ISS Radiation Instruments and the Risk Analysis Environment (RAE)

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NASA Johnson Space Center, Houston, TX

Key Questions

- ☐ What are the human spaceflight radiation limits imposed on NASA astronauts?
- ☐ How do we evaluate individual crewmember doses and risks?
- ☐ How are SRAG’s radiation measurements used to compute dose and radiation risk?

Key Questions

☐ What are the human spaceflight radiation limits imposed on NASA astronauts?

  - NASA STD-3001

NASA STD-3001 Radiation Limits

- As Low As Reasonably Achievable (ALARA)
  - Minimize radiation exposure within mission specifications and within reason

- Space Permissible Exposure Limit (SPEL)
  - Career effective dose from space radiation exposure <u>shall</u> be < 600 mSv
  - Calculated using NASA Space Cancer Risk model (i.e., Q_{NASA})
  - Purpose: reduce/prevent deleterious long-term stochastic effects (cancer)

NASA STD-3001 Radiation Limits

- Organ-Specific Limits
  - Covered by SPEL
  - Short- (non-cancer) and long-term limits
  - RBE-weighted dose: $RBE \cdot D$ [mGy-Eq]

RBE = Relative Biological Effectiveness

Suggested RBEs

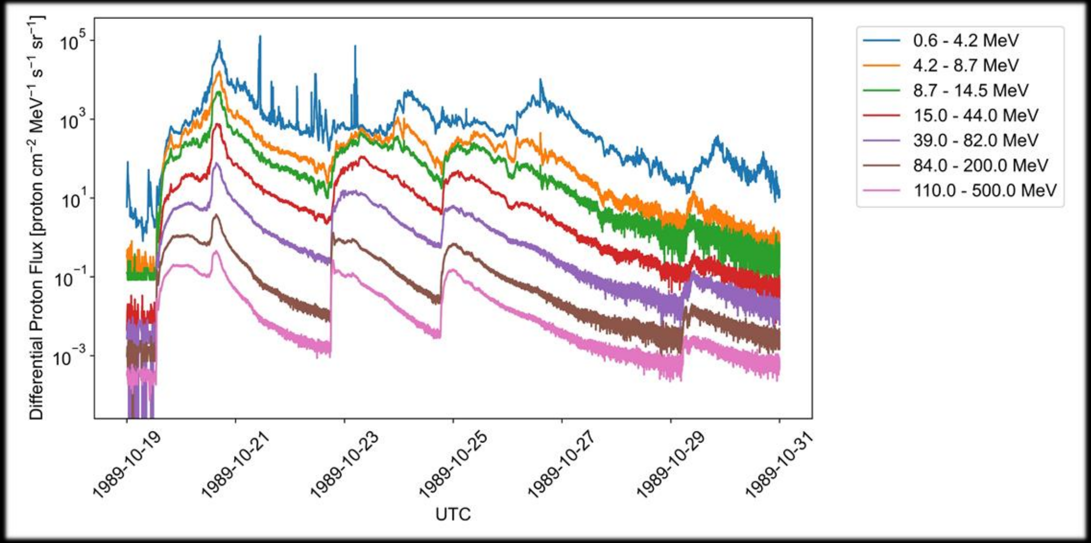
Radiation Type	Recommended RBE	Range
1 to 5 MeV neutrons	6.0	4 to 8
5 to 50 MeV neutrons	3.5	2 to 5
Heavy ions	2.5	1 to 4
> 2 MeV protons	1.5	N/A

Organ-Specific Non-Cancer Dose Limits

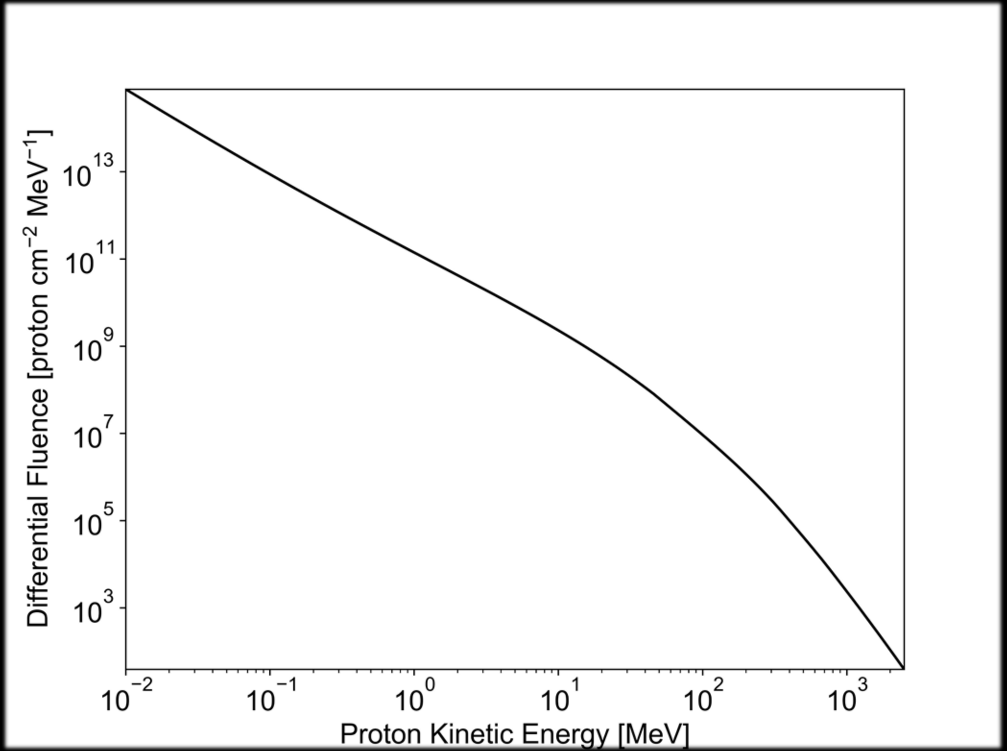
Organ	30-Day Limit	1-Year Limit	Career
Lens of Eye	1000 mGy-Eq	2000 mGy-Eq	4000 mGy-Eq
Skin	1500 mGy-Eq	3000 mGy-Eq	6000 mGy-Eq
Blood-Forming Organs (BFO)	250 mGy-Eq	500 mGy-Eq	N/A
Circulatory System	250 mGy-Eq	500 mGy-Eq	1000 mGy-Eq
Central Nervous System	500 mGy	1000 mGy	1500 mGy
Central Nervous System ($Z \geq 10$)	N/A	100 mGy	250 mGy

NASA STD-3001 Radiation Limits

- Solar Particle Event (SPE) Design Constraint
  - Shall receive < 250 mSv effective dose when exposed to October 1989
    - Design Reference SPE
    - Sum of October 1989 SPEs



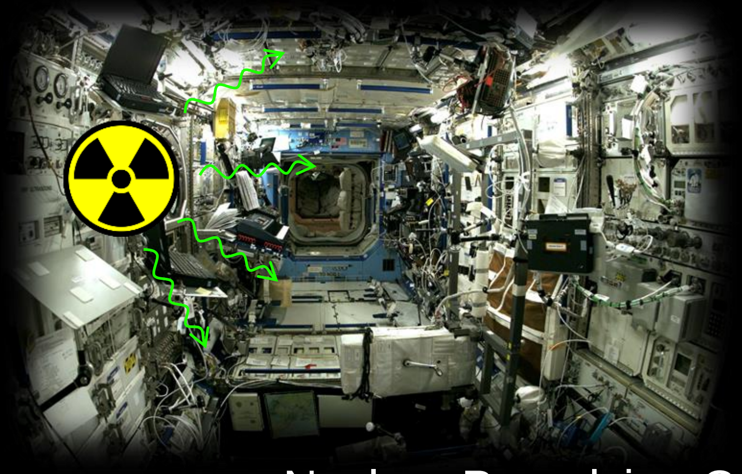
$$\int\int \mathrm{d}\Omega \mathrm{d}t \Rightarrow$$



NASA STD-3001 Radiation Limits

- Nuclear Technology Exposures
  - Shall be < 20 mSv/mission-year

- Nuclear propulsion
    - May reduce transit times, reducing doses
  - *Net* nuclear technology radiation dose
    - $\mathcal{E}_{net} = \mathcal{E}_{nuc} - \mathcal{E}_{saved}$
    - Considered when mission transit time is reduced
    - Considered alongside non-radiation risks
      - E.g., microgravity environment


Onboard Radiation Sources

Nuclear Propulsion Concept

https://www.nasa.gov/news-release/nasa-announces-nuclear-thermal-propulsion-reactor-concept-awards/

Key Questions

✓ What are the human spaceflight radiation limits imposed on NASA astronauts?

- NASA STD-3001

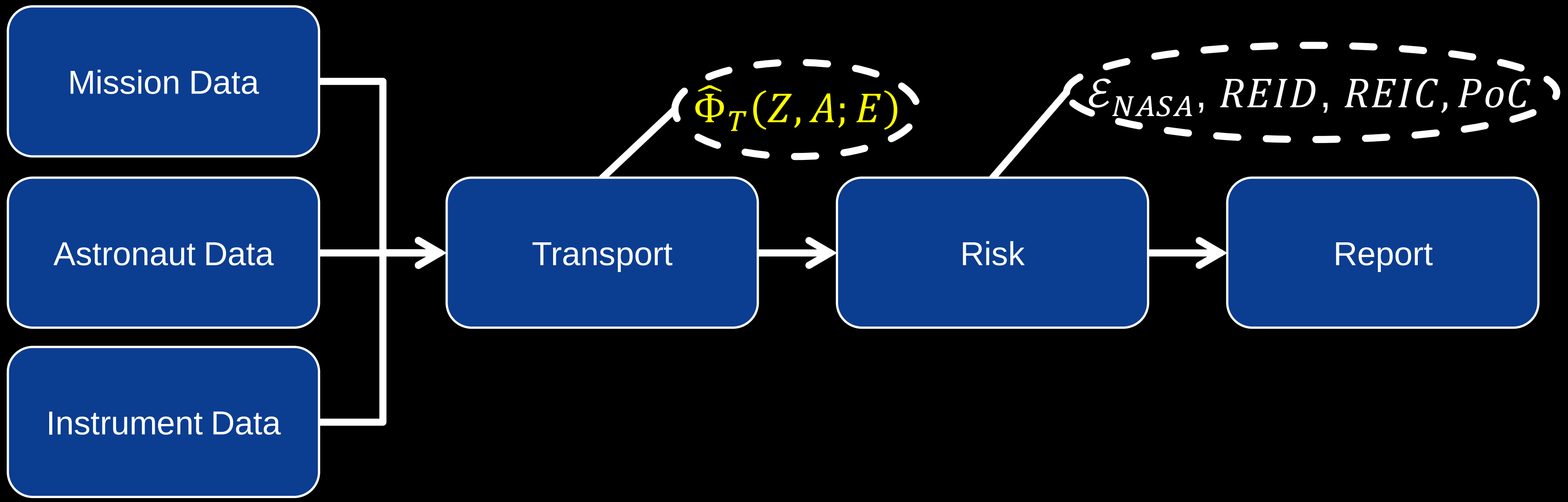
☐ How do we evaluate individual crewmember doses?

- Risk Analysis Environment (RAE)

RAE Workflow

- Risk Analysis Environment (RAE)
  - Internal, web-based tool
    - Radiation risk calculations
    - Astronaut risk report generation
  - Database of astronaut, mission, instrument, exposures, risk estimates, etc.

Basic RAE Workflow:



Mission Data

Astronaut Data

Instrument Data

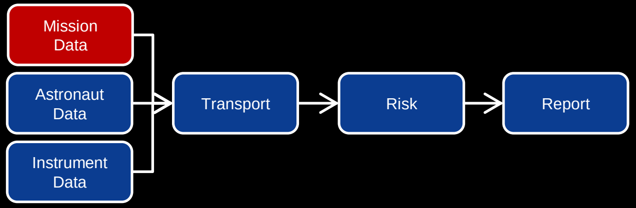
Transport

Risk

Report

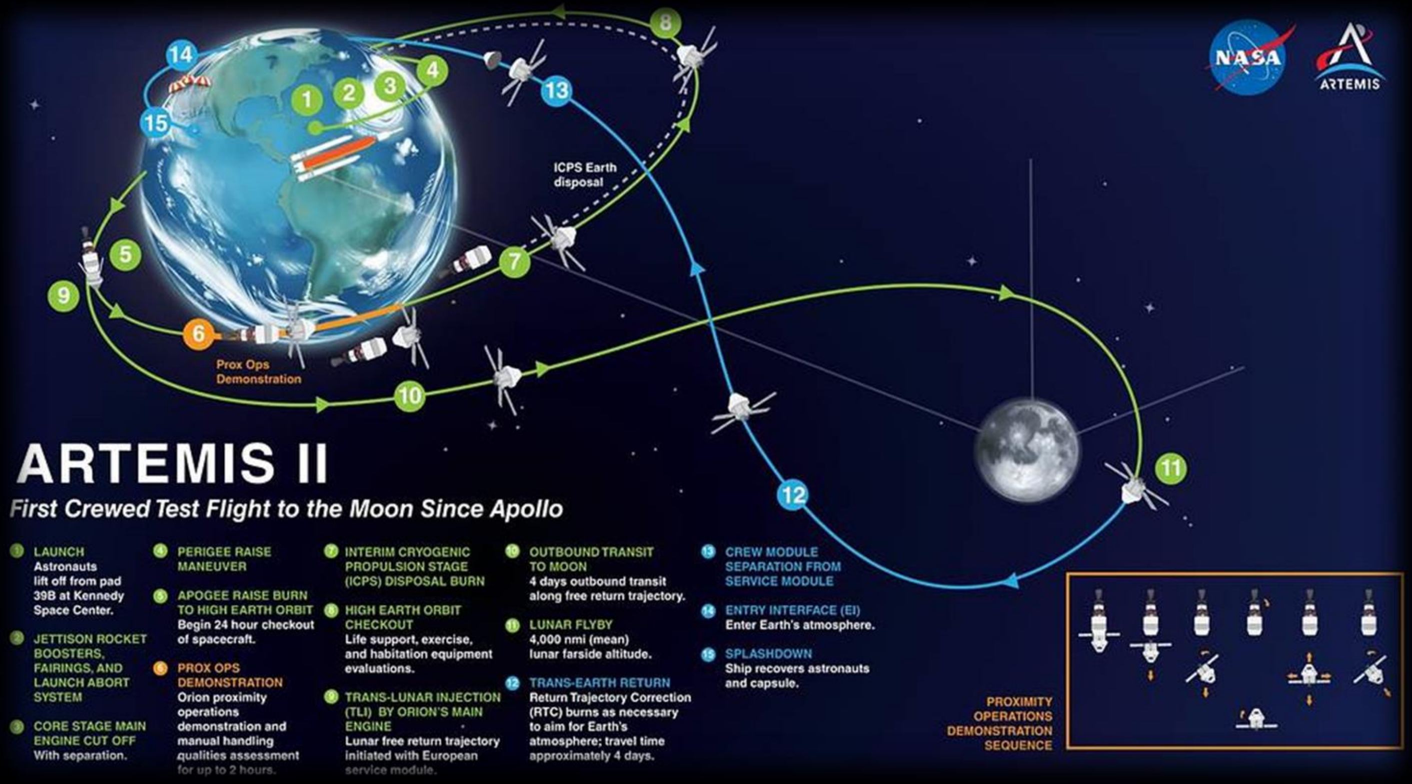
$\hat{\Phi}_T(Z, A; E)$

$\mathcal{E}_{NASA}, REID, REIC, PoC$



RAE Workflow

- Mission data
    - Launch date
    - Landing date
    - Vehicle trajectory
    - Vehicle shielding
    - GCR environment



ARTEMIS II

First Crewed Test Flight to the Moon Since Apollo

① **LAUNCH** Astronauts lift off from pad 39B at Kennedy Space Center.

② **JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**

③ **CORE STAGE MAIN ENGINE CUT OFF** With separation.

④ **PERIGEE RAISE MANEUVER**

⑤ **APOGEE RAISE BURN TO HIGH EARTH ORBIT** Begin 24 hour checkout of spacecraft.

⑥ **PROX OPS DEMONSTRATION** Orion proximity operations demonstration and manual handling qualities assessment for up to 2 hours.

⑦ **INTERIM CRYOGENIC PROPULSION STAGE (ICPS) DISPOSAL BURN**

⑧ **HIGH EARTH ORBIT CHECKOUT** Life support, exercise, and habitation equipment evaluations.

⑨ **TRANS-LUNAR INJECTION (TLI) BY ORION'S MAIN ENGINE** Lunar free return trajectory initiated with European service module.

⑩ **OUTBOUND TRANSIT TO MOON** 4 days outbound transit along free return trajectory.

⑪ **LUNAR FLYBY** 4,000 nmi (mean) lunar farside altitude.

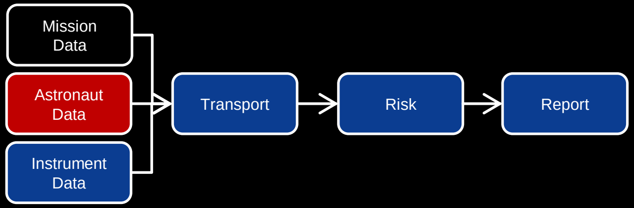
⑫ **TRANS-EARTH RETURN** Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time approximately 4 days.

⑬ **CREW MODULE SEPARATION FROM SERVICE MODULE**

⑭ **ENTRY INTERFACE (EI)** Enter Earth's atmosphere.

⑮ **SPLASHDOWN** Ship recovers astronauts and capsule.

https://www.nasa.gov/image-article/artemis-ii-map-2/



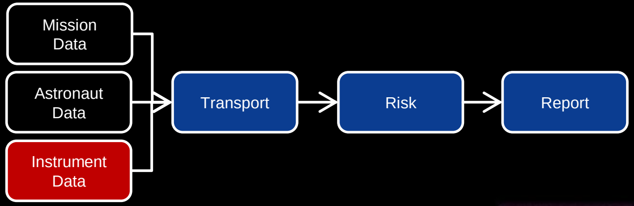
RAE Workflow

- Astronaut data
  - Demographic information
    - Date of birth
    - Name
    - Sex
    - Smoking status
    - …
  - Missions
  - Past medical radiation exposures*

  - *No longer contribute to dose limits

Artemis II Crew Portrait

https://airandspace.si.edu/stories/editorial/meet-crew-artemis-ii


Mission Data
Astronaut Data
Instrument Data
Transport
Risk
Report

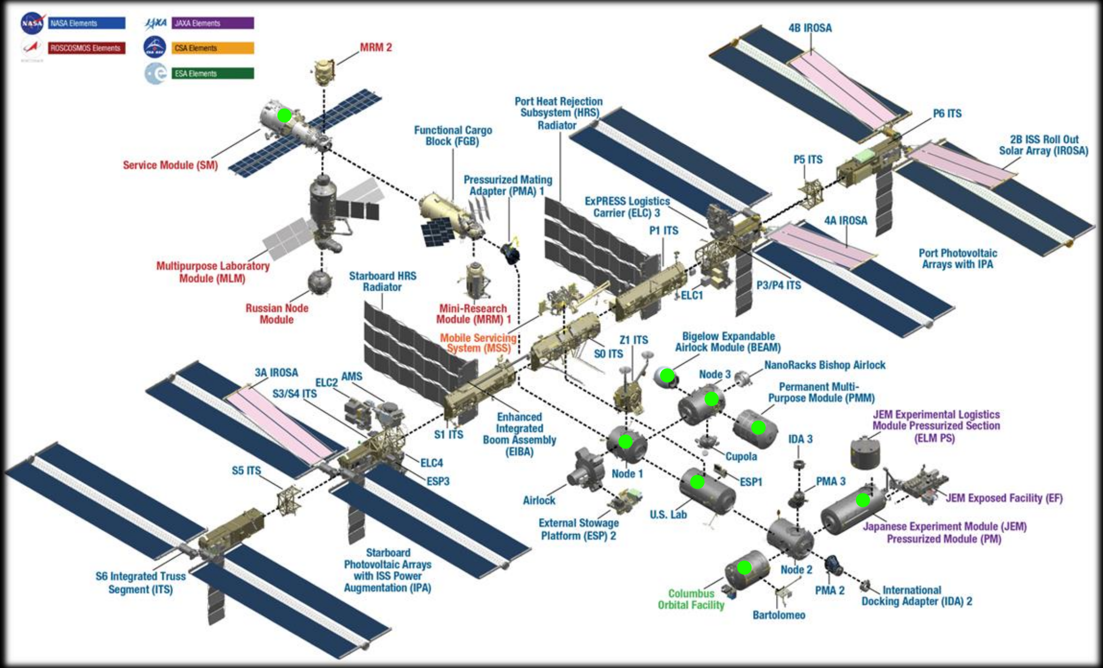
RAE Workflow

- Instrument data
  - Crew Active Dosimeter (CAD) absorbed dose
    - Crewmember dose of record
  - Area monitors
    - Radiation Environment Monitors (REM)
    - Artemis HERA on Space Station (AHoSS)
    - Radiation Assessment Detector (RAD)
    - Radiation Area Monitors (RAM)*
    - Tissue-Equivalent Proportional Counter (TEPC)*

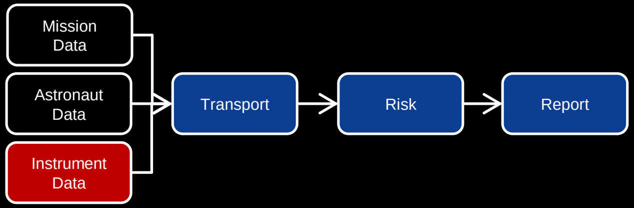
    - *defunct

CAD

SRAG ISS Detector Locations



https://www.nasa.gov/international-space-station/space-station-facts-and-figures/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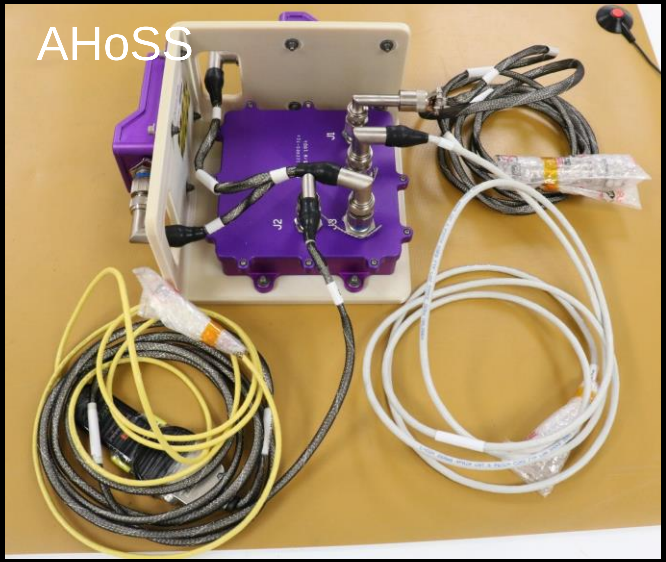
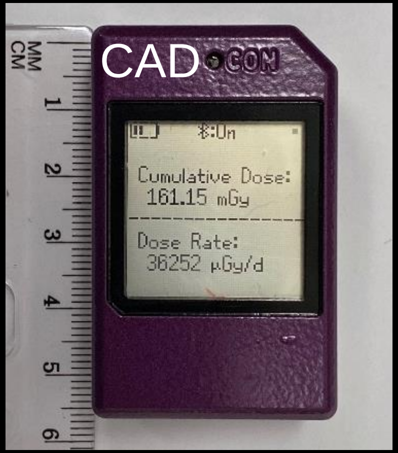
ISS Instruments

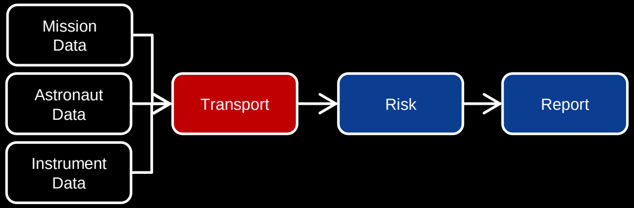

RAD


AHoSS


HRD

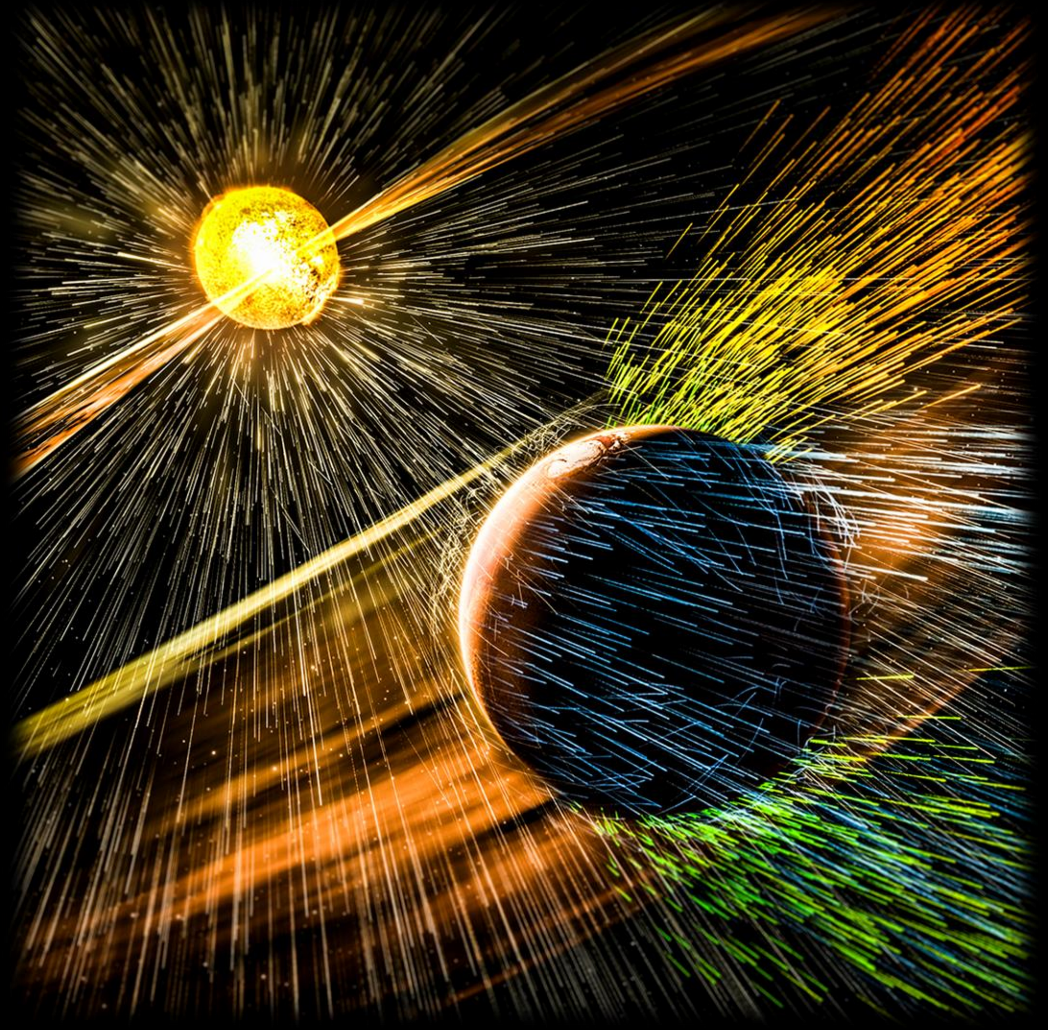

REM2


CAD



RAE Workflow

- Transport
  - HZETRN2020 via…
    - NSCR Driver – ISS missions
    - CIMIRAE – exploration missions
  - Ultimately computes $\hat{\Phi}_T(Z, A; E)$
  - Normalization
    - Scales modeled dose to match measured dose
    - Uses modeled dose to estimate modeled fluence



Key Questions

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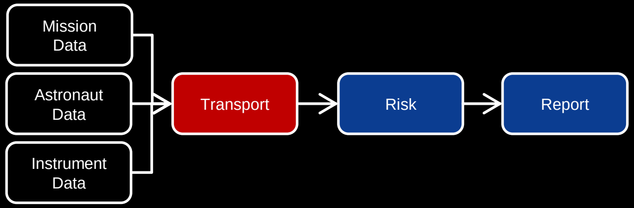
- ☐ How are SRAG’s radiation measurements used in RAE?
  - Normalization procedures to bring models in line with measurements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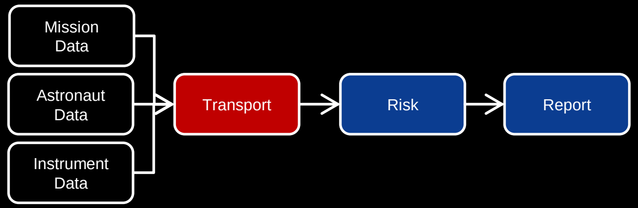
ISS Instrument Normalization

- Correcting modeled fluence $\hat{\Phi}_T(Z,A;E)$ using measurements
  - Fluence model (LEO): $\hat{\Phi}_T(Z,A;E) = c^{avg}\left(\hat{\Phi}_T^{GCR}(Z,A;E) + c^{trap}\hat{\Phi}_T^{trap}(Z,A;E)\right)$
    - q – measured quantity; $\hat{q}$ – modeled quantity
    - c^{avg}, c^{trap} – constants that relate models to measurements

- Normalization Step
  - Determine c^{trap} and c^{avg} so modeled dose and measured dose are “close”
  - Model crudely assumes $\frac{D}{\hat{D}} = \frac{\Phi}{\hat{\Phi}}$



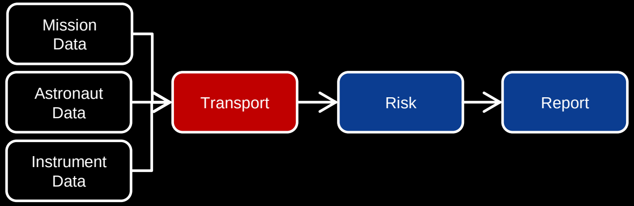
ISS Instrument Normalization

- Correcting trapped proton fluence
  - Modeled dose for detector i: $\widehat{D}_i = \widehat{D}_i^{GCR} + c^{trap}\widehat{D}_i^{trap}$
  - Measured dose for detector i: D_i
  - Let $\epsilon^2 = \sum_{i=1}^{N}\left(D_i - \widehat{D}_i\right)^2$ → Minimize with respect to c^{trap}

  - $\frac{\mathrm{d}\epsilon^2}{\mathrm{d}(c^{trap})} = -\sum_{i=1}^{N} 2\left(D_i - \widehat{D}_i^{GCR} - c^{trap}\widehat{D}_i^{trap}\right)\widehat{D}_i^{trap} = 0$

$$\Rightarrow c^{trap} = \frac{\sum_{i=1}^{N}\left(D_i - \widehat{D}_i^{GCR}\right)\widehat{D}_i^{trap}}{\sum_{i=1}^{N}\left(\widehat{D}_i^{trap}\right)^2}$$

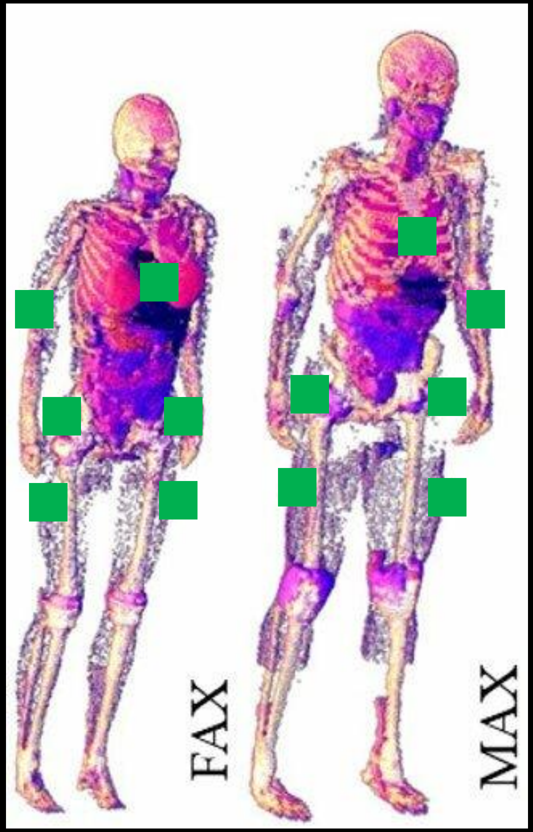
  - $\frac{\mathrm{d}^2\epsilon^2}{\mathrm{d}(c^{trap})^2} = \sum_{i=1}^{N} 2\left(\widehat{D}_i^{trap}\right)^2 > 0 \Rightarrow c^{trap}$ minimizes ϵ^2



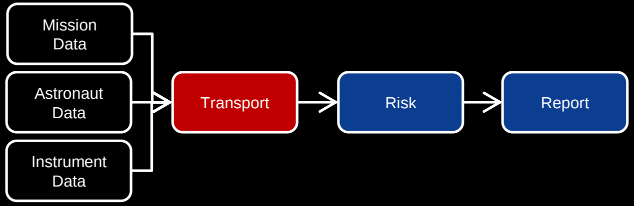
ISS Instrument Normalization

- Correcting modeled doses to match CAD doses
  - Dose differences due to CAD position relative to body
  - Modeled-to-measured CAD dose conversion factor:
    - $c^{avg} = \frac{D_{CAD}}{M}\sum_{j=1}^{M}\frac{1}{\hat{D}_{CAD,j}}$ for M considered CAD positions

🟩 = CAD Position Options

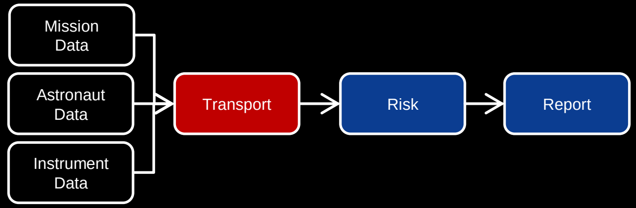


Vieira, J.W. & Andrade, Pedro & Oliveira, Alex & Lima, Vanildo & Lacerda, Isabelle & Silva, Arykerne & Santana, Ivan & Alem, Whoody & Santos, Larissa & Oliveira, Fernanda & Lima, Fernando. (2023). Development of anthropomorphic computational phantoms at the UFPE. Brazilian Journal of Radiation Sciences. 11. 01-16. 10.15392/2319-0612.2023.2243.



ISS Instrument Normalization

- Apply correction factors to modeled trapped proton and GCR fluence
  - $c^{trap} = \frac{\sum_{i=1}^{N}\left(D_i - \hat{D}_i^{GCR}\right)\hat{D}_i^{trap}}{\sum_{i=1}^{N}\left(\hat{D}_i^{trap}\right)^2}$ for N dose measurements
  - $c^{avg} = \frac{D_{CAD}}{M}\sum_{j=1}^{M}\frac{1}{\hat{D}_{CAD,j}}$ for M considered CAD positions
  - $\hat{\Phi}_T(Z,A;E) = c^{avg}\left(\hat{\Phi}_T^{GCR}(Z,A;E) + c^{trap}\hat{\Phi}_T^{trap}(Z,A;E)\right)$



Mission Data

Astronaut Data

Instrument Data

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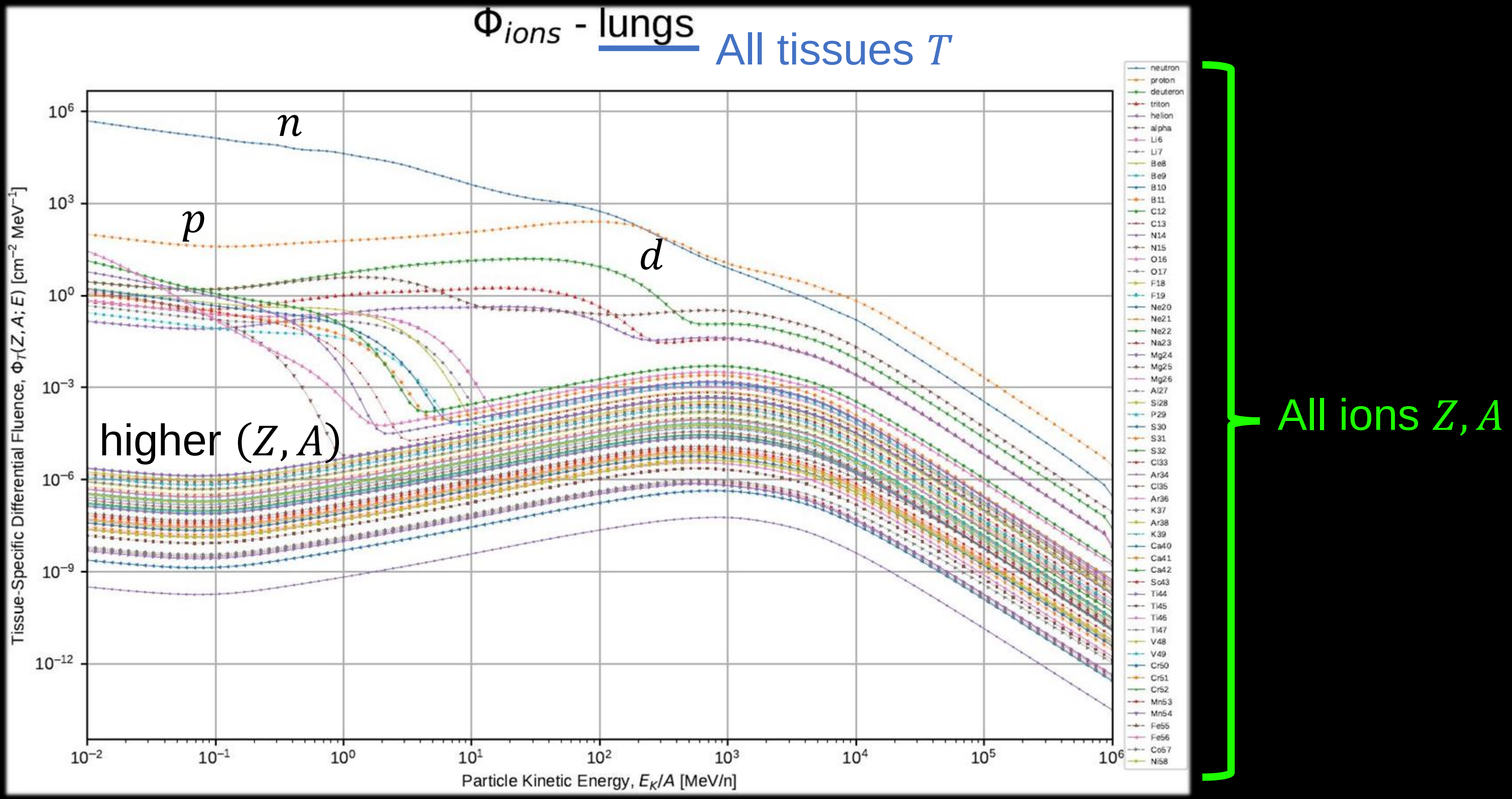
Risk

Report

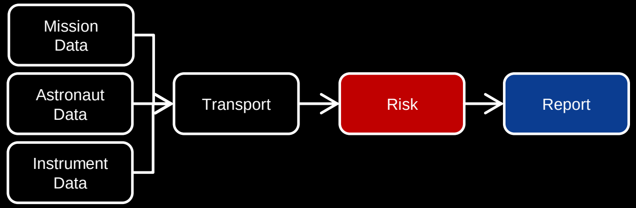
RAE Workflow

- Transfer $\widehat{\Phi}_T(Z, A; E)$ to RAE to compute risk



All tissues T

All ions Z, A



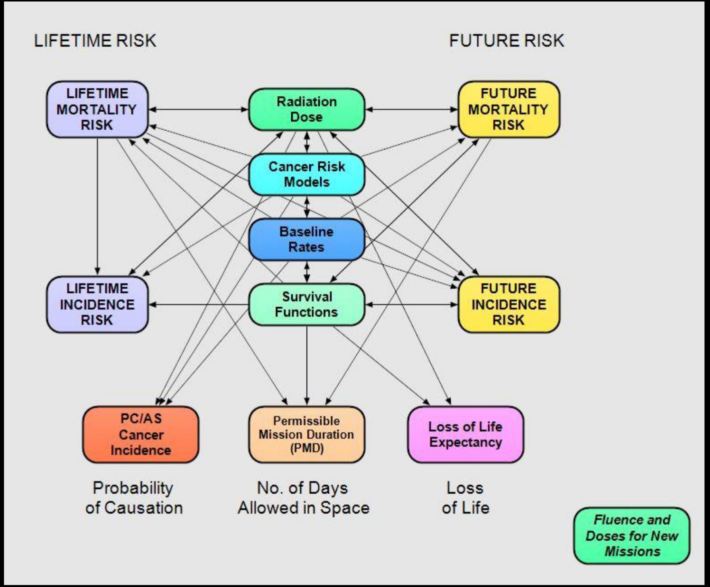
Radiation Risk Calculation

- Risk
  - Analytica implementation of NASA Space Cancer Risk model (NSCR-2012)
  - Several quantities computed from $\Phi_T(Z, A; E)$
  - Monte Carlo accounts for uncertainty in model parameters

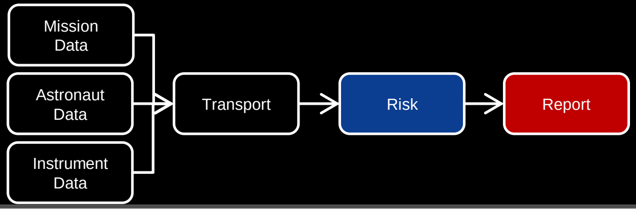
RAE Outputs

Quantity	Symbol	Formula
Dose Equivalent for Tissue *T*	H_T	$\sum_{Z,A} \int_0^\infty Q_{NASA}(Z,A,E)\, L(Z,A,E)\, \Phi_T(Z,A;E)\, \mathrm{d}E$
NASA Effective Dose	$\mathcal{E}_{NASA}$	$\sum_T w_T H_T$
Risk of Exposure Induced Death/Cancer (REID/REIC)	$REID_T$ $/REIC_T$	$\sum_{i=1}^{N} \left(\int_{a_{E_i}}^{a_{max}} \lambda_{i,T}^{(M/I)}(a, a_{E_i}, H_{i,T}) S_0(a \mid a_{E_i}) \exp\left[-\int_{a_{E_i}}^{a} \sum_{i=1}^{N} \left\{ \sum_T \lambda_{i,T}^{(M)}(t, a_{E_i}, H_{i,T}) \right\} \mathrm{d}t \right] \mathrm{d}a \right)$
Probability of (Cancer) Causation	PoC	$\frac{REIC_T}{REIC_T + B_T}$

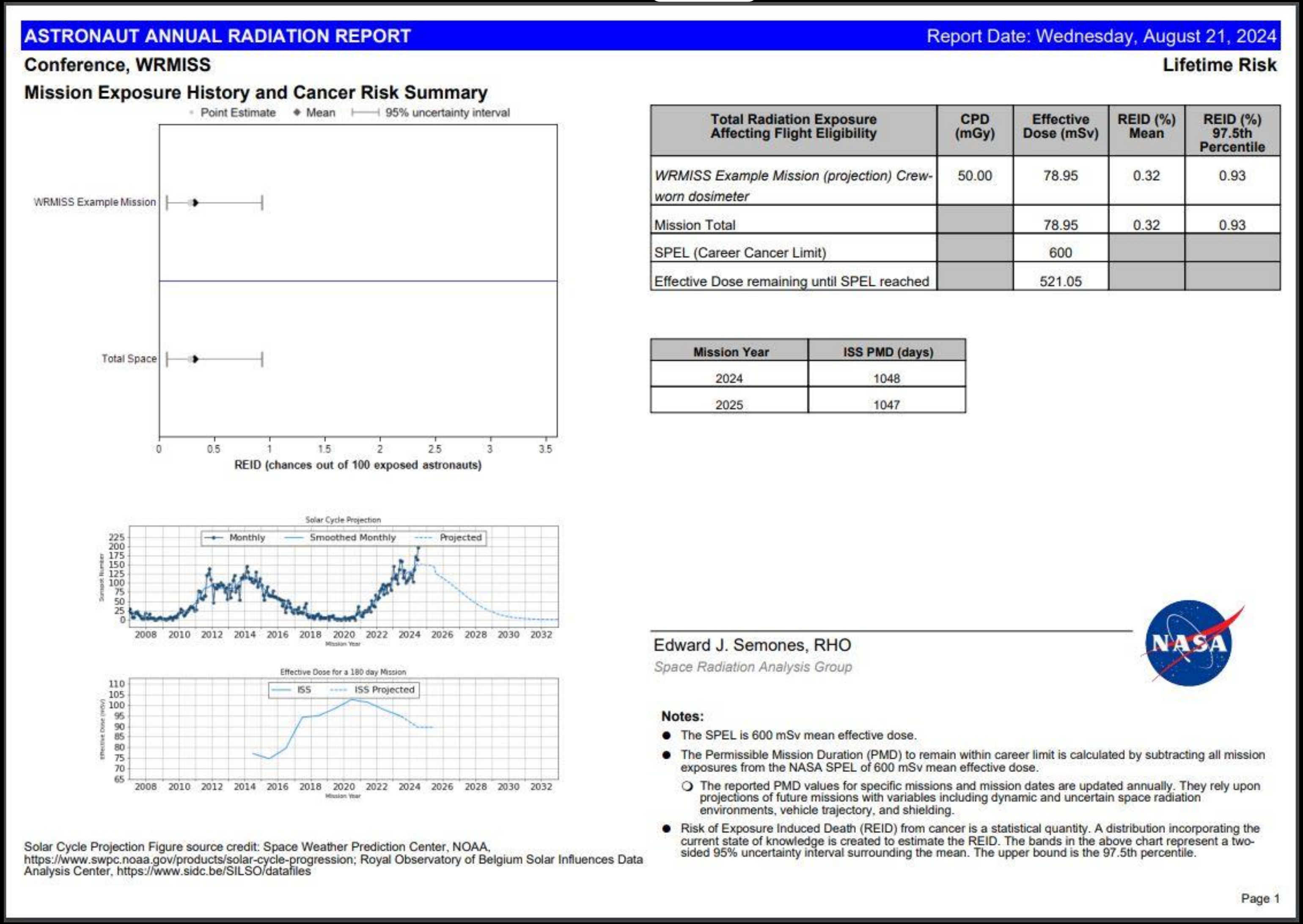
RAE Infrastructure



Reporting



- Generates risk reports
- Sent to active astronauts yearly
- Contains
  - Career effective dose (by mission)
  - REID (Lifetime)
  - REIC (Lifetime)
  - Permissible mission duration
  - Medical exposures



ASTRONAUT ANNUAL RADIATION REPORT Report Date: Wednesday, August 21, 2024

Conference, WRMISS **Lifetime Risk**

Mission Exposure History and Cancer Risk Summary

Total Radiation Exposure Affecting Flight Eligibility	CPD (mGy)	Effective Dose (mSv)	REID (%) Mean	REID (%) 97.5th Percentile
WRMISS Example Mission (projection) Crew-worn dosimeter	50.00	78.95	0.32	0.93
Mission Total		78.95	0.32	0.93
SPEL (Career Cancer Limit)		600		
Effective Dose remaining until SPEL reached		521.05		

Mission Year	ISS PMD (days)
2024	1048
2025	1047

Solar Cycle Projection Figure source credit: Space Weather Prediction Center, NOAA, https://www.swpc.noaa.gov/products/solar-cycle-progression; Royal Observatory of Belgium Solar Influences Data Analysis Center, https://www.sidc.be/SILSO/datafiles

Edward J. Semones, RHO
Space Radiation Analysis Group

Notes:

- The SPEL is 600 mSv mean effective dose.
- The Permissible Mission Duration (PMD) to remain within career limit is calculated by subtracting all mission exposures from the NASA SPEL of 600 mSv mean effective dose.
  - The reported PMD values for specific missions and mission dates are updated annually. They rely upon projections of future missions with variables including dynamic and uncertain space radiation environments, vehicle trajectory, and shielding.
- Risk of Exposure Induced Death (REID) from cancer is a statistical quantity. A distribution incorporating the current state of knowledge is created to estimate the REID. The bands in the above chart represent a two-sided 95% uncertainty interval surrounding the mean. The upper bound is the 97.5th percentile.

Page 1

Summary

- ✓ What are the human spaceflight radiation limits imposed on NASA astronauts?
  - NASA STD-3001

- ✓ How do we evaluate individual crewmember doses?
  - Risk Analysis Environment (RAE)

- ✓ How are SRAG's radiation measurements used in RAE?
  - Normalization procedures to bring models in line with measurements

Credits

- **SRAG/Risk:**
  - Mark Shavers, Luke Stegeman
- **Oak Ridge Center for Risk Analysis, Inc.:**
  - Iulian Apostoaei, Brian Thomas
- **SRAG/Vehicle Shielding Analysis:**
  - Serkan Golge, Shaowen Hu, Diego Laramore, Hatem Nounu
- **SRAG/Instruments:**
  - Tom Campbell-Ricketts, Michael Ecord, Ramona Gaza, Stuart George, Steve Johnson, Diego Laramore, Sergiy Rozhdestvenskyy, Cary Zeitlin
- **SRAG/Operations:**
  - Clayton Allison, Janet Barzilla, Ricky Egeland, Stuart George, Steve Johnson, Luke Stegeman, Philip Quinn
- **SRAG/Space Weather Forecasting:**
  - Clayton Allison, Janet Barzilla, Ricky Egeland, Steve Johnson, Tilaye Tadesse, Philip Quinn, Katie Whitman
- **SRAG/Non-Ionizing Radiation:**
  - Ramona Gaza, Sabrina Houston
- **SRAG/IT:**
  - Mark Langford
- **SRAG/Project Support:**
  - Sylvia Paden
- **SRAG/Management:**
  - Clif Amberboy, Dan Fry, Catherine McLeod, Eddie Semones

Backup

Other Agency Career Limits

Agency	Career Dose Limit
NASA	600 mSv (mean NASA effective dose)
Canadian Space Agency	1000 mSv (mean NASA effective dose)
European Space Agency	1000 mSv (ICRP60)
Japan Aerospace eXploration Agency	500-1000 mSv (age, sex-dependent, ICRP60)
Roscosmos	1000 mSv (ICRP60)

TREAT Astronauts Act

- Became law in 2017

- Healthcare for former NASA astronauts
  - NASA pays for…
    - Monitoring
    - Diagnosis
    - Treatment
  - Spaceflight associated conditions only

- Was condition space radiation induced?
  - Probability of causation calculation needed

National Aeronautics and Space Administration

In 2017, the NASA Transition Authorization Act was signed into law. Part of the provisions of this law include the "To Research, Evaluate, Assess, and Treat Astronauts Act," also referred to as the "TREAT Astronauts Act." TREAT authorizes NASA to monitor and diagnose potential conditions and treat conditions associated with spaceflight.

What you need to know about . . .

The TREAT Astronauts Act

WHAT TREAT MEANS TO FORMER ASTRONAUTS:

- A more comprehensive program of monitoring, diagnosis and treatment services to current and former astronauts.
- Potential for early detection of health conditions that may be associated with spaceflight or spaceflight training to develop a richer evidence base of occupational health data.
- Contribute to an improved understanding of the long-term impacts of spaceflight for future crews, vehicles and exploration missions.

AM I ELIGIBLE FOR COVERAGE UNDER TREAT?

YES . . .
- If you are a former United States Government **astronaut or payload specialist** who has flown in space.
- Participation is **voluntary.**

NO . . .
- Other U.S. government employees
- Commercial spaceflight astronauts who were never employed by NASA
- International partner astronauts
- Employees of a foreign government
- Private individuals or tourists

FREQUENTLY ASKED QUESTIONS:

Q. Does TREAT cover conditions not associated with spaceflight?
A. No, TREAT only covers treatments for conditions that NASA has determined are associated with spaceflight.

Q. Who determines what conditions are associated with spaceflight?
A. The NASA Administrator delegates this authority to the NASA Chief Health & Medical Officer (CHMO).

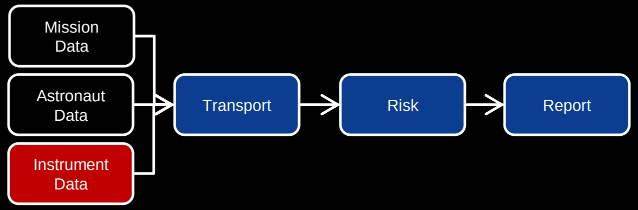
Q. Does TREAT coverage replace my health benefits plan as my primary insurance provider?
A. No, health plans typically exclude occupational conditions. TREAT covers occupational conditions when NASA is a secondary payer.

Q. How do I access services covered through TREAT?
A. Access to services are under the JSC Flight Medicine Clinic.

For expanded FAQs go to https://www.nasa.gov/hhp/treat-act-faqs

For more information, visit the TREAT Astronauts Act website at www.nasa.gov/hhp/treat-act.
To access services, contact the Johnson Space Center Flight Medicine Clinic at 281-483-7999.

https://www.nasa.gov/wp-content/uploads/2023/03/treat-astronautics-act-1.pdf?emrc=ba3f6d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ISS Instruments & Operational Requirements

- Internal Environment Monitoring – RAD, AHoSS, REM2
- External Environment Monitoring – Alpha Magnetic Spectrometer
- Personal Dosimetry – CAD (IVA), Pille (EVA)
- Neutron Monitoring – RAD, HRD
- Alarming – RAD
- Continuous Data Stream – RAD, AHoSS

ISS Medical Operations Requirements

7.5.1.1	The ISS Program shall prevent unacceptable deterministic effects to critical tissues by ensuring crew exposures do not exceed the dose values given in Table D-8.	RAE
7.5.1.2	The ISS Program shall manage crewmembers' ionizing radiation exposures following the principles of "As Low As Reasonably Achievable" (ALARA).	RAE
7.5.2.1	Each crewmember shall wear a personal radiation dosimeter at all times during a mission, including during IVA and EVA.	CAD & Pille
7.5.3.2.1	Instrumentation shall monitor the environment in habitable volumes of the ISS and provide information for estimating organ doses.	REM2, AHoSS, RAD
7.5.10.2	Preflight, crew radiation exposure histories shall be reviewed and the current mission exposures and risks shall be predicted based on planned mission activities. A minimum buffer dose of 0.1 Sv shall be included in the projected dose calculations for assignment of a crewmember to an ISS flight.	RAE (0.1 Sv not a thing anymore)
7.5.3.2.1.1	Instrumentation shall monitor the time-resolved LET spectrum, or as a surrogate, the lineal energy (y) spectrum.	REM2, AHoSS
7.5.3.2.1.2	Instrumentation shall monitor the time-resolved energy- and direction-dependent distribution of charge-identified particles inside ISS.	REM2, AHoSS, RAD
7.5.3.2.1.3	Radiation monitoring instruments shall provide the capability to characterize the neutron contribution to crew exposures.	RAD, HRD
7.5.3.2.2	External active radiation area monitoring shall monitor the time-resolved direction-and energy-dependent charged-particle spectra immediately exterior to the vehicle.	AMS
7.5.5.2	Time-resolved measurements of the energy- and direction-dependent distribution of charge-identified particles shall be made in various habitable module. Instrumentation shall be capable of surveying the majority of various modules.	REM2, AHoSS
7.5.5.3	Mobile instruments for internal charged-particle surveys shall be relocated periodically to various ISS habitable volumes.	REM2, AHoSS
7.5.6.1	Detailed data from time-resolved energy- and direction-dependent charged-particle detector shall be down-linked weekly or more frequently for analysis on a time scale that precludes loss of data or to support contingency evaluation for real-time flight support.	REM2, AHoSS, RAD
7.5.6.2	Dose rate from charged-particle monitoring equipment shall be continuously transferred to the ground for operational evaluation and real-time flight support.	AHoSS, RAD
7.5.7	At least one onboard active instrument shall have the ability to alert the crew when exposure rates exceed a set threshold.	RAD

Nomenclature

Quantity	Symbol	Quantity	Symbol
Linear Energy Transfer (LET)	L		
NASA Quality Factor	Q_{NASA}		
Tissue Weighting Factor	w_T		
Differential Fluence Distribution	$\Phi_T(Z, A; E)$		
Attained Age	a		
Assumed maximum lifetime	a_{max}		
Age at exposure i	a_{E_i}		
Excess Cancer Mortality/Incidence Rate for exposure i and tissue T	$\lambda_{i,T}^{(M/I)}\left(a, a_{E_i}, H_{T,i}\right)$		
Baseline Survival Probability at age a given that the subject is alive at age a_{E_i}	$S_0\left(a \mid a_{E_i}\right)$		
Number of missions	N		
Excess Absolute Risk	EAR_T		
Baseline Risk	B_T		