"RBE's to assess risks/limits for the cardiovascular and CNS are largely unknown – research program must inform"

A Drake Equation "Equivalent"

- So, what if we were to apply the same Drake equation treatment to radiation mitigation – having a mix of physics-based and evidence-based variables, statistical variables, theories, and ethical terms – in order to understand and sufficiently solve a very complex problem? What might the equation look like?

What do we know, what do we need to know for what endpoint?

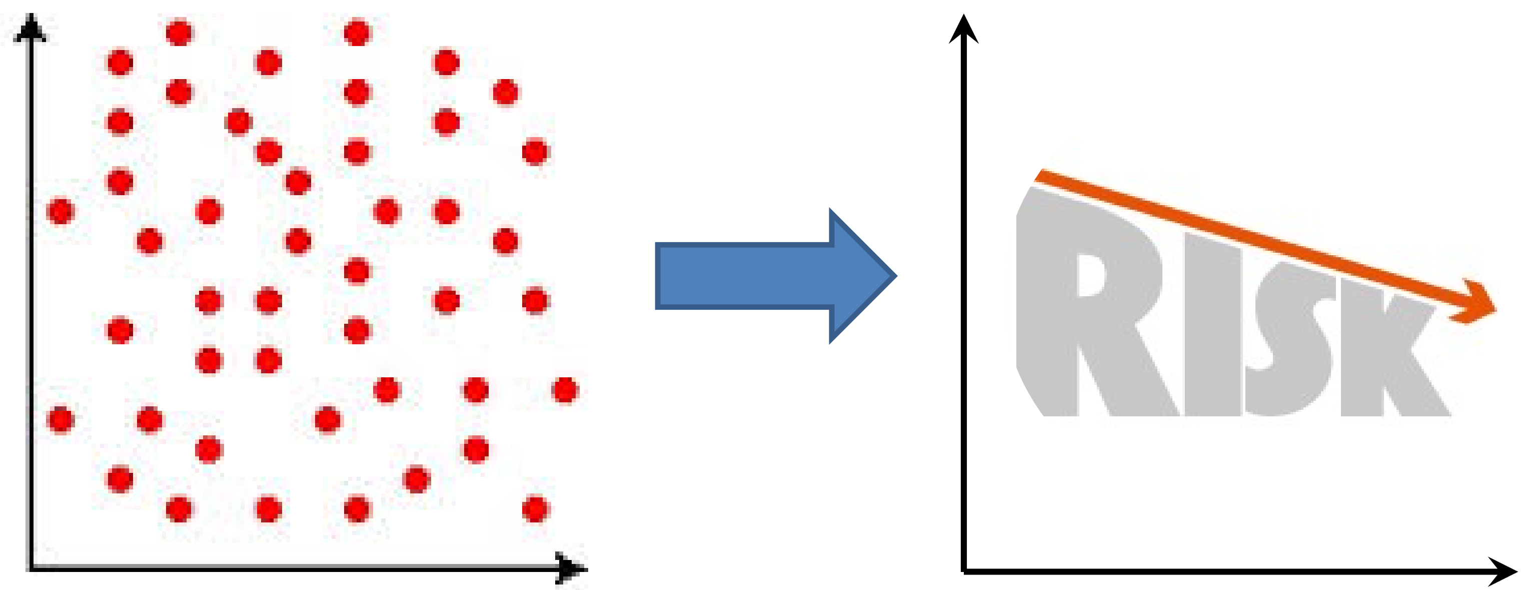
$$M = E \cdot R \cdot H \cdot P \cdot L \cdot T \cdot U \cdot D \cdot S$$

M	Radiation Mitigation	L	Target location
E	Ethics	T	Exposure time and point in time of Solar Cycle
R	Radiation types and magnitudes	U	Uncertainty and Error of forecasts, models, research
H	The effect of radiation on human performance and health	D	Design, Development, Test, and Evaluation
P	The effect of radiation on materials, parts, components	S	Success Criteria

- Enables broad scope identification and characterization of contributing multi-discipline, multi-scale factors that play a role in radiation mitigation
  - "fraction"/depth/magnitude of their contributions
  - the strength of their interactions
  - the investments and divestments we should make at what time

Asking the Question a different way…

- Do we currently have and need a complete, holistic, systematic approach to "sufficiently" protect crew and assets from radiation?
- We certainly have a lot of activities underway, some related, some not related



Asking the Question a different way…

- Are we learning as a whole, in the human and non-human/robotic domains, from these diverse activities to be efficient with our problem solving and decision making?
- What is the contribution of each factor to the whole?
- Are we perpetuating an approach without a specific, measureable goal? How do we know when we're "there"?
- How do we derive the success criteria across the contributing domains?

Option A
• 20 g/cm2 • Adult male of a certain later age • 3% REID with 95% confidence interval • Operational solutions such as burying oneself under trash and logistics is adequate • Changes in the ethical levels for long-term exposure are arbitrary but meet our desires without a basis in measured experience • Many caveats

Option B
• Uncertainty in our models, risk calculations, device and instrument performance is not currently tolerable • Derive a tolerable, measurable solution • Synchronize with design formulation and analysis, and fold in to our near-term mission plans

If Option A, then why expend or invest in further development?

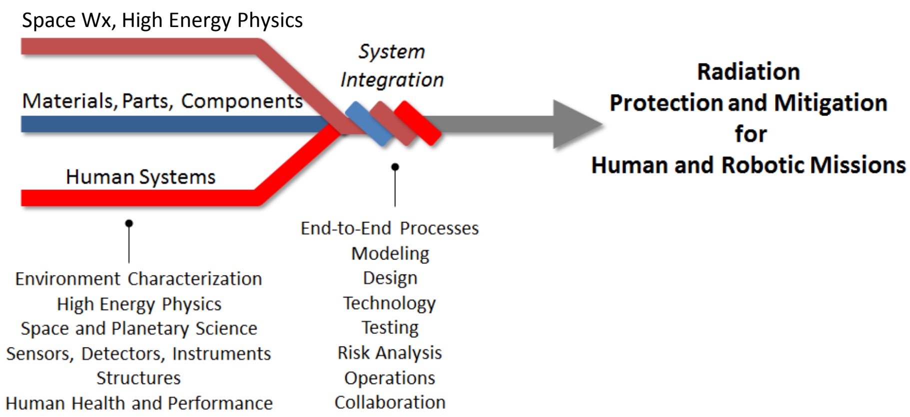
System of Systems

- "A set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities" with a unified goal to improve performance measures, e.g. risk, cost, robustness, reliability, etc. *
- The capability of an SoS is greater than the sum of the capabilities of the constituent parts *

*Source: U.S. Department of Defense (DoD) *System Engineering Guide for System-of-Systems Engineering* (Version 1, August 2008)

Goals

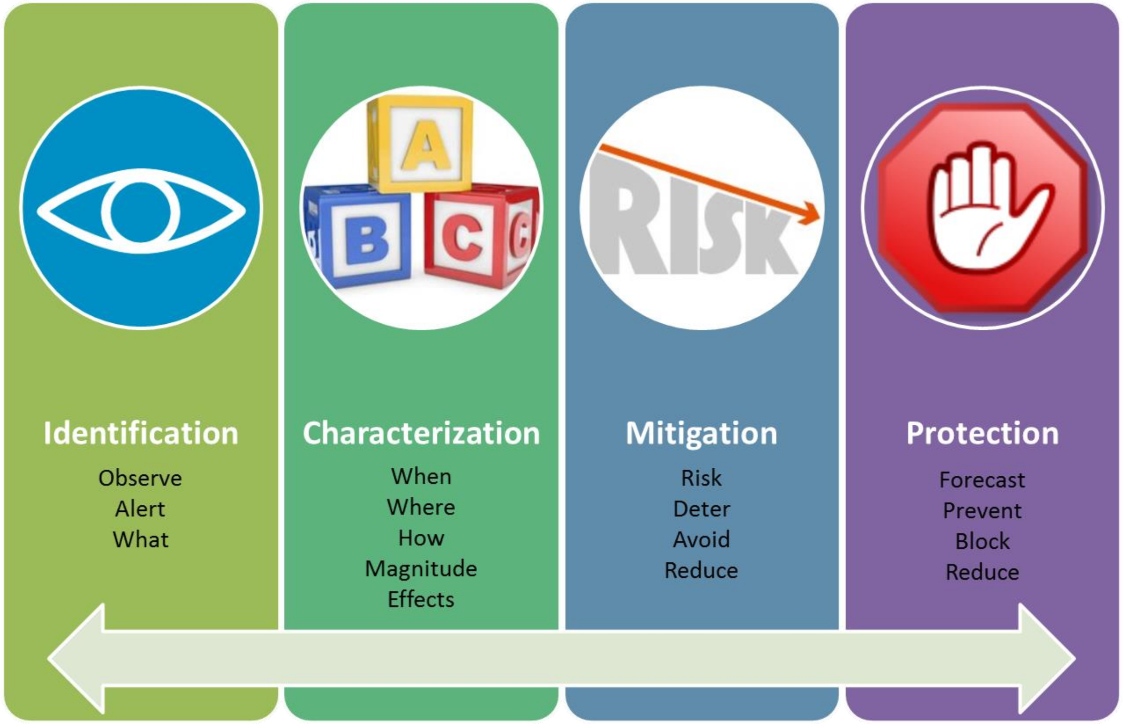
- To move beyond a theoretical and academic perspective to an application perspective, via an end-to-end process with a collaborative structure



- To facilitate breakthrough and crosscutting radiation mitigation solutions
- Derive a comprehensive metric(s) to understand what "there" is
- **To create an emergence process that will breed unique capabilities and solutions from the integration of and collaboration within and across traditionally "independent" human and robotic domains, disciplines, scales, organizations, providers, developers, etc.**

System of Systems Framework for Radiation Mitigation

- Identify contributing disciplines, organizations, technologies, data sources, and "subsystems" with interactions and touchpoints
- Identify operational timeline/phases i.e. observation, prediction, effects, response



A Potential Systems View

Stimulus	Response at different scales to different exposure times, doses, repetition, etc.	Altering the Natural Response	Mitigating or Enhancing the Response; Altering the Degree of the Response
Origin	What changes and how?	Viability	Active shielding
Characteristics	What changes when?	Structure	Passive shielding
Environment / Space Wx	What changes for how long?	Chemistry	Mechanical shielding
Transfer / Transport	What changes and why?		Electronic / Electromechanical shielding
	Natural defense mechanisms		Pharmacological
	Combined environment effects		Pre-Disposition, Crew Selection
	Magnitudes that cause failure		Biological countermeasures
	Recovery after exposure		Time, Duration
	Degradation vs Performance		Prediction, modeling

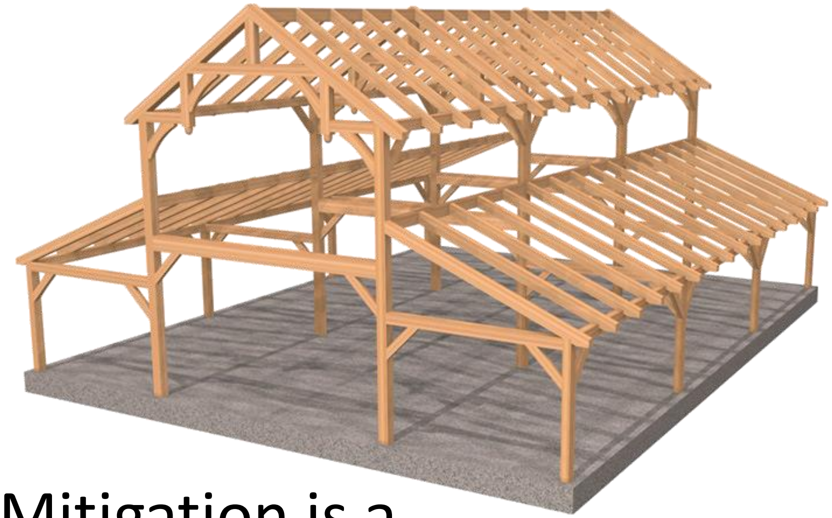
Establishing a System of Systems Architecture

- Clarify high level technical objectives
- Identify systems key to SoS objectives
- Define current performance of the SoS
- Identify performance objectives of subsystems
- Develop architecture overlay for the SoS
  - Addresses concept of operation for the SoS
  - Encompasses functions, relationships, and dependencies of constituent systems, both internal and external
  - Includes end-to-end functionality and data flow and communications
  - Options and trades

System of Systems Architecture

- Methodology developed by Department of Defense

- SoS can take different forms where management authority and direct interactions between subsystem "organizations" vary



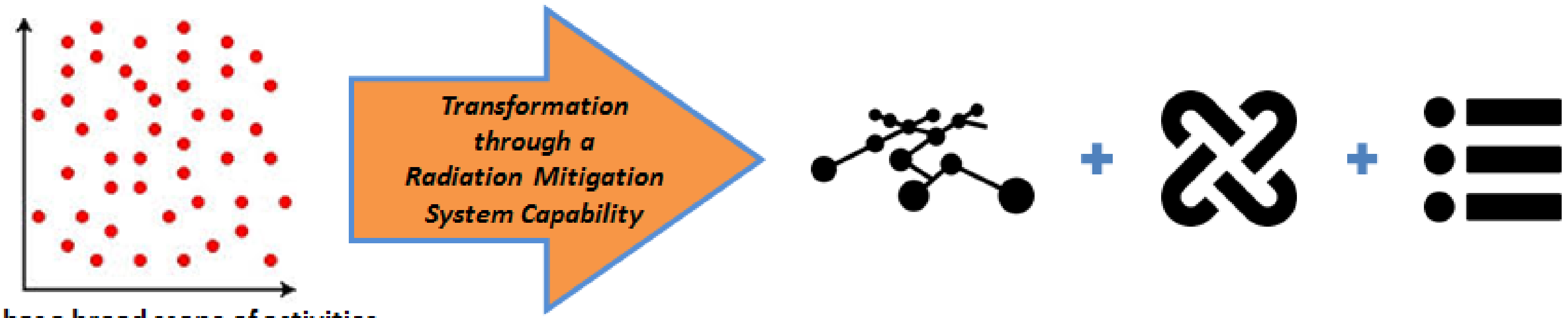
- What may work best for Radiation Mitigation is a Collaborative
  – the component systems interact more or less voluntarily to fulfill agreed upon central purposes
  – The central players collectively decide how to interact, thereby providing some means of enforcing and maintaining standards

Let's Start: Models Interaction Activity

- Help visualize and communicate the connections, interfaces, linkages, gaps, interactions, and use of forecasting and analytical models and tools within and across user and subject matter domains
- Identify existing, new, and planned submodules, independent modules, and "plug-ins"
- Increase awareness of community to submodules, independent plug-ins, etc. that they may be able to utilize and may currently not be aware of
- Identify overlaps and efficiencies in existing models
- Identify and suggest commonalities of data and functionality across models
- Encourage information exchange across users and subject matter domains

Let's Start: Models Interaction Activity, cont.

- Workshop attendees, at their leisure, to identify radiation and mitigation models, submodels, independent modules, plug-ins, etc.
- May identify specific items in use or desired (but please indicate so)
- May identify desired interaction with other existing models



NASA has a broad scope of activities, but are we truly integrated?

Summary

- Need to better define what is “acceptable” or “tolerable”, degree(s) of uncertainty and establish the metric(s) to know when we have arrived at an “acceptable” and/or “tolerable” level bounded by a technically feasible risk posture and ethical guidelines
  - Risk is linked to Uncertainty
  - Uncertainty linked to lack of tangible evidence
- A System of Systems for radiation mitigation will enable a method for deriving and instituting multi-disciplined, multi-scaled, integrated, end-to-end solution set of a complex system
  - Impact of contributing systems on the entire system; the measure(s) of impact
  - Information accessibility and application according to its intended context
  - Test and verification through full “lifecycle” and mission phase intention

Summary, cont.

- A System of Systems provides the opportunity to look at even larger complex systems
- Establish consistent success criteria with an implementation plan and methodology to be synchronous with vehicle formulation, development, and implementation and help to guide smart, logically sequenced decisions and investments

$$M = E \cdot R \cdot H \cdot P \cdot L \cdot T \cdot U \cdot D \cdot S$$

To create an emergence process that will breed unique capabilities and solutions from the integration of and collaboration within and across traditionally "independent" human and robotic domains, disciplines, scales, organizations, providers, developers, etc.

Backup Information

More evidence that we haven't figured it out…

System Maturation Team and Evolvable Mars Campaign Objectives

PROVING GROUND TEST OBJECTIVE	DESCRIPTION
TRN901. Demonstrate operation of single event effect tolerance for wide band gap power switching.	Develop high voltage high current radiation tolerant switching and switch drive devises. Develop high voltage, high current radiation tolerant diodes.
WIS602. Demonstrate cislunar transit habitat (EMC transit hab not ICH) airlock and EVA system servicing accommodation for ability to support nominal deep space mission EVA operations	This objective will … 3) demonstrate EVA system operation in radiation environment.
WIS801. Demonstrate characterization and mapping of physical, mineral, chemical, volatile, and water resources	Remote sensing survey and assessment by Electromagnetic & particle-based techniques for resource deposit mapping – in-space testing (illumination, thermal gradients, shadowing, radiation noise)
WIS808. Demonstrate the feasibility of 3-D construction of structures; the feasibility of shielding construction in micro-g from simulated NEA materials	Develop and demonstrate in-situ regolith concrete types of materials and characterize materials properties, including radiation and high-velocity impacts in-situ shielding effectiveness (NEA/Moon/Mars). Develop NEA and Mars regolith simulants. Re-cycling and re-purposing of existing mission waste stream (packaging, trash, descent stages) into radiation shielding and manufacturing feedstock
STH217, 218 Evaluate SPE radiation protection capabilities.	Advanced radiation sensors will be incorporated into the habitat to measure the astronauts' exposure to radiation in real time so that they can take shelter during solar particle events, to assess the effectiveness of radiation shielding, and to validate radiation transport models for the habitat structure. Key to this FTO is real time monitoring to know the radiation types and characterize the actual radiation environment as it changes over the mission time.
STH219. Evaluate crew responses to deep space radiation environments.	Time-serial analysis of crew samples and crew tests at pre-flight, and several post-mission times can be used to ascertain early biological responses to space radiation and establish a baseline for longer missions with higher exposures. The cislunar galactic cosmic ray (GCR) environment contains all energy components, which is not true of the ISS orbit due to protection by Earth's magnetic field. Blood, urine, and other tissue samples for gene, protein, cytogenetic, and other changes. Crew lens imaging for protein changes and cataract risk. Cognitive testing of crew to study possible early CNS effects.

More evidence that we haven't figured it out…

System Maturation Team and Evolvable Mars Campaign Objectives, cont.

PROVING GROUND TEST OBJECTIVE	DESCRIPTION
STH220. Evaluate the interaction between combined microgravity and Galactic Cosmic Rays (GCR), and validation of NASA's predictive models of biological effects using mice or human cell culture models.	How can experimental models of carcinogenesis be applied to reduce the uncertainties in radiation quality effects from SPE's and GCR, including effects on tumor spectrum, burden, latency and progression (e.g., tumor aggression and metastatic potential)?
STH221. Evaluate the capabilities on the effects of radiation/storage on plant growth/seed viability, effect of radiation/storage on beneficial plant microbes/probiotics.	Seed viability, plant growth, and probiotic viability must be evaluated through possible mission scenarios and durations, or infrastructure must be provided and validated to protect plant and beneficial microbe viability.
STH227. Evaluate the ability to provide and prepare meals.	The food system acceptability and nutritional stability must be demonstrated through possible mission scenarios and durations, or infrastructure must be provided and validated to protect the nutrition content and quality of the food (cold storage, protection from radiation).
STH240. Evaluate Human System usable data from a sufficient fraction of the identified instruments and data sources is captured and deemed sufficient for enabling post flight analysis bounded by the Measures of Performance captured within this FTO.	Radiation - flight crew cabin
STH241. Evaluate the capabilities of refrigeration or freezing and the effects of deep space radiation on the crew food system/supply, nutritional stability, and acceptability/variety over long durations in the deep space environment.	Evaluate the stability of nutrients and overall acceptability of the food system after exposure to deep space radiation.
STH1506. Demonstrate that crew can quickly locate all critical logistics (RFID system) in radiation environment.	This objective will demonstrate that crew can quickly locate all critical logistics (RFID system) in radiation environment.
STH1514. Demonstrate that crew can successfully operate in relevant radiation environment for short periods of time (physiological and vehicle test).	This objective will demonstrate that crew can successfully operate in relevant radiation environment for short periods of time (physiological and vehicle test). This objective may be achieved with radiation layout verification through sensing.
STH1515. Demonstrate that crew can successfully deploy an SPE radiation shelter.	This objective will demonstrate that crew can successfully deploy an SPE radiation shelter.

System Maturation Team Performance Gaps

SYSTEM MATURATION TEAM	DESCRIPTION
EVA	Need a pressure garment which is designed to function in the relevant environments (gravity, dust, radiation, thermal, plasma, etc). Develop the avionics systems for the pressure garment such as radiation hardened and wearable biomedical system. Develop the avionics systems for EVA radiation hardened HD camera/video, graphical display and navigation capability, etc.
ISRU	Develop and demonstrate in-situ regolith concrete types of materials and characterize materials properties, including radiation in-situ shielding effectiveness (NEA/Moon/Mars). Re-cycling and re-purposing of existing mission waste stream (packaging, trash, descent stages) into radiation shielding and manufacturing feedstock
Power	Develop High voltage , High Current Radiation Tolerant Switching and Switch Driver Devices, Radiation Tolerant Diodes

Note: SMT Performance Gaps: The SMT data repository has not yet compiled Crew Health and Performance gaps.