

Space Radiation Research and Exploration Missions

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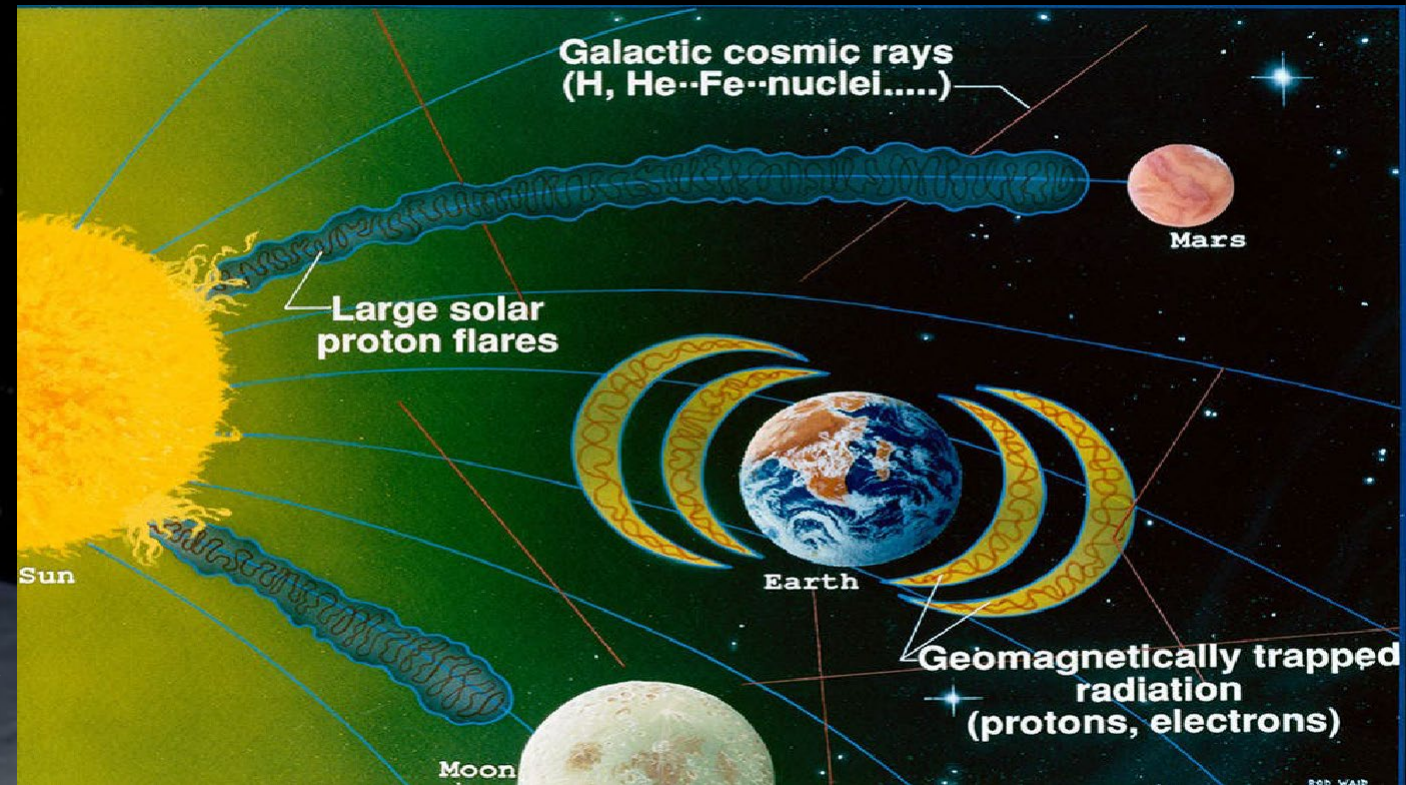
Beyond LEO Space Radiation Environment

Solar Proton Events (SPE)

- Low to medium energy protons
- Travel along magnetic field lines and can arrive quickly if well connected to vehicle
- Shielding is effective
- Space weather monitoring, dosimetry systems, and operations are key to keeping exposures to safe levels

Galactic Cosmic Radiation (GCR)

- Continuous background of low dose rate radiation
- Fully charged atomic nuclei - from H to U
- Accelerated to extremely high energies - broad energy spectrum from 10's of MeV to >50 GeV
- Intensity varies with ~9.5 to 12 year solar cycle
- Highly penetrating difficult to shield against
- More biologically damaging compared with Earth radiation



Solar Max: Highest probability of SPE, GCR intensity at lowest levels
Solar Min: GCR intensities at highest levels; Lower probability of SPE

Space Radiation Health Risks

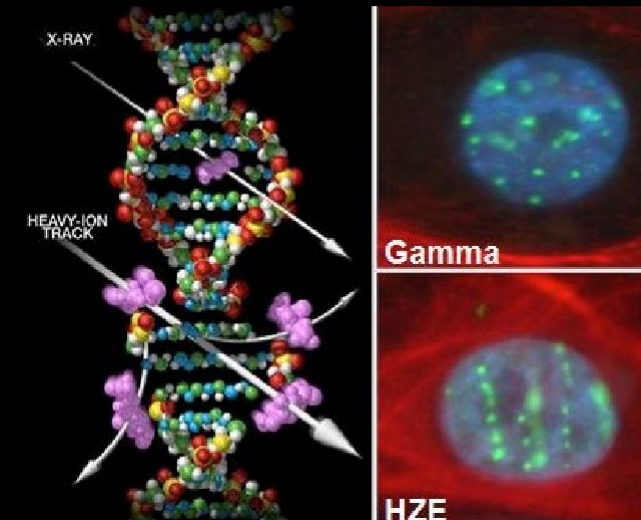
Major Risks -

- Acute Radiation Syndromes from solar particle events
- Central Nervous System Effects – inflight and post mission
- Radiation Carcinogenesis
- Degenerative Diseases – cardiac and vascular



Unique Biological Challenges -

- *Radiation Quality Effects*
- *Low dose-rates in space*
- *Translation to humans*
- *Quantifying combined spaceflight stressors*



DNA Damage in Cells: Space radiation (HZE) dense ionizing particle track

NASA Radiation Standards - Summary

Astronaut's total career effective radiation dose (In 3001, Vol 1 Rev B)

600 mSv

Universal for all ages and sexes, 3% mean risk of cancer mortality, effective dose calculated using 35-year-old female
An individual astronaut's total career effective radiation dose due to space flight radiation exposure shall be less than **600 mSv**.

Galactic Cosmic Radiation (GCR) (under consideration) - achievable with $\sim 10\text{g/cm}^2$ Al

For missions beyond low Earth orbit, vehicles and habitat systems shall provide sufficient protection to reduce exposure from galactic cosmic radiation (GCR) **by 15%** compared with free space such that the effective dose from GCR remains below 1.3 mSv/day for systems in free space and below 0.8 mSv/day for systems on planetary surfaces.

250 mSv

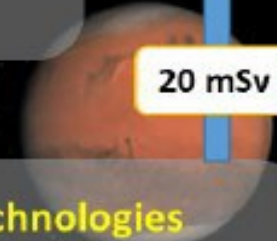
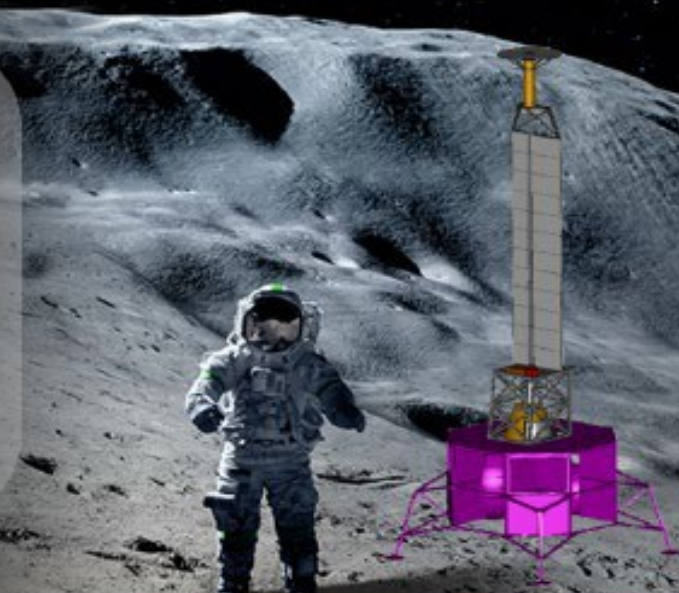
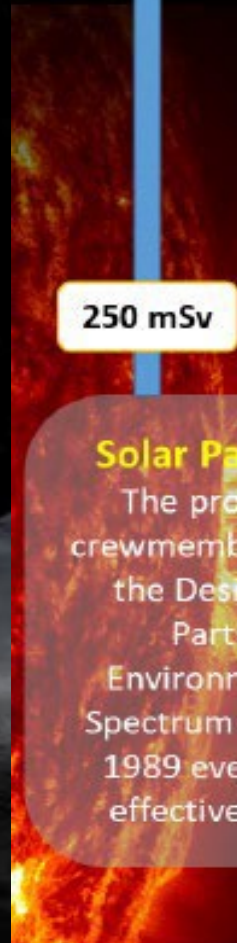
Solar Particle Event (SPE)

The program shall protect crewmembers from exposure to the Design Reference Solar Particle Event (SPE) Environment Proton Energy Spectrum (sum of the October 1989 events) to less than an effective dose of **250 mSv**.

20 mSv

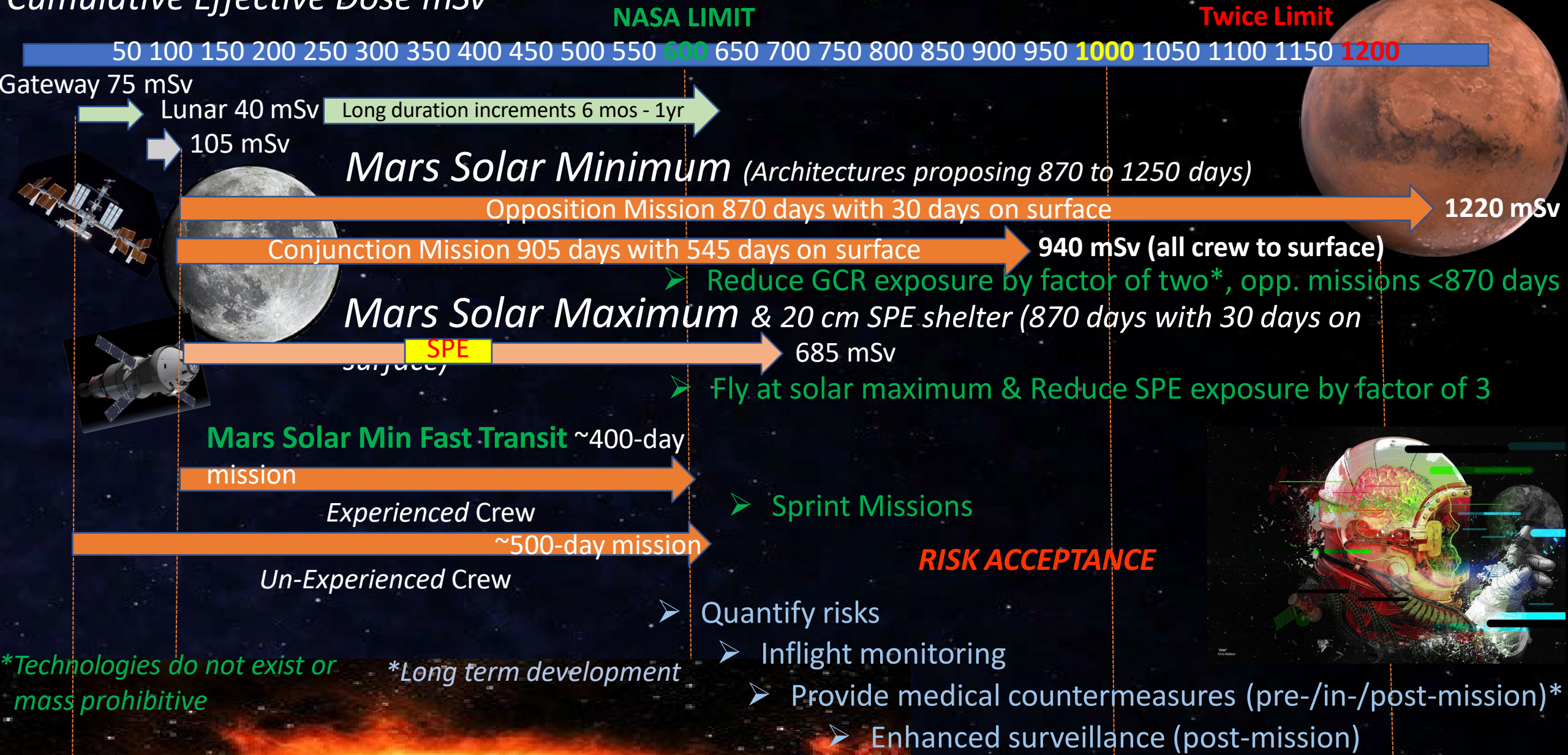
Nuclear Technologies

Radiological exposure from nuclear technologies emitting ionizing radiation (e.g., radioisotope power systems, fission reactors, etc.) to crew members shall be less than an effective dose of **20 mSv** per mission year (prorated/extrapolated to mission durations).

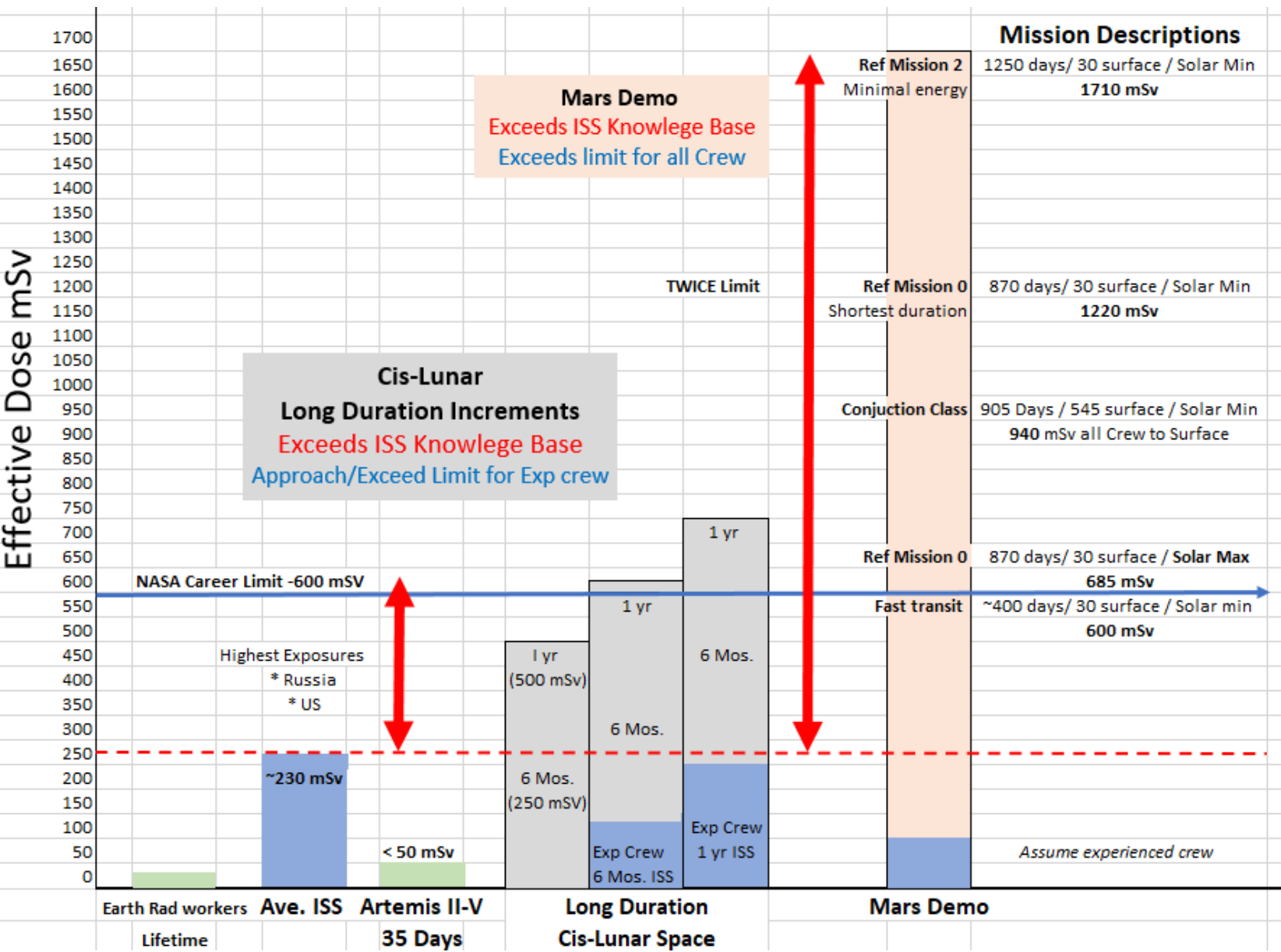


Risk Posture for M2M Missions

Cumulative Effective Dose mSv



Radiation Risk Posture for the Moon 2 Mars Mission Segments



Foundational Exploration Segment (6 mos to 1 yr. cis-lunar space/surface; <250 to 500 mSv)

- Knowledge gap between our average ISS experience (200-300 mSv) and limit (600 mSv)
 - Possibility exists of crossing thresholds for increased risks of cardiac, vascular, cerebrovascular, and neurocognitive diseases
 - Evidence of excess risk in terrestrial cohorts, but data are inclusive.
- Additional protection strategies needed for experienced crew and those most sensitive to radiation

Mars (870 to 1250 days; ~685 to >1700 mSv)

- Exposure levels well outside spaceflight knowledge
- Lack of risk characterization: significant gap between 200-300 mSv and >1700 mSv.
- In >600 mSv dose range, added potential exists for in-mission CNS performance decrements
 - Risk levels are not well understood
 - Effects of the combined stressors of spaceflight unknown
- Additional protection required for all crew

06 Advanced Habitation Systems

Space Radiation Protection

TX06.X.X: NASA OCT Technology Taxonomy

Gap type:

K- knowledge, requires scientific research

D – development (TRL 1-4)

T – Technology (TRL 5-9)

E – engineering (TRL 5-9 mission specific)

Physical Mitigation Technologies

Biological Mitigation

(TX06.5.4)

1.1 Space Weather Forecasting

- (D) SPE forecasting tools
- (D) Earth – independent alert system
- (K) GCR forecasts: Predictive models of solar cycle modulation

(TX06.5.5)

1.2 Radiation Monitoring

- (E) On-board dosimetry systems
- (T) Adv. space radiation env. characterization systems

(TX06.5.3)

1.3 Effective Shielding

- (E) SPE shielding
- (T/E) GCR shielding - passive
- (T) Combined GCR/SPE shielding - active

(TX06.5.1)

1.4 Predictive Models of Crew Health Risks

- (K) Probabilistic health risk models

(TX06.5.2)

1.5 Biomedical Countermeasures and Surveillance

- (K) Biomedical countermeasures
- (K) Biomarkers & Technologies for In-flight Monitoring and Health Management

Major Asset: Space Weather architecture

Major Asset: NASA Space Radiation Laboratory

Galactic Cosmic Ray Protection

State of art

- Within the current M2M architecture, shield technologies and fast Mars transit to reduce GCR exposures - by any significant ($>\sim 50\%$) amount - are currently mass prohibitive.
- Optimized aluminum shielding can reduce GCR by $\sim 15\%$, but Mars exposures still $>$ twice career limit
- High hydrogen materials can further reduce free space exposures ($\sim 30\%$) – buys 3 months longer transit times
- Active shielding concepts do not offer dramatic improvement over passive shielding and introduce new risks in the case of system failures
- Missions at solar max can reduce exposures by $\sim 50\%$ - current models are focused on intensity rather than duration

Enabling

- M2M Architecture - Radiation protection strategy to meet limits and/or significantly reduce risks is needed

Key Performance Metric – Reduce exposures and/or risk by a factor of two

Galactic Cosmic Radiation: Biological Knowledge Gaps

State of the art:

- Vehicle/Passive shielding, ALARA principle
- Operational model to evaluate radiation induced cancers
- Limit crew time on ISS to within career standards

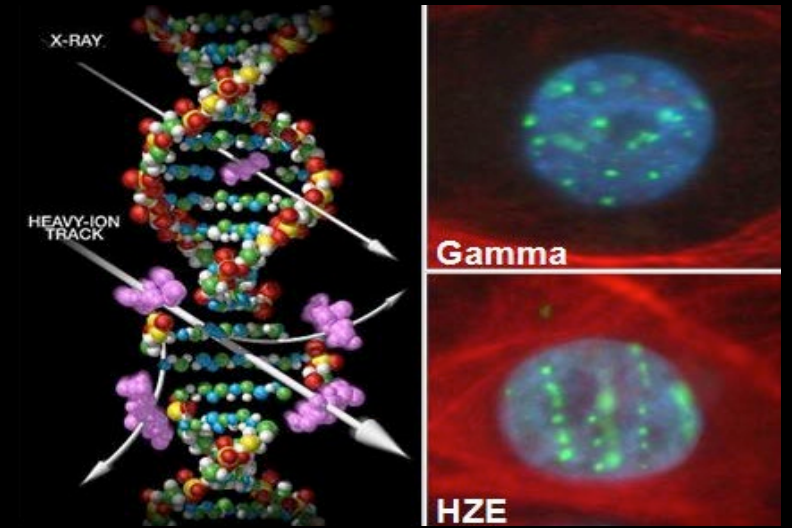
Research Needs: Goal – reduce biological risks by 50%

• (K) Probabilistic health risk models

- Perform necessary research to quantify risks at increasingly large exposures
- Risk models of cardiovascular disease and late neurodegenerative diseases
- Capability to evaluate in-mission radiation risks to the central nervous system
- Methodologies to evaluate interaction of radiation with other spaceflight stressors
- Understand the biology of individual sensitivity/susceptibility
- Provide capability for personalized risk estimates to inform medical countermeasures and disease surveillance

• (K) In-flight diagnostics and preventative medical countermeasures

- Identification of biomarkers of tissue injury & behavioral health
- Compact diagnostics
- Validated countermeasures focused on disease prevention



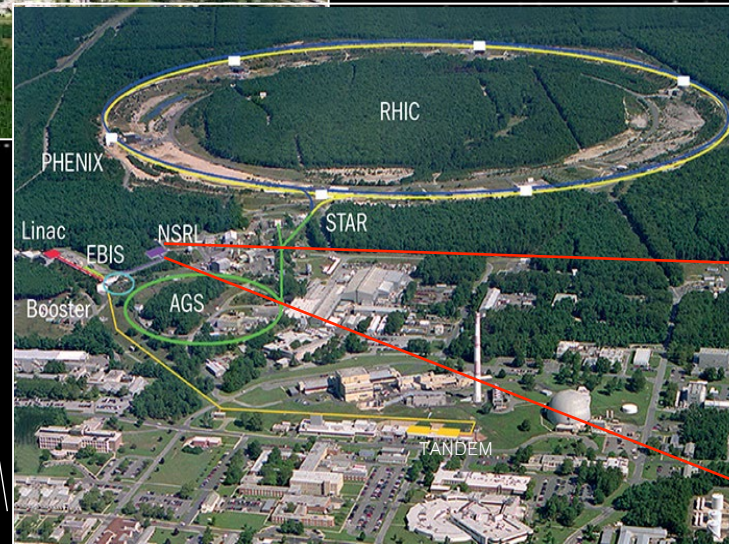
DNA Damage in Cells: Space radiation (HZE) dense ionizing particle track

(Cucinotta & Saganti, Patel & Huff, NASA)



NASA Space Radiation Laboratory

NASA Space Radiation Laboratory (NSRL) at DOE Brookhaven National Lab



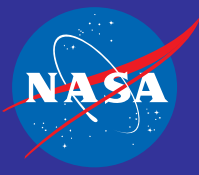
NSRL

- Simulates space radiation - high energy ion beams (H^+ ; He, Fe, Si, C, O, Cl, Ti, etc.)
- GCR Simulator
- 3 experimental campaigns per year
- Animal and cell biology facilities
- Heavily utilized by NASA & commercial spaceflight and DOD Missile Defense Agency

Images courtesy of BNL

GCR Simulator Beam Definition

Normalized to 500 mGy



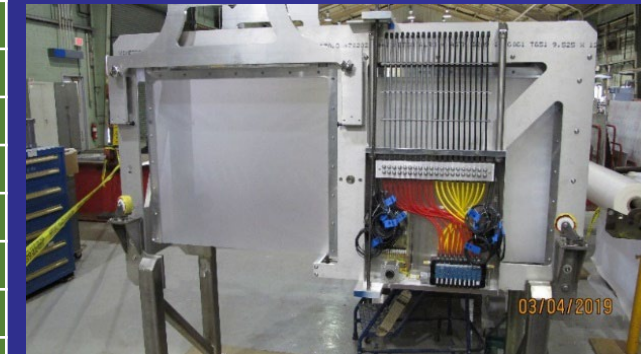
GCR Simulation Beam consists of 33 beams

- 4 H energies plus degrader (65-75% dose)
- 4 He energies plus degrader (10-20% dose)
- 5 Heavy ions: C, O, Si, Ti, Fe (6-8% dose)

Ion	Energy (MeV/n)	Range (cm)	LET (keV/μm)	Dose (mGy)
¹ H	100	<i>Polyethylene degrader to</i>		
¹ H	150	15.9	0.54	35.0
¹ H	250	38.1	0.39	68.9
¹ H	1000	326.6	0.22	123.6
⁴ He	100	<i>Polyethylene degrader to</i>		
⁴ He	150	16.0	2.17	7.5
⁴ He	250	38.3	1.56	16.4
⁴ He	1000	327.8	0.88	24.9
¹² C	1000	110.1	7.95	11.7
¹⁶ O	350	17.0	20.8	15.4
²⁸ Si	600	22.7	50.2	8.1
⁴⁸ Ti	1000	32.5	109.5	4.5
⁵⁶ Fe	600	13.1	175.1	4.1
Total				500.0

Ion	Energy (MeV/n)	Range (cm)	LET (keV/μm)	Dose (mGy)
¹ H	20.0	0.43	2.59	30.4
¹ H	23.3	0.56	2.29	6.7
¹ H	27.2	0.75	2.02	7.4
¹ H	31.7	0.98	1.79	8.0
¹ H	37.0	1.30	1.58	8.7
¹ H	43.2	1.72	1.39	9.3
¹ H	50.3	2.26	1.23	10.0
¹ H	58.7	2.99	1.09	10.6
¹ H	68.5	3.95	0.97	11.1
¹ H	79.9	5.20	0.86	11.2
¹ H	100.0	7.76	0.73	27.2

Ion	Energy (MeV/n)	Range (cm)	LET (keV/μm)	Dose (mGy)
⁴ He	20.0	0.43	10.34	11.0
⁴ He	23.3	0.57	9.14	2.1
⁴ He	27.2	0.75	8.06	2.2
⁴ He	31.7	0.99	7.12	2.3
⁴ He	37.0	1.31	6.29	2.5
⁴ He	43.2	1.73	5.56	2.6
⁴ He	50.3	2.28	4.92	2.7
⁴ He	58.7	3.01	4.36	2.7
⁴ He	68.5	3.97	3.86	2.7
⁴ He	79.9	5.23	3.43	2.7
⁴ He	100.0	7.81	2.90	6.1



Large binary filter system used to deliver lower energy H and He beams – installed 2019

Envisioned Future



Integrated radiation protection technologies* to increase permissible mission duration by a factor of two (~400 days to >800 days) within acceptable mission constraints.

**GCR/SPE shielding, advanced environmental characterization, biomarker surveillance, countermeasures, predictive health models*



Image Credit: NASA Artemis JM1058

Accurate SPE forecasting to minimize crew exposure levels (increase reliability of 24-hour SPE predications by a factor of ~2.5) and optimize mission operations (increase reliability of 7-day SPE forecast by a factor of ~5).



Image Credit: NASA/Pat Rawlings, SAIC

Compact Earth-independent, on-board space environment observation system as accurate as current Earth-based assets.

BACK UP

1. Perform necessary research to quantify risks from GCR

- In 450 mSv to ≥ 600 mSv – understand risk of cardiac & vascular diseases and late neuro cognitive impairments
- In >600 mSv – understand in-mission CNS performance decrement
- Evaluate combined spaceflight hazards
- Develop computational tool set

2. Understand the biology of individual sensitivity/susceptibility

- Leverage terrestrial radiation research (*incl. NCI, ICRP*)
- Develop capability for personalized risk assessment and protection plan

3. Provide *In situ* monitoring of crew health to inform countermeasure deployment

- Biomarkers of tissue injury and/or early disease indicators*
- In-space validation during missions >6 months

4. Provide cross-risk[^] biological countermeasures to reduce adverse health outcomes

- Focus on disease prevention
- Target common disease pathways^{^^}
- Validate terrestrial approaches for space applications

5. Post mission, leverage terrestrial advances in early detection and personalized treatments

- Enable return to flight for multiple missions
- Maintain high quality of life

ICRP Task Group 11

developing report reviews the current science relevant to the topic of individual response to radiation.

Understand International partner plans & interest

- Radiation Countermeasures
- -omics

*Appropriate **biomarkers** may include global indicators of radiation damage and response to the body, such as, chronic inflammation, alterations in genomic integrity, fidelity of DNA repair pathways, and other emerging evidence-based biomarkers.

[^]**Cross risk:** Cardiac and vascular diseases, CNS performance decrements and late neurocognitive impairments, accelerated aging, and cancers

^{^^}Ex. of **common targets:** chronic inflammation, mitochondrial dysfunction, oxidative stress, DNA damage, etc.

SPE SHIELDING

Requirements & Design Guidance vary across Systems

Existing Vehicles/Programs

- ✓ ALARA
- ✓ Orion: <150 mSv effective dose from Aug 1972 event
- ✓ Gateway: <250 mGy-eq to BFO from sum of 1989 events
- ✓ Human Landing System:
 - Initial missions: ALARA
 - Sustaining:* <250 mSv effective dose from sum of 1989 events

*New Standard 3001 Vol. 1 SPE shielding guidelines:
Design reference spectrum – Sum of Oct 1989 events*

Table 6—Recommended Shielding Guidelines for SPEs

<i>Mission Location and Duration</i>	<i>Shielding*</i>	<i>Type(s) of Shielding</i>	<i>Comments</i>
<i>Celestial surface any duration</i>	<i>10 cm (or g/cm²) water equivalent surrounding the astronaut; Considers celestial surface shielding contribution</i>	<i>Reconfigurable shielding already within the vehicle</i>	<i>Timeline of SPEs allows for reconfiguration</i>
<i>Beyond low Earth orbit <6 months</i>	<i>15 cm (or g/cm²) water equivalent surrounding the astronaut</i>	<i>Reconfigurable shielding already within the vehicle; Shielding may include personal protective equipment (PPE)</i>	<i>Timeline of SPEs allows for reconfiguration</i>
<i>Beyond low Earth orbit > 6 Months</i>	<i>20 cm (or g/cm²) water equivalent surrounding the astronaut</i>	<i>Integrated vehicle and/or reconfigurable Shielding which may include PPE</i>	<i>Long-duration missions increase the probability of the crew being exposed SPEs</i>

**The shielding required to meet the standard (utilizing existing mass when feasible).*

Estimated SPE effective dose using guidelines for new programs

✓ Mars Surface: 25 mSv

✓ 145 mSv

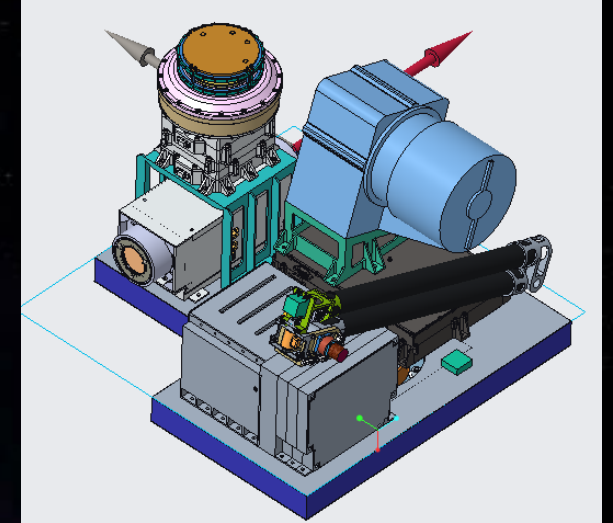
✓ Mars Transit: 107 mSv

**New Limit from NASA STD 3001 update in 2022*

Solar Particle Events – Development Gaps

State of the Art:

- **Storm shelters & dosimetry:** Technology exists; engineering, design, and mass optimization
- **Space Weather:** Forecasting with Earth-centric observations and real time ops communication
- **Medical Countermeasures:** In case of accidental exposure, terrestrial MCM's exist (BARDA)



HERMES on Gateway

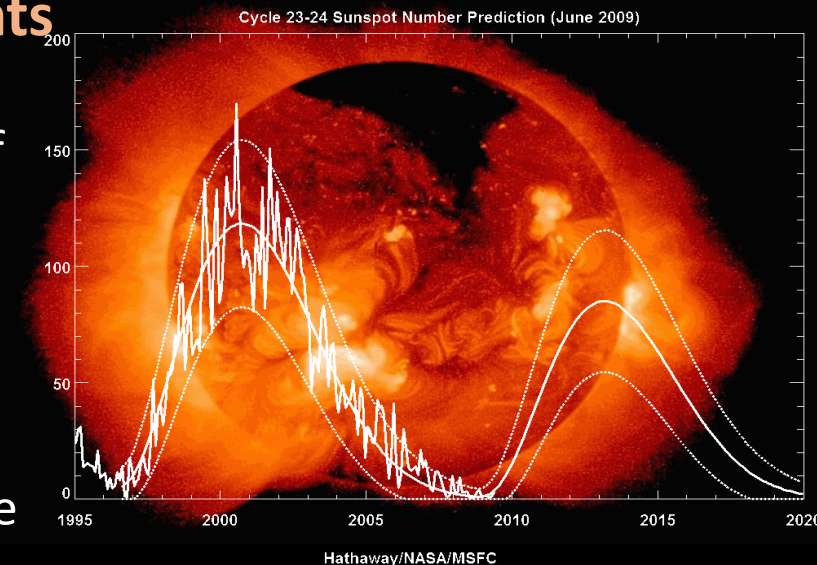
Research and Technology needs:

Accurate real-time operational forecasting of solar particle events

- Increase accuracy & warning times in advance of storm – 24 hrs
- Reliable predictions of peak flux, duration, magnitude and time evolution of event – over hours to >7 days
- All-clear periods

Earth-independent monitoring and forecasting

- Miniaturized onboard instrument suite for space weather observation
- Possibility of new space weather architecture platforms along Sun-Mars Line
- Autonomous forecasting & warning software



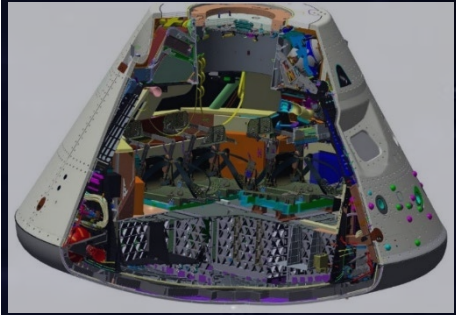
Space Radiation Protection: Engineering Gaps

State of the Art:

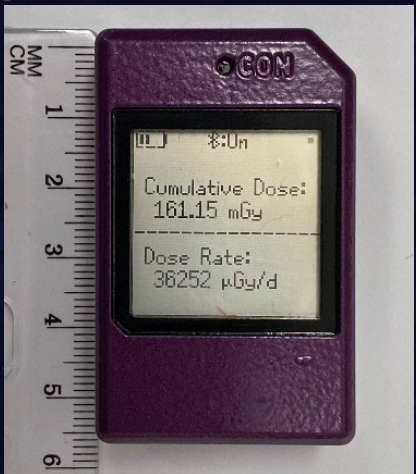
- HZETRN/OLTARIS design tool supplies models and methods to optimize spacecraft shield design and verify requirements
- Reconfigurable mass provides SPE protection on Orion
- Active (CAD & HERA) and passive dosimetry systems demonstrated on ISS and Orion

Sustaining Engineering meet Program Requirements

- Maintain transport and engineering design tool capabilities
- Continued engineering required to supply reliable dosimetry systems
 - Processing electronics become obsolete every 5-10 yrs
 - Each system must meet vehicle mass, power, volume requirements
 - On-board testing & validation required for each crewed vehicle
- Skilled workforce
 - Support commercial suppliers & requirements verification of new vehicles
 - Maintain on-board dosimetry suite for each flight



Shield Models



Crew Active Dosimeter



Artemis-I Hybrid Electronic Radiation Assessor (HERA)



SpaceX utilizing OLTARIS for shield evaluation

Protection from GCR: Mars Demo Mission



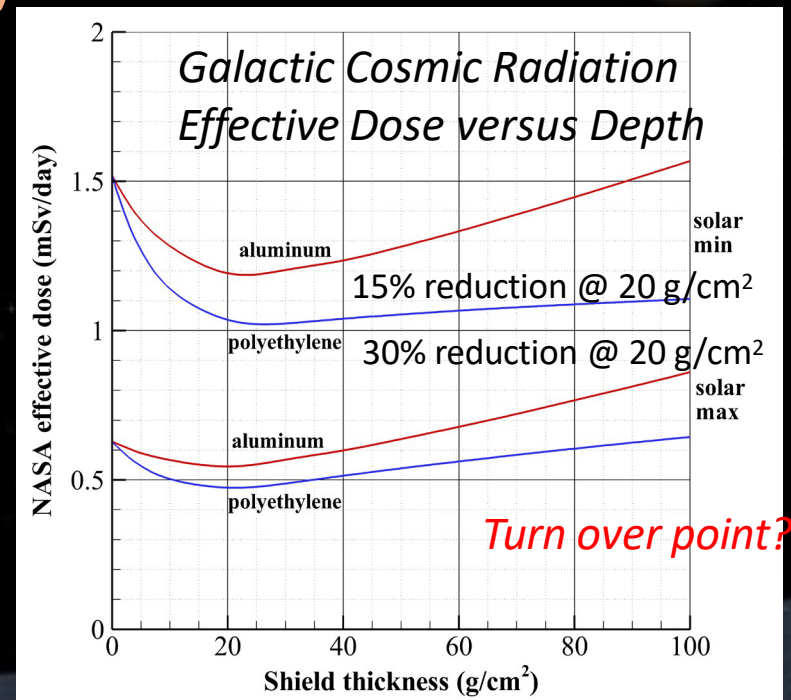
Goal: Return crew safely and mitigate health impacts (RT 3)

Physical Mitigation

Propulsion – Sprint missions less than ~500 days

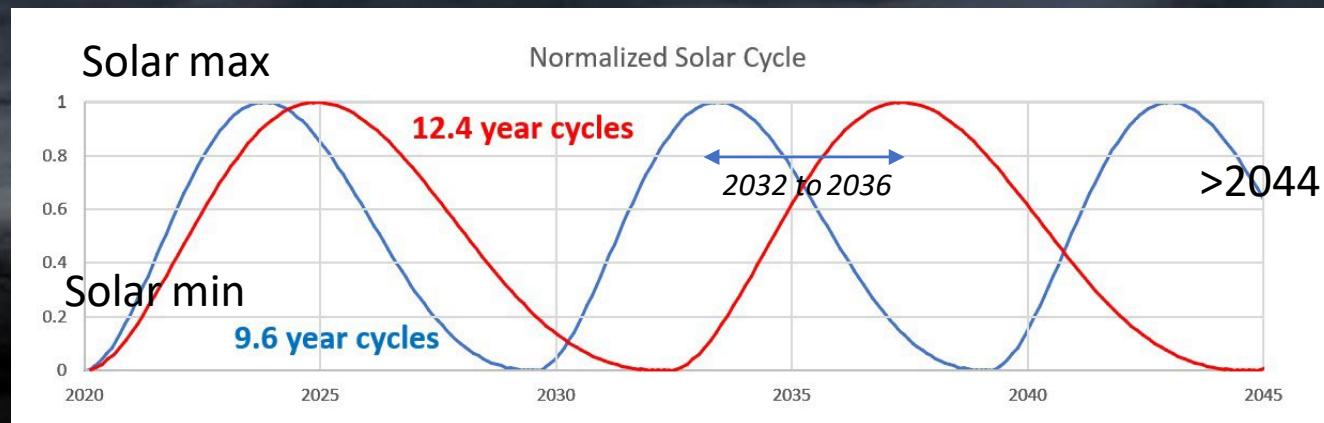
Thick Shield Concepts (T) - Cheap mass to orbit

- Improve transport & nuclear model uncertainty by factor of 2.
- Lunar surface measurements needed to validate/ optimize shield thickness (>80 to >100 g/cm²)
- (T) Adv. neutron detectors/measurements from 100 MeV to >1 GeV needed.

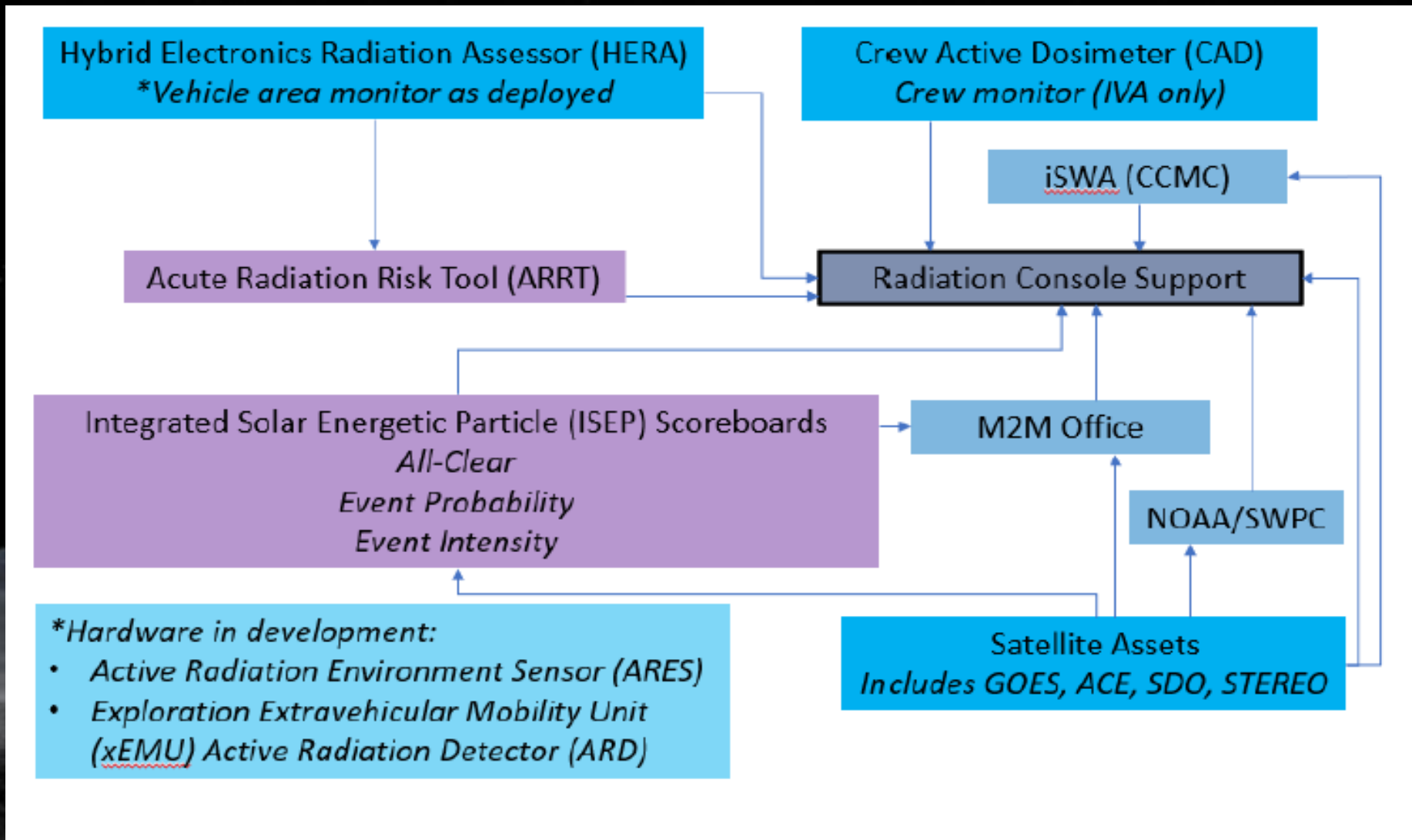


Plan Mission during Solar Maximum (K)

- Measurements / models supporting predictions of solar cycle durations >10 years in advance
- Alignment of mission architecture departure dates w/ solar max



Human Lunar Return: Radiation Operations Artemis II - V



Biological Mitigation

Space Radiation Protection Gap Details

1.4 Predictive Models of Crew Health Risks

- **(K) Probabilistic health risk models**

- Long-term health models for cancer, cardiovascular disease, late neurodegenerative diseases
- Capability to provide personalized risk estimates to inform medical countermeasures and disease surveillance
- Capability to evaluate in-mission radiation risks for CNS
- Methodologies to evaluate interaction of radiation with 4 other hazards of spaceflight

Ground Based Only

1.5 Biomedical Countermeasures and Surveillance

- **(K) Biomedical countermeasures**

- Validated CMs with known safety profile, mode of action, and efficacy in reducing space radiation induced damage covering the large range of radiogenic cancers and other degenerative health effects.

- **(K) Biomarkers & Technologies for In-flight Monitoring and Health Management**

- Deliver evidence base of at least 2 predictive biomarkers
- Miniaturize commercial diagnostic technologies.

Spaceflight Validation: Incremental Approach

- Understand pharmacokinetics and pharmacodynamics (PK/PD) for human dosing in space environment. Utilize ISS as research platform (If CM identified for flight by end-of-life - needed) or Commercial LEO destinations (possible), Gateway (possible) (Missions >14 days).
- Monitor efficacy on Gateway and lunar surface for missions of ~180 days.

- Test measurement technology in space environment on ISS if technology is identified by end-of-life (2030 - needed) or at Commercial LEO destinations (possible).
- In-situ monitoring (biomarkers) of crew for missions of ~180 days on Gateway and Lunar Surface.