Space Radiation Technologies for Human Missions beyond Low-Earth-Orbit

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Comparison of Shielded Radiation Human Exposures

Terrestrial Exposures

- Round trip NY to London: < ~0.1 mSv
- One adult chest x-ray: ~0.1 mSv
- Computed Tomography (CT) of Brain: 1.6 mSv
- Background from natural radiation: 3 mSv/yr
- Radiation worker exposure limit: 50 mSv/yr

Deep Space – Gateway and Transit

- Outside Earth's magnetosphere in free space
- GCR of greatest concern
- Dose eq. rate: 2 to 3 x's ISS

Mars Mission:

- 700 to 900-day mission w/ 30 days on surface
- ~1 to 1.3 Sv

ISS Low Earth Orbit

- Typical dose-rates: ~ 0.6 mSv/day
- Magnetosphere offers protection against SPEs (except high energy tail) and low energy GCR
- Exposure from trapped radiation and high energy GCR
- 6 months (50 – 100 mSv) to 1 yr missions (100 – 200 mSv)

Mars Surface

- Protection via atmosphere & planetary shielding
- Dose eq. rate similar to ISS

Lunar Mission

- Artemis sorties (30 day): 40 - 55 mSv
- 1-year missions: 300 – 400 mSv

Lunar Surface

- Protection from planetary shielding
- Increased neutrons
- Dose-rate ~1.5x ISS

Large solar particle events:

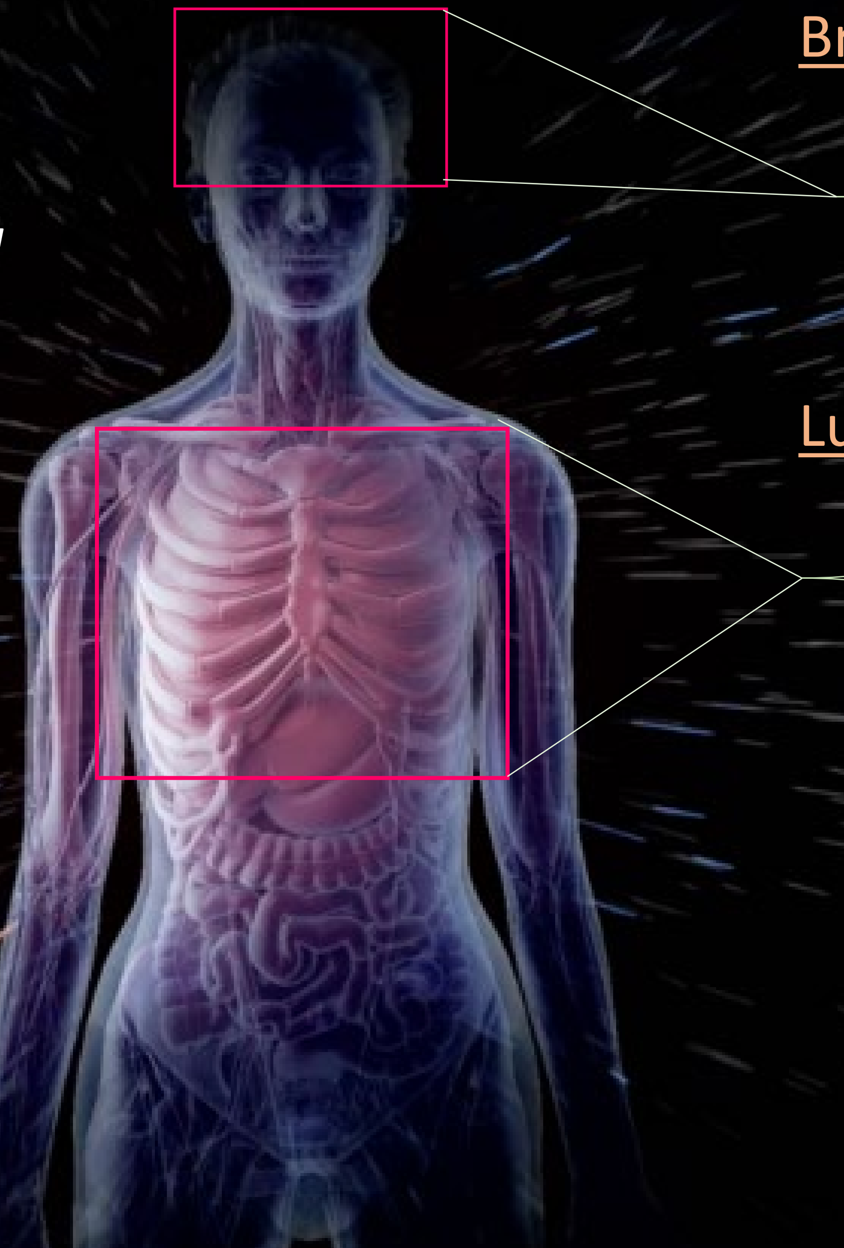
- Shield to < 250 mSv
- Venus swing-by increased exposure risk

Galactic Cosmic Rays:

The physics of spatial and temporal scales

Whole body hits

- 13,456 protons/sec
- 728 He/sec
- 38 HZE/sec



Brain tracks/sec

669 proton
36 He
2 HZE

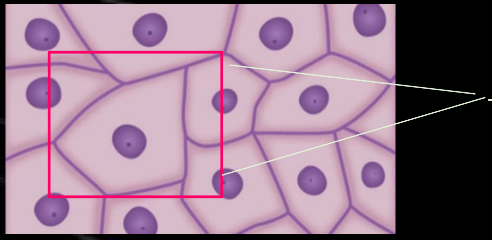
Targets within the CNS may be larger - ~500 μm^2

Lung tracks/sec

1,833 proton
99 He
5 HZE

Larger areas may be reflective of non-target effects/tissue microenvironments

Cell nucleus hits/yr



126 proton hits/yr
7 He hits/year
0.5 HZE hits/yr

"…every cell nucleus in an astronaut's body would be hit by a proton every few days and by an HZE ion about once a month" Cucinotta, F.A., Durante, M., *Lancet Oncol* **7**: 431-435; 2006; Curtis and Letaw, *Adv. Space Res.* **9**: 293-298; 1989. → Similar findings.

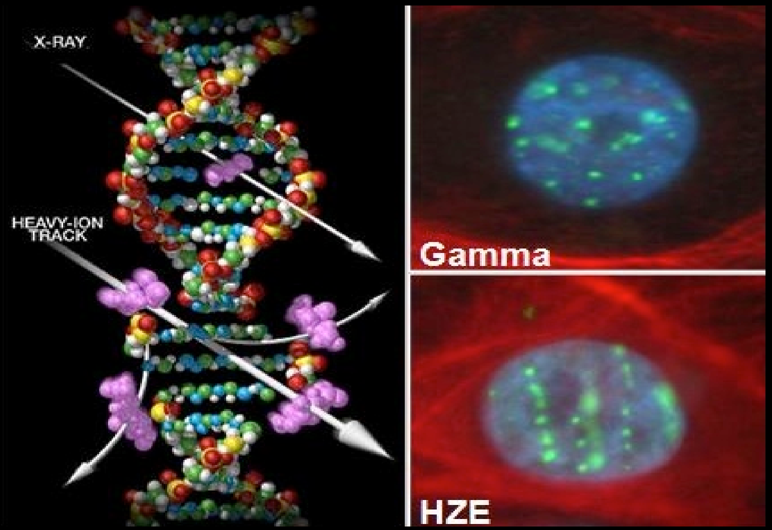
Space Radiation Health Risks

Major Risks -

- Acute Radiation Syndrome
- Radiation Carcinogenesis
- Degenerative Diseases – cardiovascular
- Central Nervous System Effects

Biological Challenges – Assessing risk and validating countermeasures

- Radiation quality effects
- Low dose-rates in space
- Translation of experimental models to humans
- Understanding individual radiation susceptibility
- Ground-based simulation of space environment
- Quantifying combined spaceflight stressors

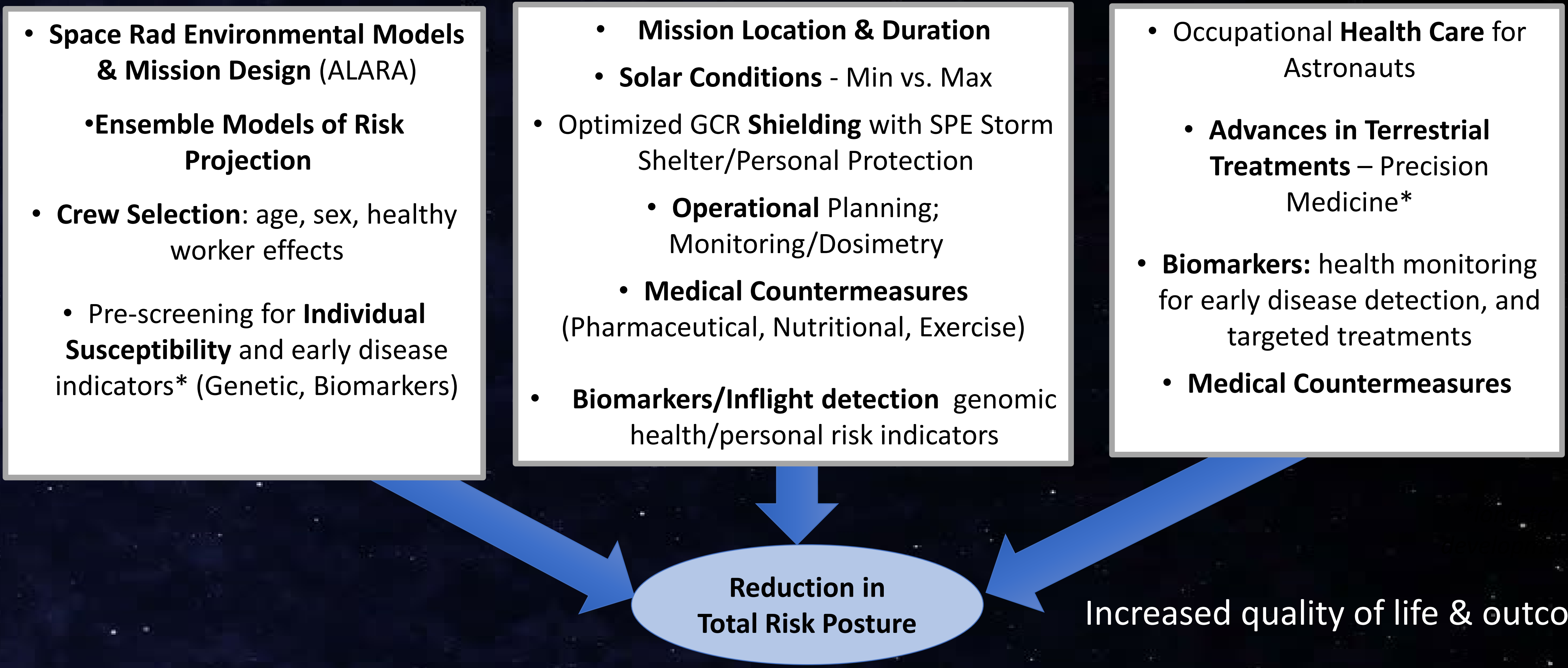


DNA Damage in Cells: Space radiation (HZE) dense ionizing particle track

(Cucinotta & Saganti, Patel & Huff, NASA)

Reducing Exploration Mission Radiation Risks

A combination of mission, vehicle systems, operations, medical countermeasures, and crew selection, as well as post mission health care will enable an acceptable risk posture for long duration missions.



Pre - Mission

- **Space Rad Environmental Models & Mission Design** (ALARA)
- **Ensemble Models of Risk Projection**
- **Crew Selection**: age, sex, healthy worker effects
- Pre-screening for **Individual Susceptibility** and early disease indicators* (Genetic, Biomarkers)

In - Mission

- **Mission Location & Duration**
- **Solar Conditions** - Min vs. Max
- Optimized GCR **Shielding** with SPE Storm Shelter/Personal Protection
- **Operational** Planning; Monitoring/Dosimetry
- **Medical Countermeasures** (Pharmaceutical, Nutritional, Exercise)
- **Biomarkers/Inflight detection** genomic health/personal risk indicators

Post - Mission

- Occupational **Health Care** for Astronauts
- **Advances in Terrestrial Treatments** – Precision Medicine*
- **Biomarkers:** health monitoring for early disease detection, and targeted treatments
- **Medical Countermeasures**

Reduction in Total Risk Posture

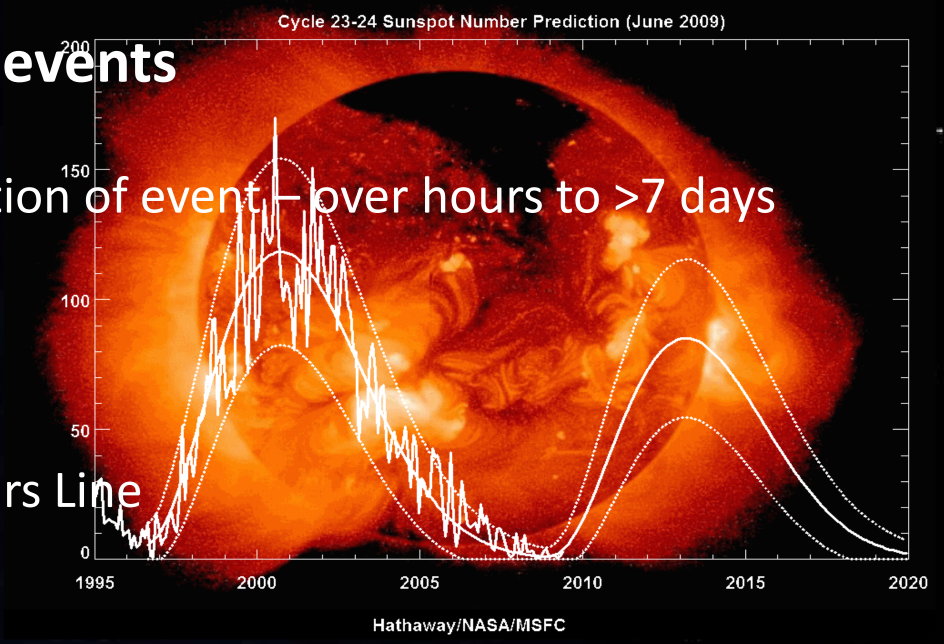
Increased quality of life & outcomes

The Physical Perspective - Technology Challenges:

Accurate real-time operational forecasting of solar particle events

- Increase 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

Cycle 23-24 Sunspot Number Prediction (June 2009)



Hathaway/NASA/MSFC

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

Prediction of solar cycle durations

- Measurements and models supporting predictions >10 years in advance

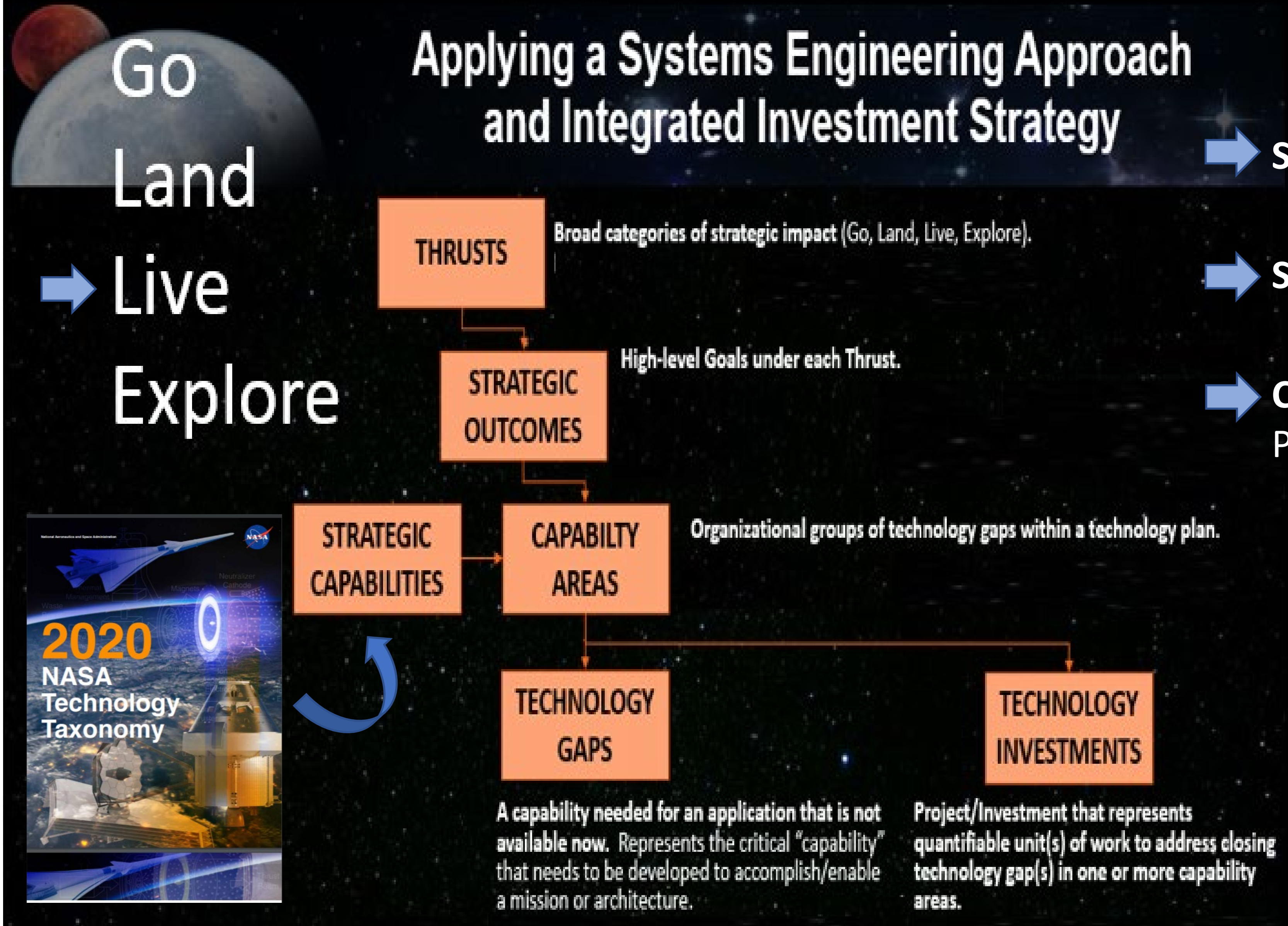
Advanced space radiation environment characterization

- High energy neutron detectors for >100 MeV neutrons up to 1 GeV neutrons
- Mass power volume, sufficient resolution

Effective GCR Shielding – Passive and Active

- Advancement & integration of lightweight, multifunctional materials - mass solutions with ~20% reduction
- Positive trade of active systems compared with passive, high reliability

Radiation Protection: STMD Strategic Framework



Go

Land

Live

Explore

Applying a Systems Engineering Approach and Integrated Investment Strategy

THRUSTS – **Broad categories of strategic impact** (Go, Land, Live, Explore).

STRATEGIC OUTCOMES – **High-level Goals under each Thrust.**

STRATEGIC CAPABILITIES

CAPABILTY AREAS – **Organizational groups of technology gaps within a technology plan.**

TECHNOLOGY GAPS – **A capability needed for an application that is not available now.** Represents the critical "capability" that needs to be developed to accomplish/enable a mission or architecture.

TECHNOLOGY INVESTMENTS – **Project/Investment that represents quantifiable unit(s) of work to address closing technology gap(s) in one or more capability areas.**

Alignment with Space Radiation Protection

Strategic Outcome: Enable long-duration human exploration

Strategic Capability: TX06 Advanced Habitation Systems

Capability Areas: Space Radiation Protection

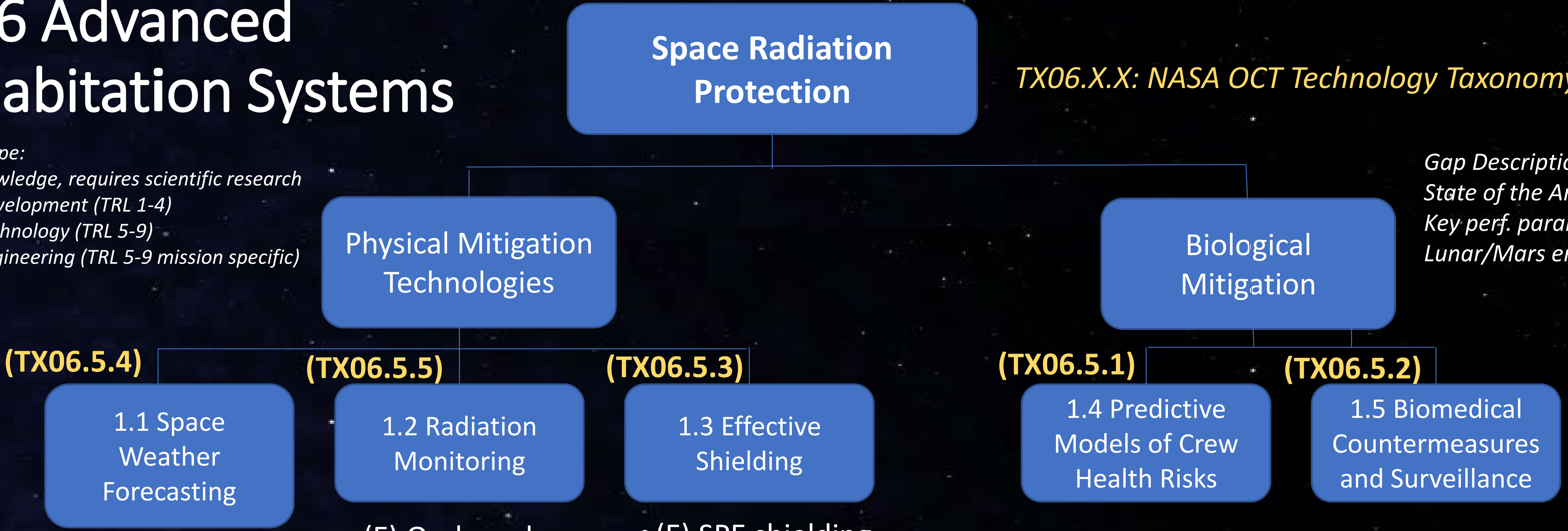
- Space Weather Forecasting
- Radiation Monitoring
- Shielding
- Predictive Models of Crew Health Risks
- Biomedical Countermeasures & Surveillance

06 Advanced Habitation Systems

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)

Gap Description
State of the Art
Key perf. parameters
Lunar/Mars enabling



Space Radiation Protection

Physical Mitigation Technologies

(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
- **<TBD>:** *In-situ* env. monitoring

(TX06.5.3) 1.3 Effective Shielding

- (E) SPE shielding
- (T) Combined GCR/SPE shielding - active
- (T) GCR shielding - passive
- **<TBD>:** Vehicle analysis tool sets

Biological Mitigation

(TX06.5.1) 1.4 Predictive Models of Crew Health Risks

- (K) Probabilistic health risk models
- **<TBD>:** Radiobiology Effects Database

(TX06.5.2) 1.5 Biomedical Countermeasures and Surveillance

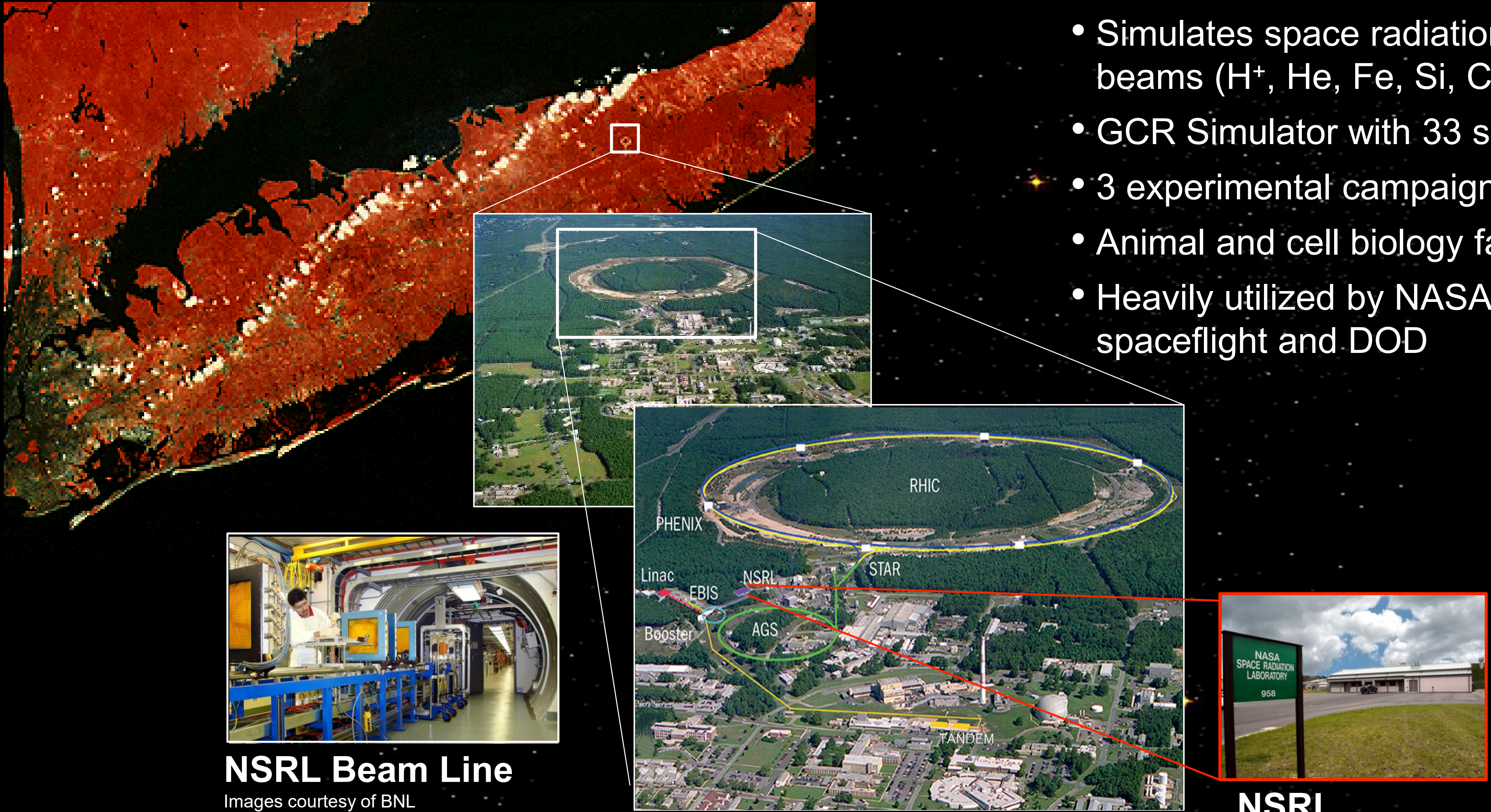
- (K) Biomedical countermeasures
- **<in work>: (K)** Personalized crew protection & biomarker surveillance
- **<TBD>:** Intelligent human system technologies for mission operations

***Major Asset:** Space Weather architecture*

***Major Asset:** NASA Space Radiation Laboratory*

NASA Space Radiation Laboratory at Brookhaven National Lab

- Simulates space radiation - high energy ion beams (H^+, He, Fe, Si, C, O, Cl, Ti, etc.)
- GCR Simulator with 33 sequential ions
- 3 experimental campaigns per year
- Animal and cell biology facilities
- Heavily utilized by NASA & commercial spaceflight and DOD



NSRL Beam Line

Images courtesy of BNL

NSRL

NSRL GCR Simulator Beam Definition

Simulates LET dose distribution to critical organs/tissues within shielded vehicle

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	*Polyethylene degrader to*		
^{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	*Polyethylene degrader to*		
^{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***

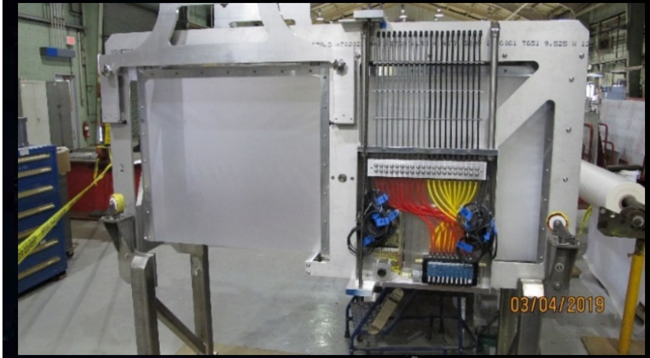
21 unique switches with ~ 75 min delivery time

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**

Laser Ion source

Control system & software



Large binary filter system

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 JM 058

Image Credit: NASA/Pat Rawlings, SAIC

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).

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

extra

Gap Definitions

Knowledge Gap: unknown data (e.g., chemical and physical properties) that will ultimately drive hardware requirements; these gaps typically require additional scientific research in order to close.

Technology Gap: *new and/or novel performance* or function that has not been demonstrated (solutions to this gap type are generally TRL 1-4); this gap type aligns with the “New” Technology TRL 1-4 definition within the NASA Technology Readiness Assessment Report (2016)

Development Gap: at least one potential solution has been identified, but additional work is required to ensure feasibility of the *new and/or novel performance or function* in a specific operational application (solutions to this gap type are generally TRL 5-9); this gap type aligns with the “New” Technology TRL 5-9 definition within the NASA Technology Readiness Assessment Report (2016)

Engineering Gap: performance or function is well accepted (*not new or novel*), but requires engineering development for a specific mission (solutions to this gap type are generally TRL 5-9).

Architecture Gap: unknown mission parameters that will ultimately drive hardware requirements; further refinement of mission plans to clarify capability need.

Operations Gap: crewed and uncrewed mission operations considerations, including training and flight operations, that differ from current standards of practice and need to be defined and/or tested in order to enable the mission.