Orion EM-1 Internal Environment Characterization: The Matroshka AstroRad Radiation Experiment

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2019 ASEC

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Presentation Outline

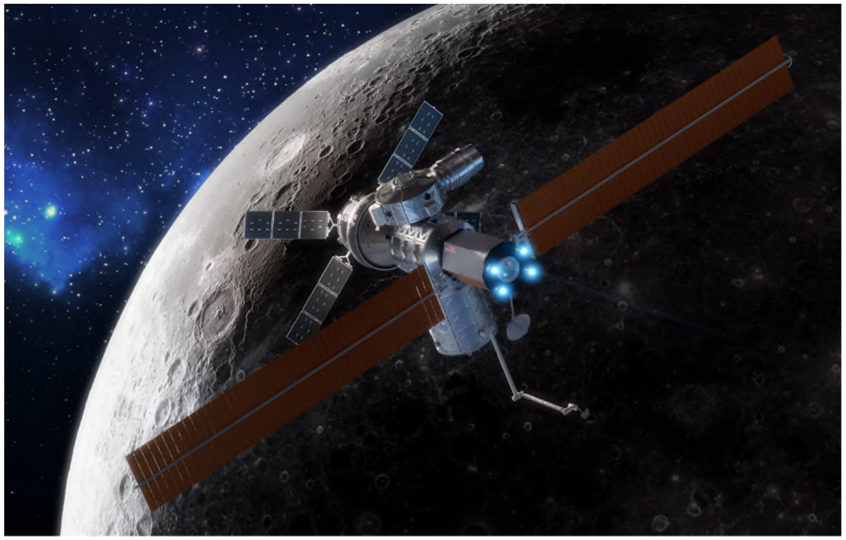
- Orion
- AstroRad
- ISS Matroshka

- Matroshka AstroRad Radiation Experiment (MARE) on Exploration Mission 1

Orion MPCV

- **The Orion Multipurpose Crew Vehicle (MPCV) is NASA's next generation spacecraft for human exploration of the solar system**
- **Exploration Flight Test 1 (EFT-1) successfully executed December 2014**
  – High eccentricity high altitude orbit to 3600 mi
- **EM-1 (Exploration Mission 1) is scheduled for 2020**
  – 21-42 days mission to Cis-lunar space
- **EM-2 is scheduled for 2022**
  – First crewed flight
- **First Gateway element also scheduled for 2022**
  - Power and Propulsion Element PPE
- **EM-3 is scheduled for 2024**
  – First crewed mission to the lunar surface


Image Credit: NASA

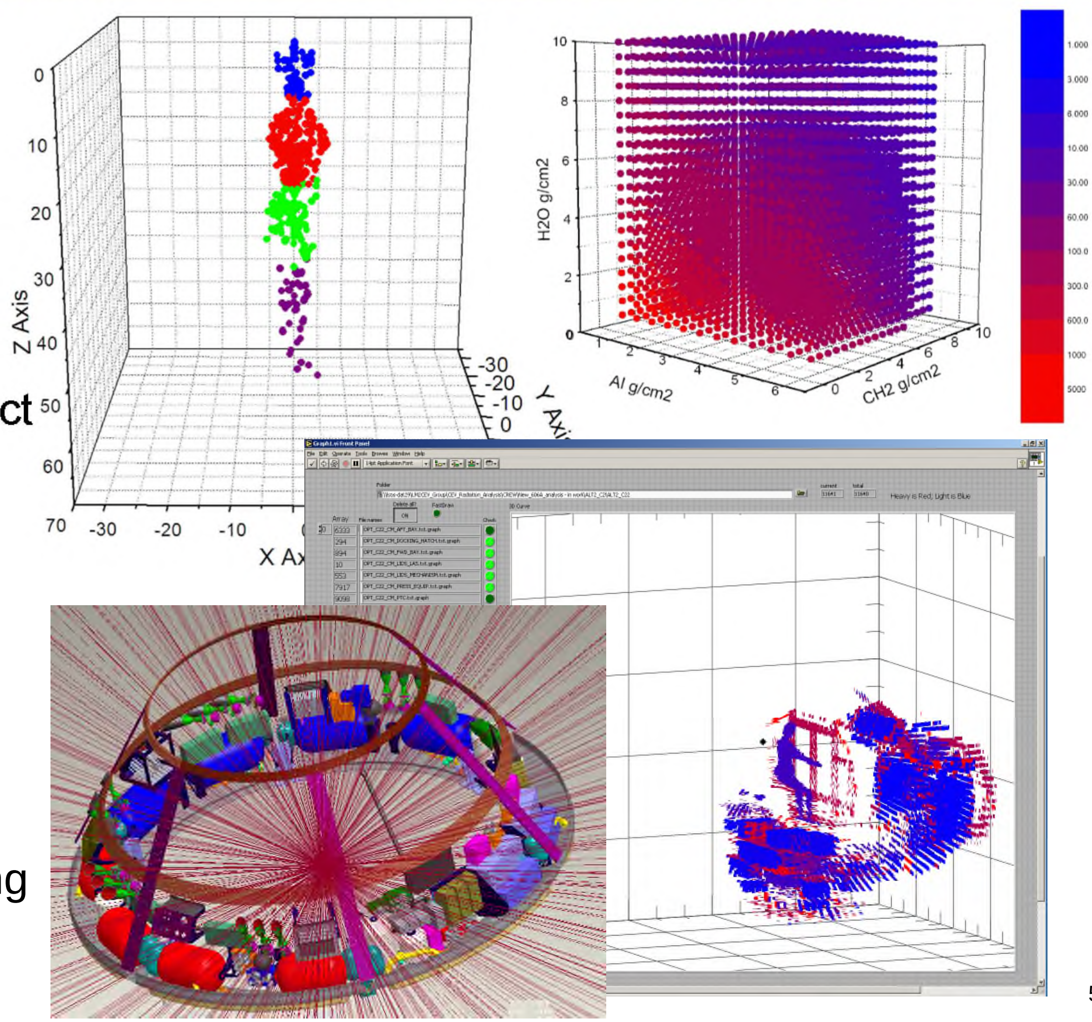


Orion Ionizing Radiation

- **Orion spacecraft design requirements address both electronic systems (e.g., avionics) and crew protection**
  - First NASA human spacecraft to implement an Ionizing Radiation Control Plan (IRCP)
    - Systematic decomposition of SRD high level requirement “Orion shall meet its functional, performance, and reliability requirements during and after exposure to the mission radiation environment”
  - First NASA spacecraft on which Crew radiation protection is levied as a design driving requirement
    - CxP-70024 Constellation Program Human Systems Integration Requirements
      - Spacecraft design “shall provide radiation protection consistent with ALARA and not to exceed crew exposure of E = 150 mSv for design reference environment”
    - SLS-SPEC-159 Cross-Program Design Specification for Natural Environments
      - Aug 1972 Solar Particle Event SPE (King parameterization)
- **Evolution of radiation protection requirements beyond Orion**
  - Townsend et al., Life Sciences in Space Research 17 (2018) 32–39
  - BFO limit of 250 mGy-equivalent for the design SPE chosen as Oct 1989
  - ALARA, storm shelter availability within 30 min of event onset

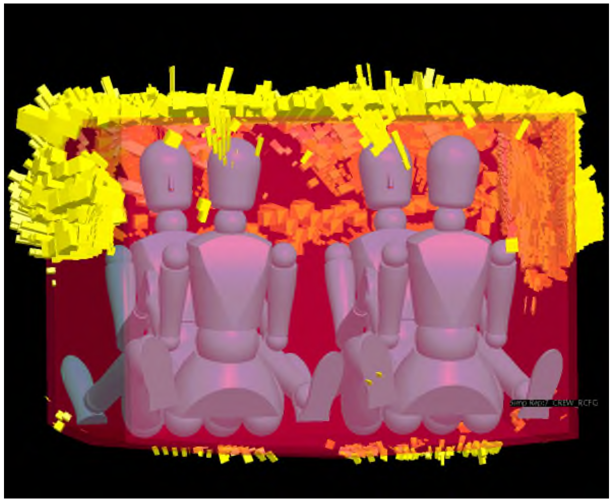
Orion Requirement Verification

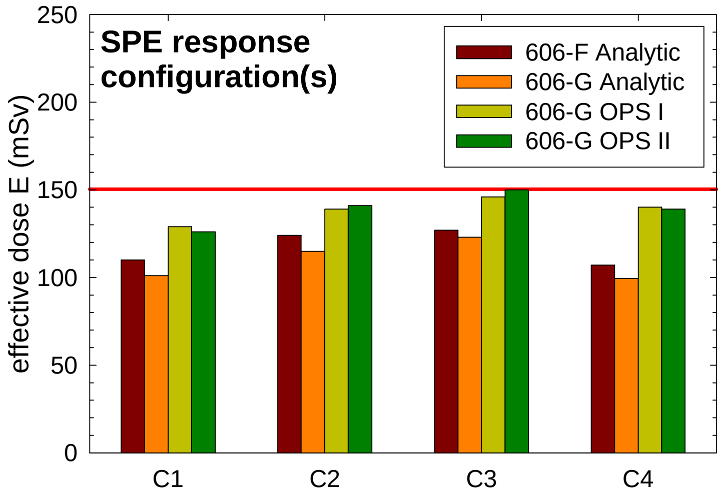
- **Crew Radiation Analysis**
  - Manufacturing quality Orion CAD model
    - 20,000 parts & assemblies, 100 GB
    - Mass/density and material properties
  - Vehicle shielding by ray tracing
    - 4 origin points/crew member, 10k directions
  - Body self-shielding from anatomically correct human models (~600 organ points)
  - Ray-by-ray total converted to 3-material equivalents (Al, HDPE, H_2O)
  - Point dose equivalent calculations by deterministic transport software HZETRN
    - Definition of design reference environment
  - Integrated to obtain organ dose equivalent
  - Effective dose calculated w/ tissue weighting factors per NCRP Report 132 (2000)

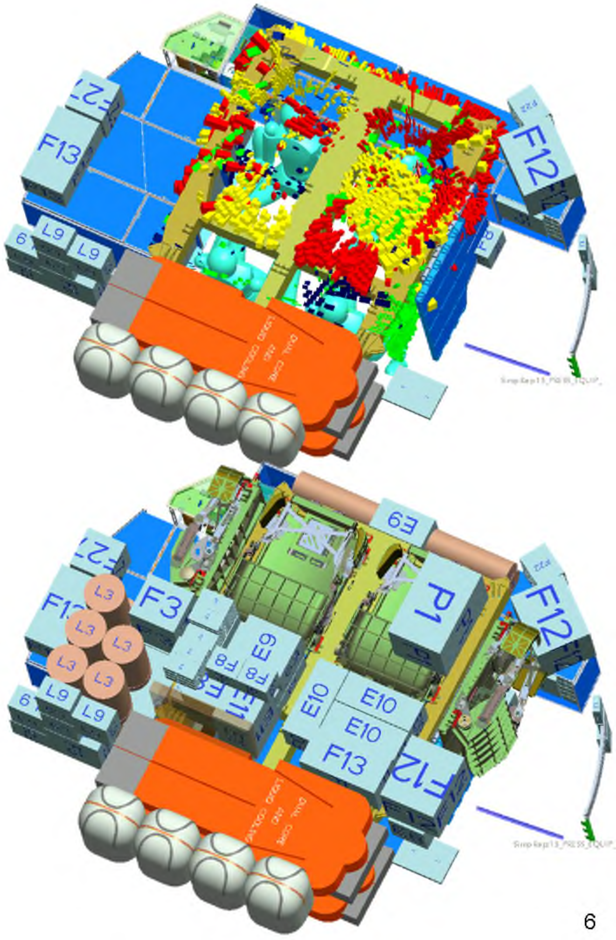


Cabin Configuration Optimization

- **Optimization of cabin components locations in lieu of flying dedicated shielding**
  - Quasi-exponential decay of radiation exposure w/ shielding areal density
  - Consistent with ALARA
  - Large number of variables renders closed solution difficult
  - Semi-analytical method example: visualization of additional shielding location required to achieve predefined target shielding thickness endpoint





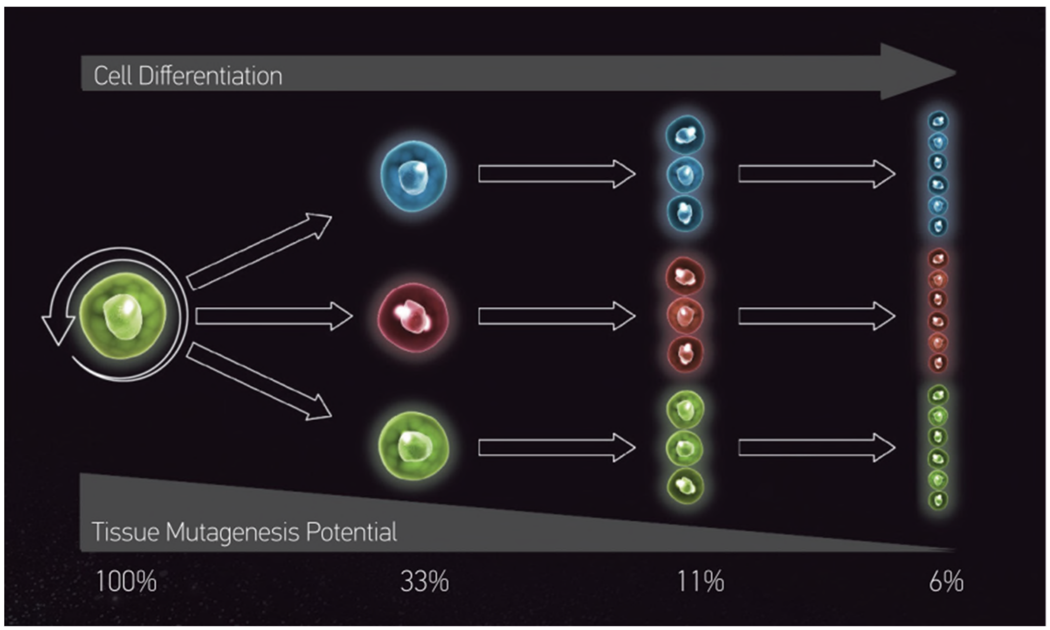


Radiation Vest for Astronauts: AstroRad

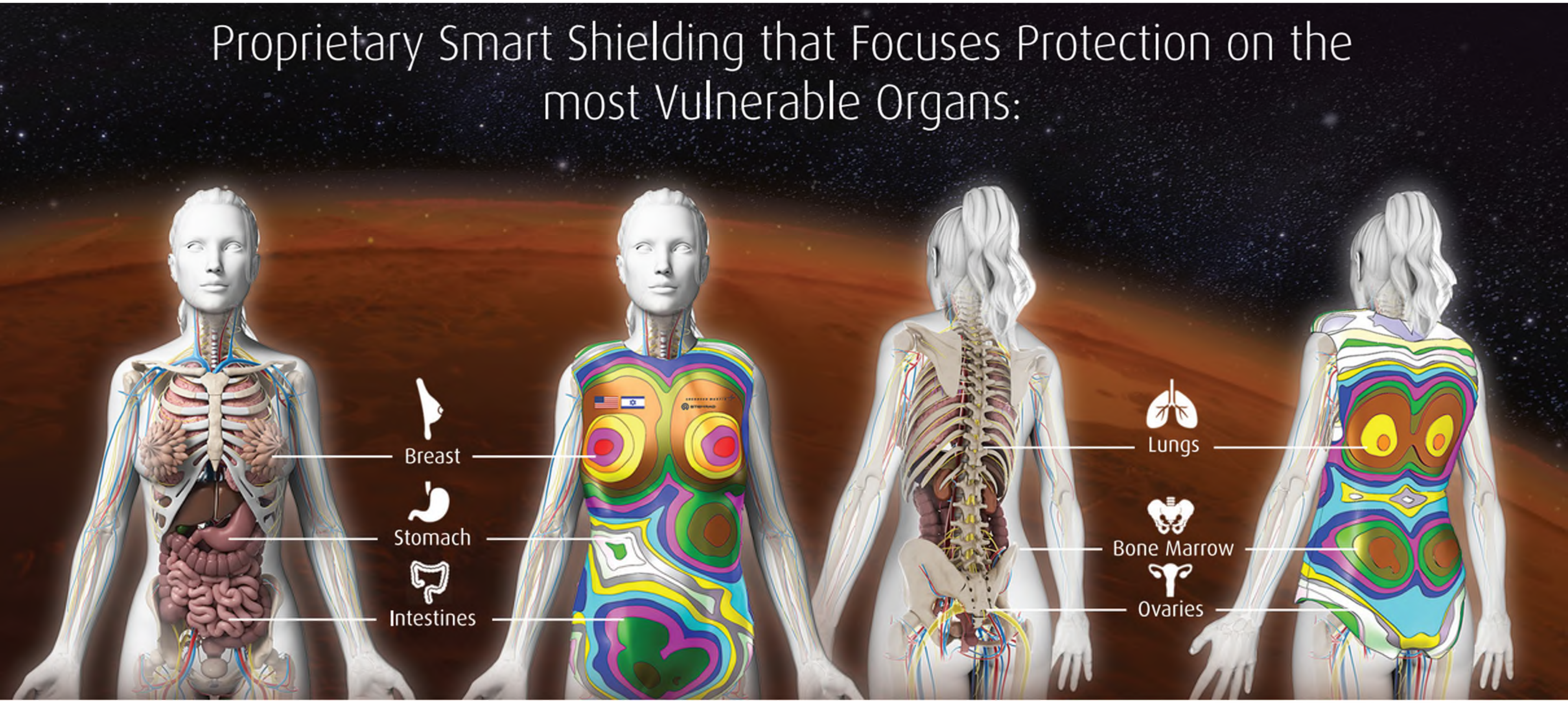
SPACE FLORIDA

רשות החדשנות
Israel Innovation Authority

- **Collaboration between Lockheed Martin Space and StemRad Israel**
  – Portable radiation protection for astronauts
  – Provides preferential protection to stem cell rich organs and tissues
  – Designed for flexibility and ergonomics
  – Ergonomic evaluation aboard the International Space Station pending (launch on SpX-18 July 2019)

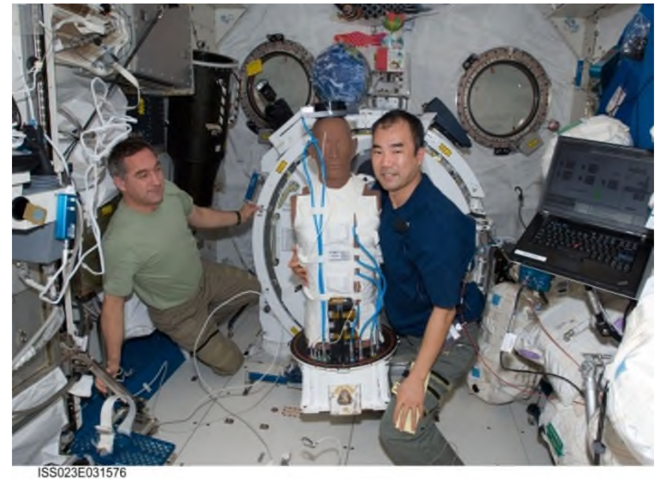


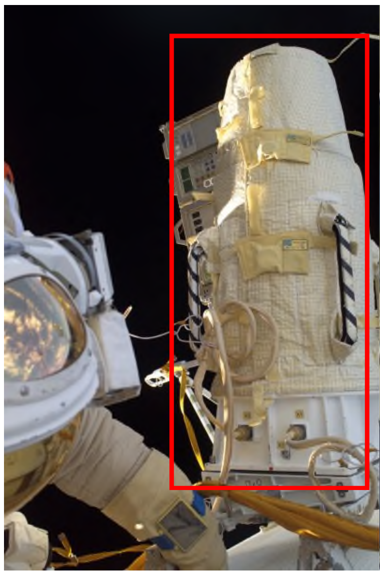
AstroRad


Proprietary Smart Shielding that Focuses Protection on the most Vulnerable Organs:
Breast
Stomach
Intestines
Lungs
Bone Marrow
Ovaries

ISS Matroshka

- **Series of radiation measurements in radiation therapy phantoms on ISS**
  - Body internal dose mapping using radiation detectors on the surface of, and inside radiotherapy phantoms. Both extra- and intra-vehicular.

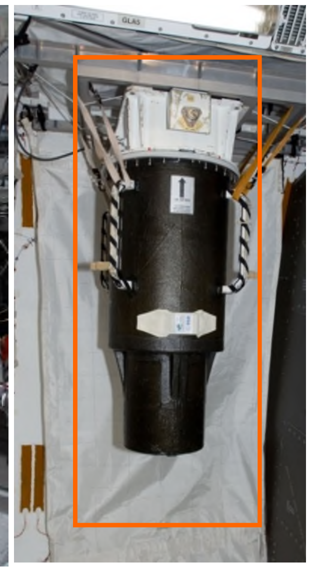




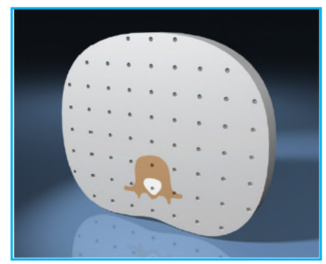
MTR-1 539 days (2004–05)

MTR-2A 337 days (2006)

MTR-2B 518 days (2007–09)



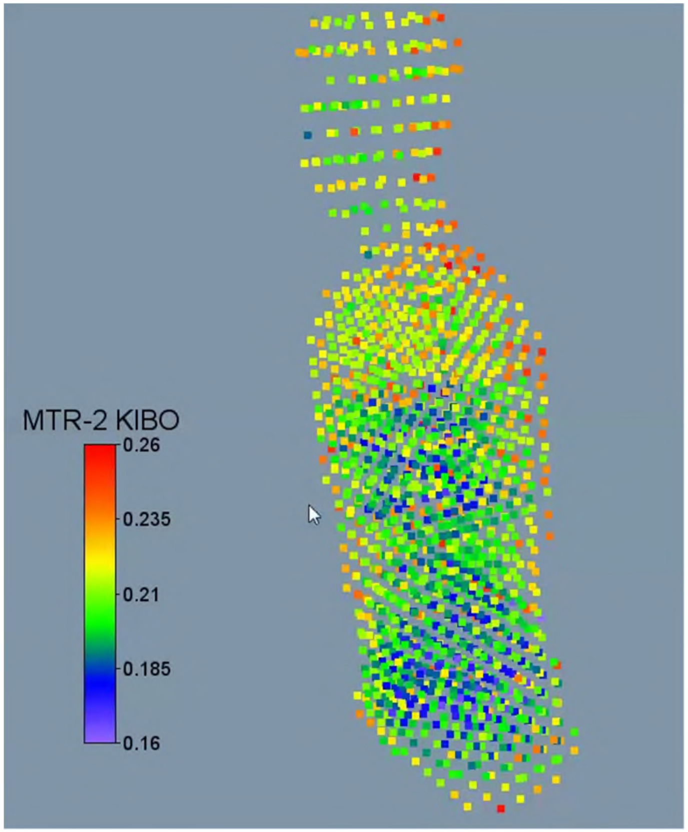
MTR-2 KIBO 310 days (2010–11)

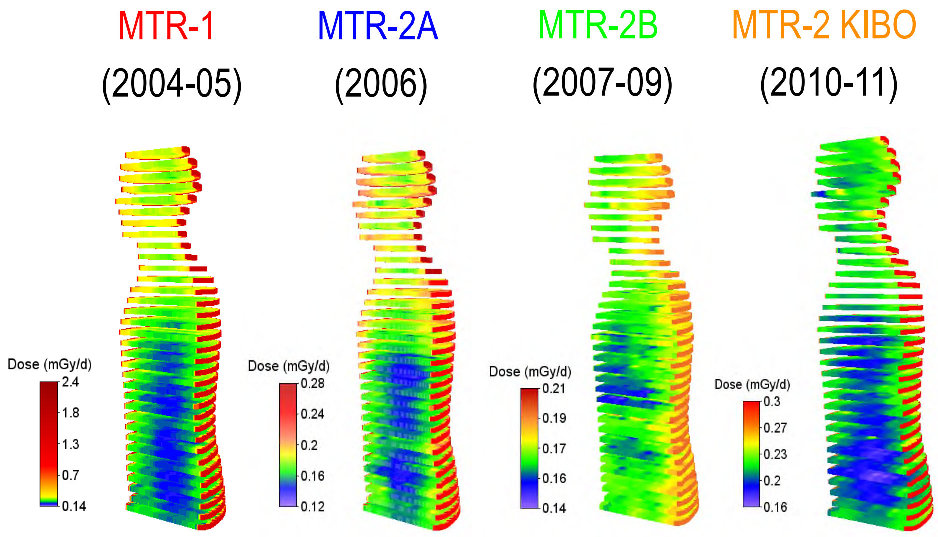


http://www.cirsinc.com/file/Products/701_706/701%20706%20ATOM%20PB%20050418.pdf

DLR

ISS Matroshka





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– Zhou, D., Semones, E., O'Sullivan, D., Zapp, N., Weyland, M., Reitz, G., Berger, T., Benton, E.R. Radiation measured for MATROSHKA-1 experiment with passive dosimeters. Acta Astronautica (2010), 66, 301 – 308
– Reitz, T. Berger *et al.*, Astronaut's organ doses inferred from measurements in a human phantom outside the International Space Station, *Radiat. Res.* 171 (2), 225-235 (2009)

ATOMINSTITUT

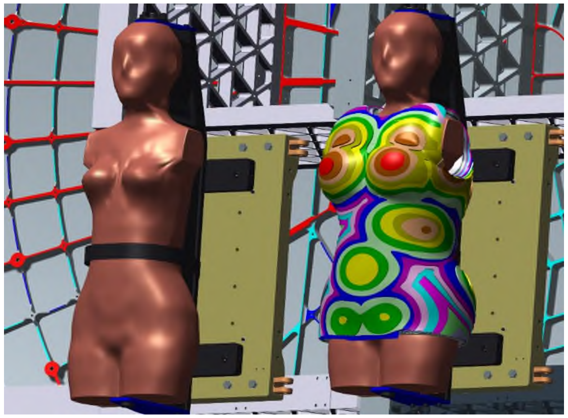
THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

DLR

Matroshka AstroRad Radiation Experiment (MARE)

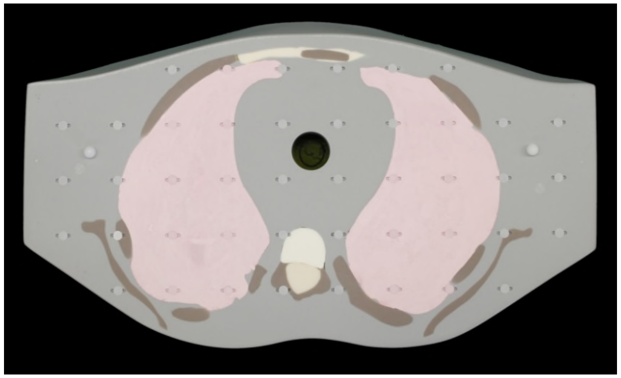
- Lockheed Martin invited feedback as part of Orion radiation protection efforts
- Israel Space Agency (ISA) and the German Aerospace Center (DLR) proposed MARE as an international science payload
- NASA approved the proposal in May 2017 and manifested it aboard the EM-1 flight.

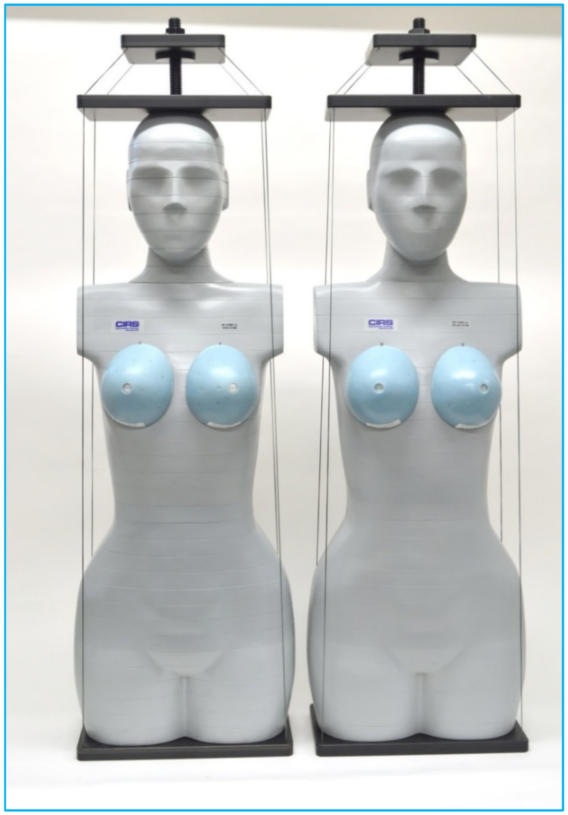
- MARE description
  - Two tissue-equivalent radiation phantoms inside the Orion cabin
  - Fitted with active and passive radiation detectors
  - One phantom fitted with the StemRad-manufactured AstroRad vest
- MARE is managed by DLR and ISA, with NASA as a co-PI
  - Lockheed Martin personnel co-located with Orion support development of MARE science objectives and efficient payload integration aboard the Orion vehicle



MARE: CIRS Phantoms

- **ATOM® 702 Female model**
  - Zohar 35.88 kg / Helga 35.99 kg
  - Tissue equivalent material, Artificial bone
  - 38 slices with TLD/OSLD holes (3 cm custom grid)



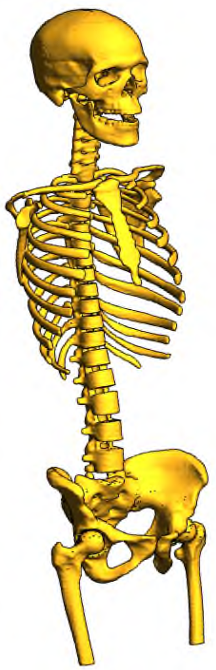


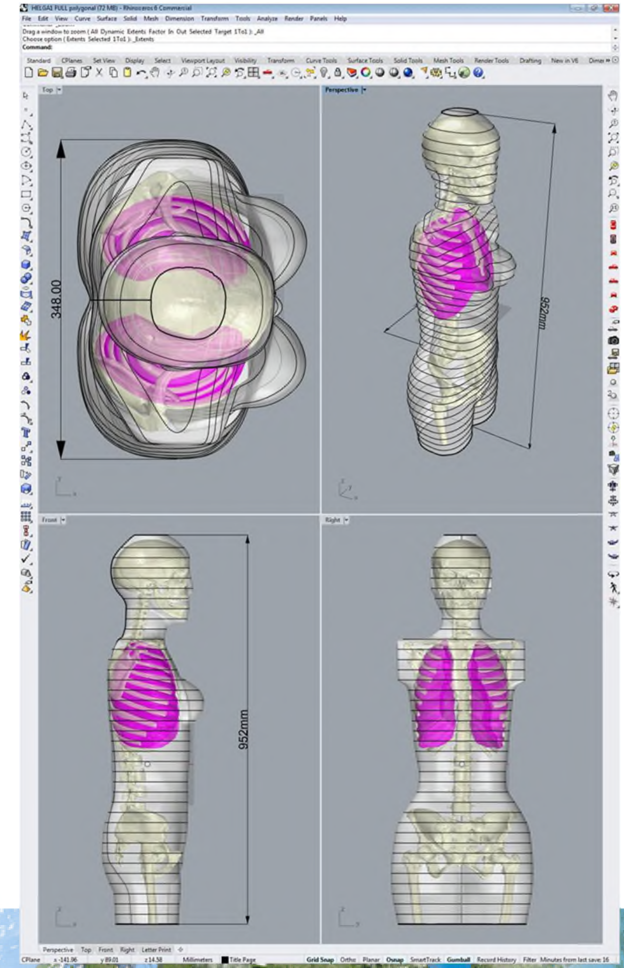
http://www.cirsinc.com/products/modality/33/atom-dosimetry-verification-phantoms

DLR

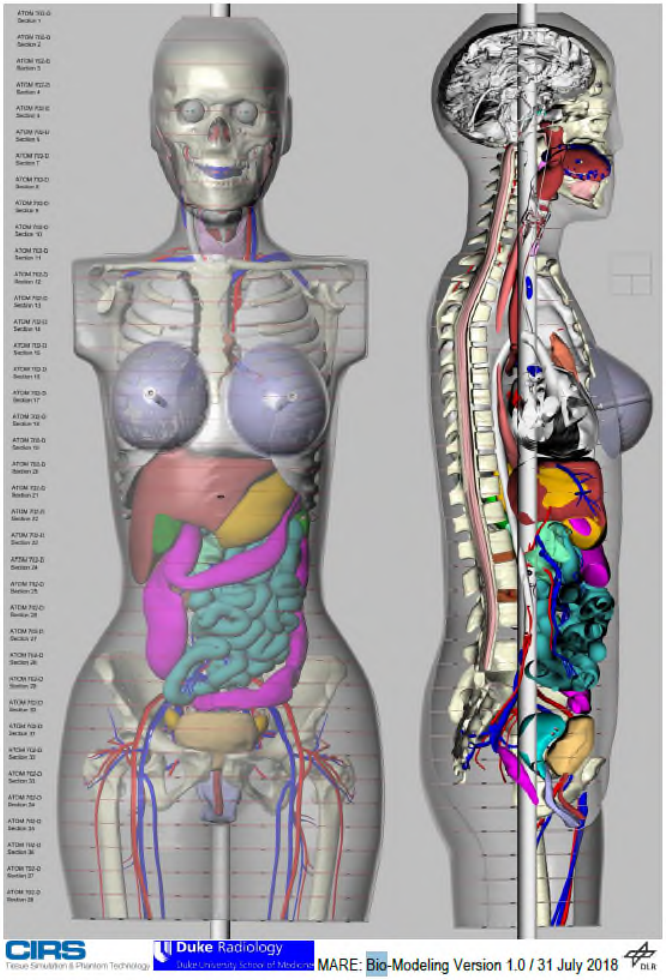
MARE: CIRS Phantoms Internal

- **CT scan performed on each phantom**
- **CT scan data are used to generate CAD models**
- **CAD models are used for AstroRad vest customization and radiation analysis**

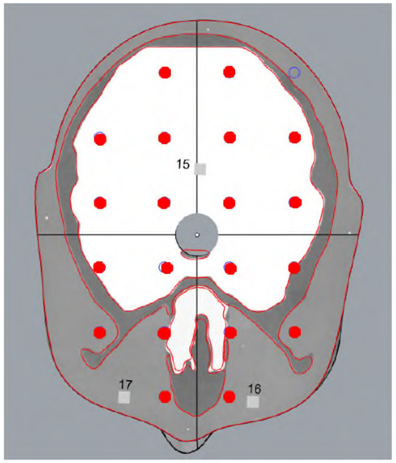


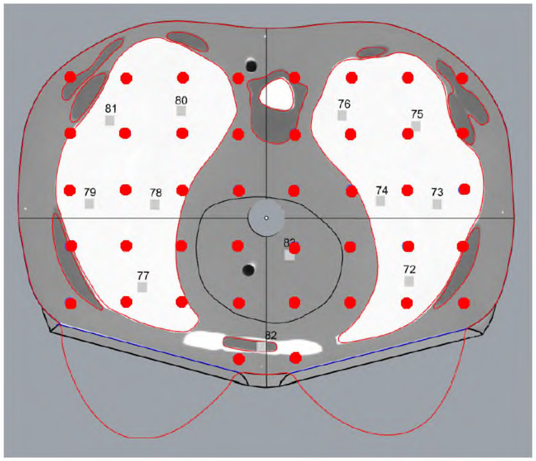


Bio-modeling



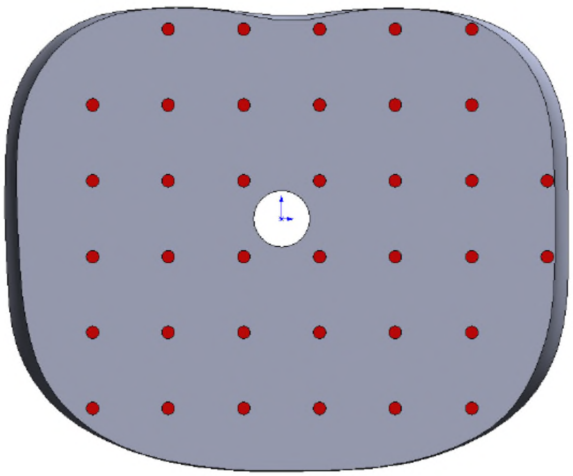
- **Radiation phantom materials**
  - Soft tissue, bone, lung, brain, and breast (and void)
- **CAD Bio-modeling**
  - Courtesy of W. Paul Segars, Ph.D., Duke University School of Medicine
  - Outlines organ shapes within the average soft tissue
  - Associates TLD grid locations with specific organs, allowing for organ dose calculations (analytic prediction & measurements)

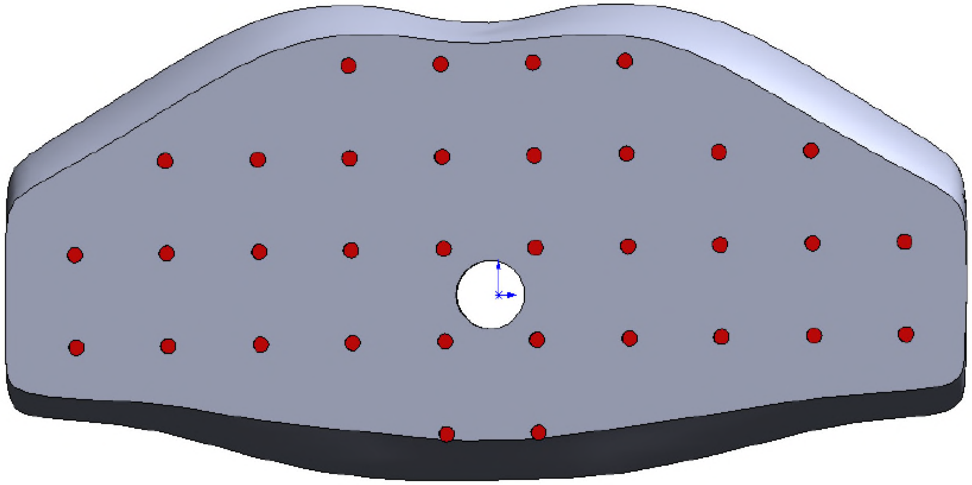




Internal Dose Mapping

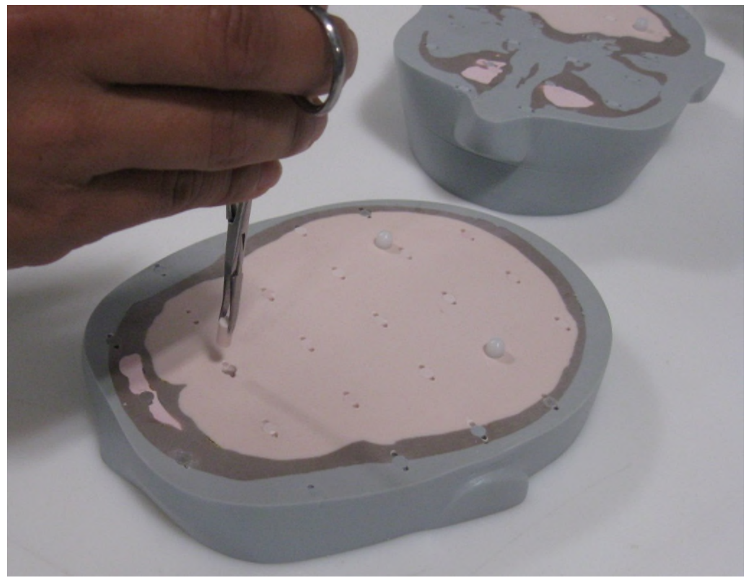
- **Passive dosimeters internal to the phantoms**
  - 3 cm x 3 cm grid
  - 6000 TLDs provided by DLR (750 measurement points/phantom, 4 TLDs/measurement point
  - 2000-3000 TLDs & OSLDs provided by NASA JSC (1000-1500 /phantom)

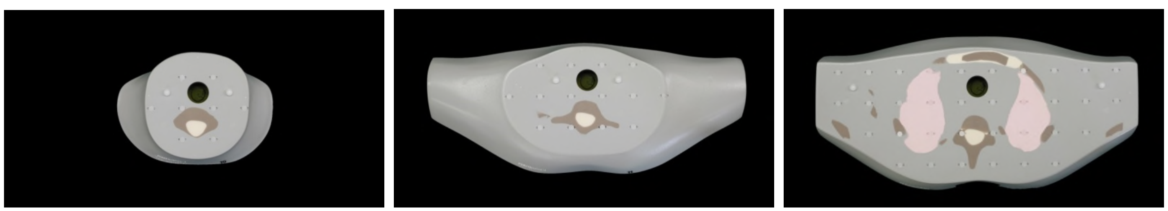


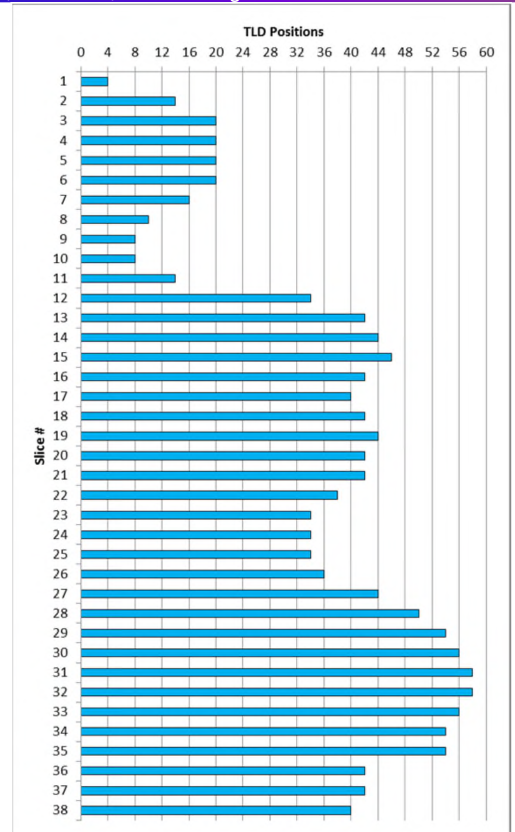


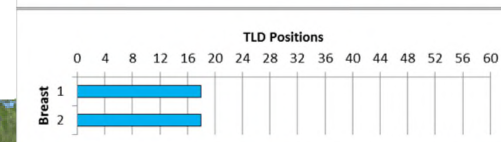
Helga TLD Positions

Helga: 1392, Zohar: 1383 (DLR: 6000 TLDs, NASA: 2-3000 TLDs/OSLDs)





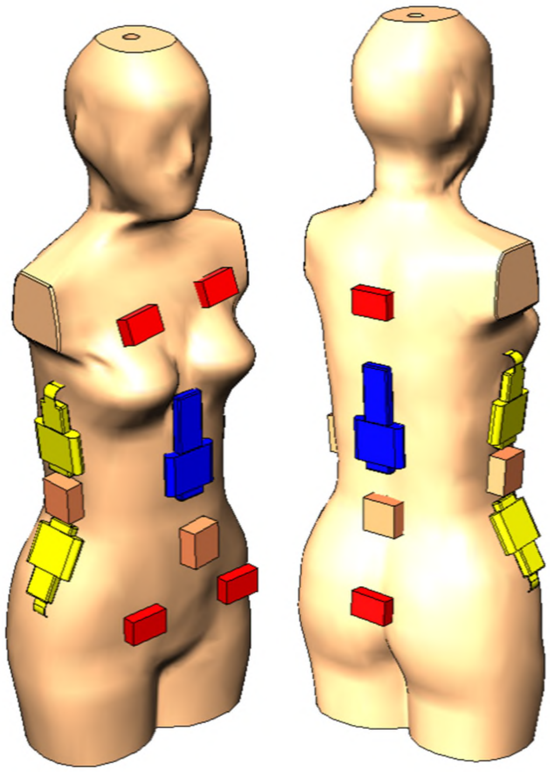




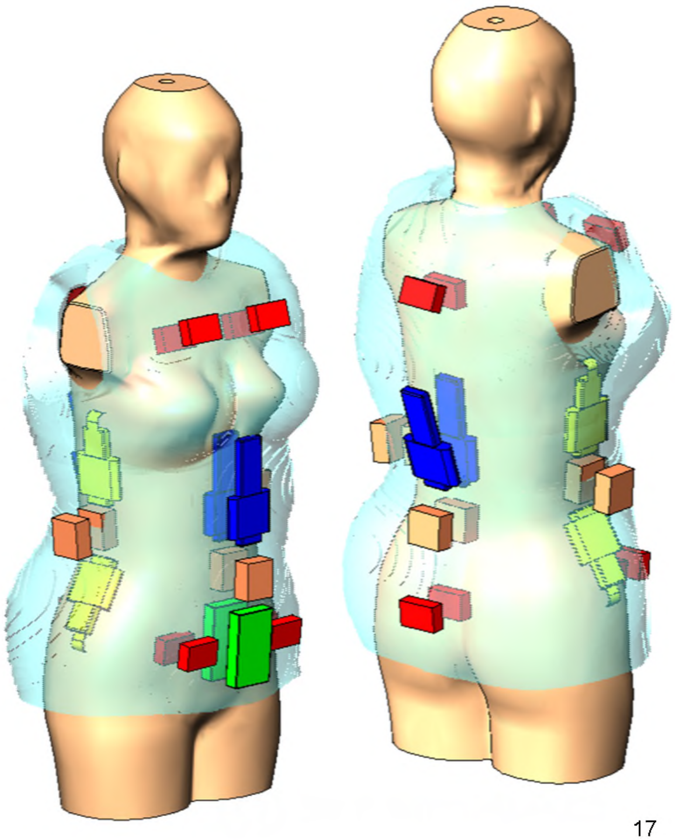
DLR

Location Radiation Detectors

- Active detectors for surface (skin) and organ location measurements
- DOSIS Passive Dosimeter Packages (PDPs) for surface (skin) measurements
- PDPs provided by DLR for organ measurements (TLD + CR-39)



# Helga	Detector	Org	# Avis
2	M-42 Compact	DLR	4
5	M-42 Split	DLR	5
6	CPAD	NASA	12
1	EAD-MU-O	ESA	2
4	DOSIS PDP	DLR	8
5	DLR PDP	DLR	5



DLR M42

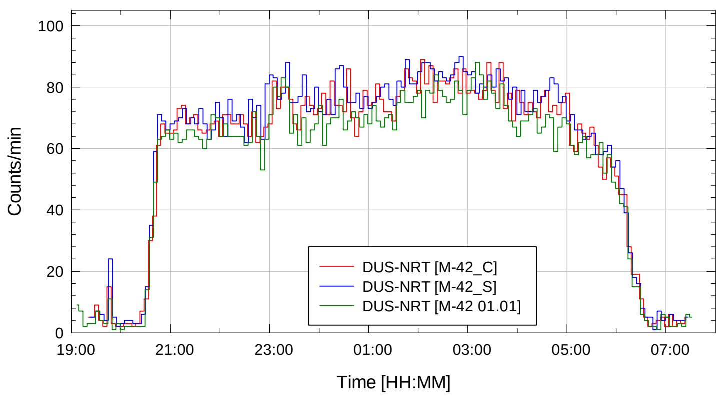
- **Silicon Detector**
  - 1 cm^2 area, 300 µm thickness
  - Energy range 0.06-20 MeV (Si), 1024 channels
  - Autonomous operation
  - Launch detection (accelerometer)
  - Two versions “Split” and “Compact”

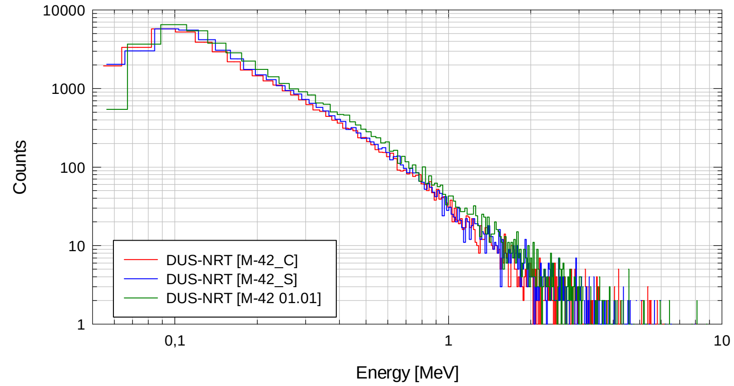
Device	Dimensions	Mass (g)
M-42_C	142 x 38 x 13 mm^3	108
M-42_C (batteries)	Diam. 14.55 mm Height 50.3 mm	2 x 18
M-42_C (battery housing)	72.5 x 54 x 13 mm^3	40
M-42_C (total)		184

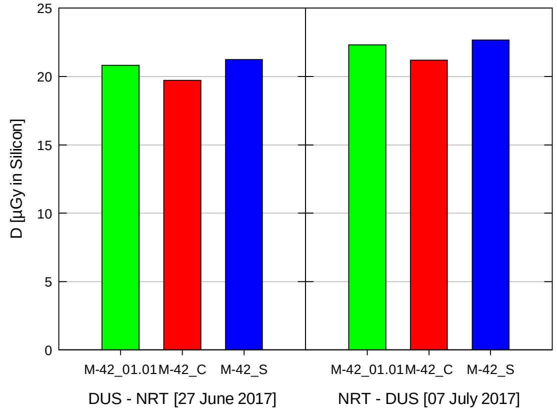
Device	Dimensions	Mass (g)
M-42_S	DH: 54 x 38 x 13 mm^3 EB: 106 x 38 x 13 mm^3	120
M-42_S (batteries)	Diam. 14.55 mm Height 50.3 mm	2 x 18
M-42_S (battery housing)	72.5 x 54 x 13 mm^3	40
M-42_S (total)		196

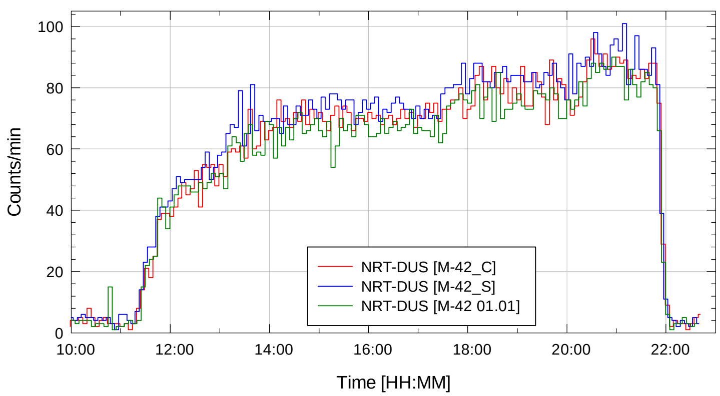
DLR

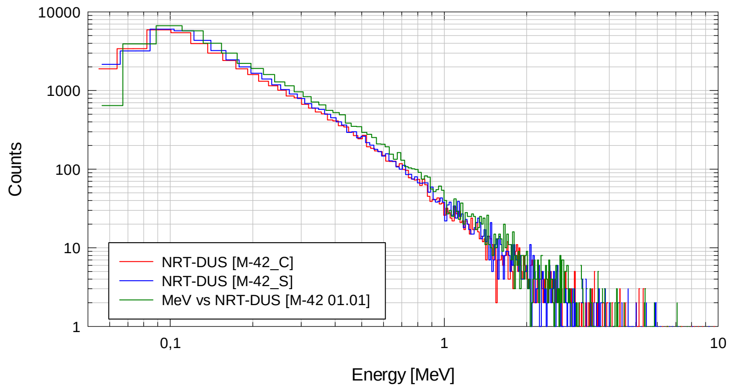
DLR M42 DUS-NRT and return









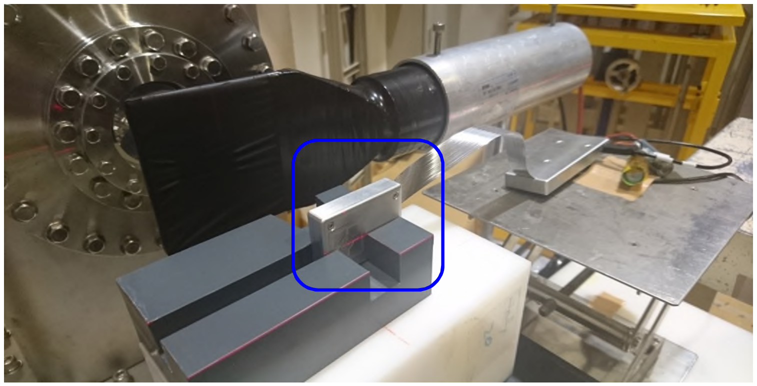


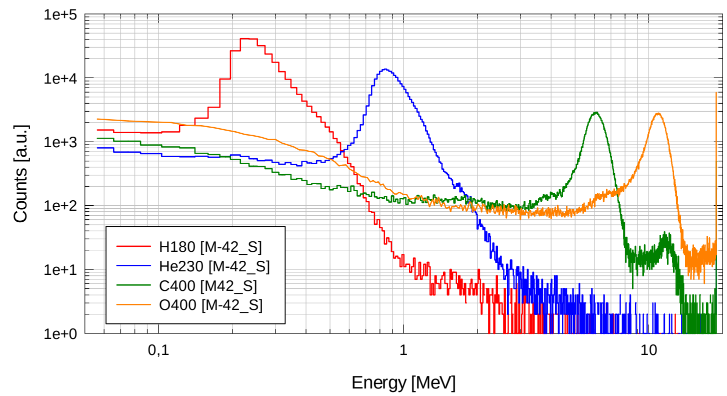
DUS-NRT: 20.56 ± 0.78 µGy in Si
NRT-DUS: 22.07 ± 0.77 µGy in Si

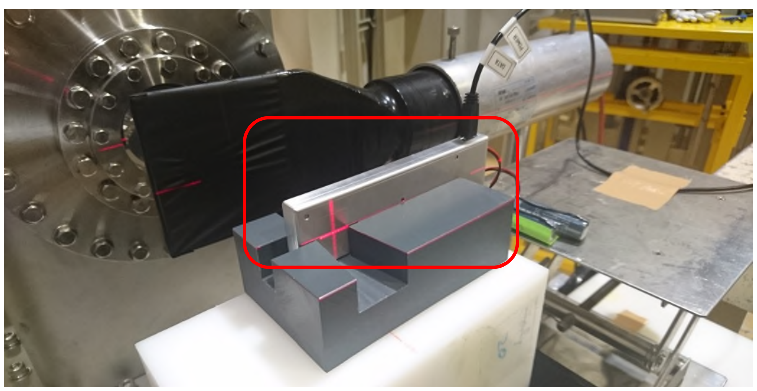
DLR

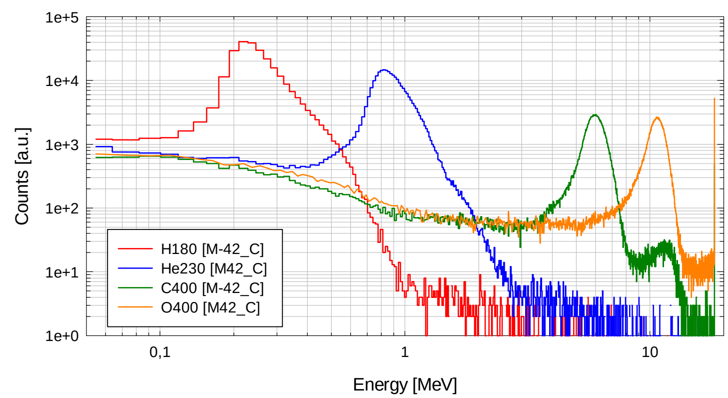
DLR M42 HIMAC Exposure

HIMAC Research Project 17H374





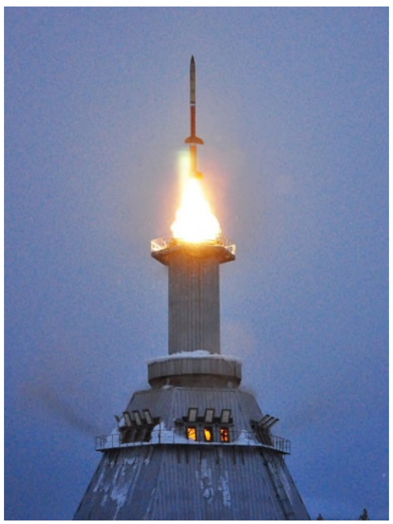


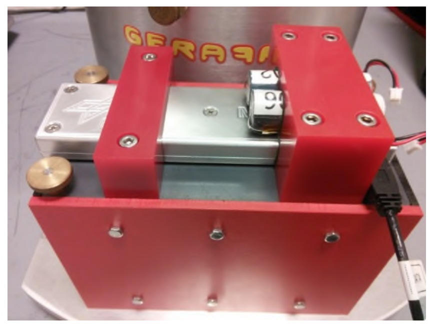


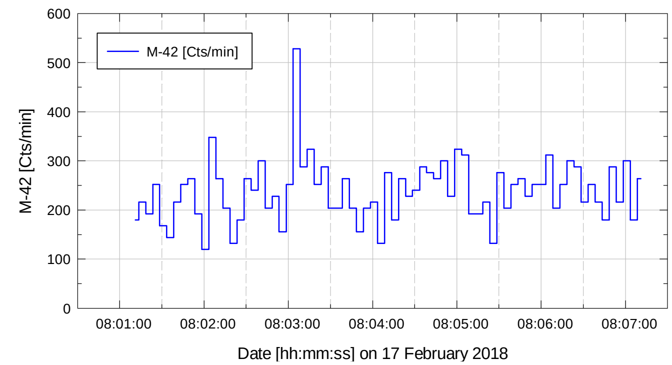
DLR

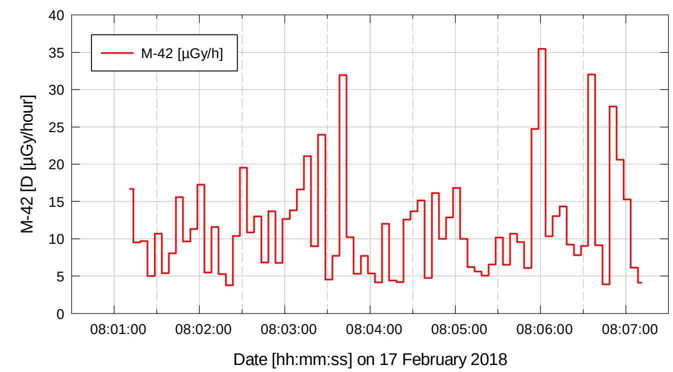
DLR M42 MAPHEUS testing

- **Load detector test performed aboard MAPHEUS DLR research rocket**
  - Max Altitude = 260 km
  - Flight Time = 14 min 10 s (6 min microgravity)
  - Launched from the European Space and Sounding Rocket Range, Kiruna, Sweden (Feb 2018)









NASA CPAD

R. Gaza for the MARE team
2019 ASEC, Los Angeles, CA

- **Crew Personal Active Detector**
- **ISS Tech Demo currently in progress**
- **Variable storage rate, no load detector needed**
- **Direct Ion Storage (Mirion Technologies)**
- **Mass <35 g, volume = 5.4 x 3.4 x 1.8 cm^3**
- **Battery life >10 months (configuration dependent)**
- **Display for crew information includes dose rate and cumulative dose**
- **Additional CPADs to be flown on EM-1 outside of MARE**

ESA Active Dosimeter (EAD)

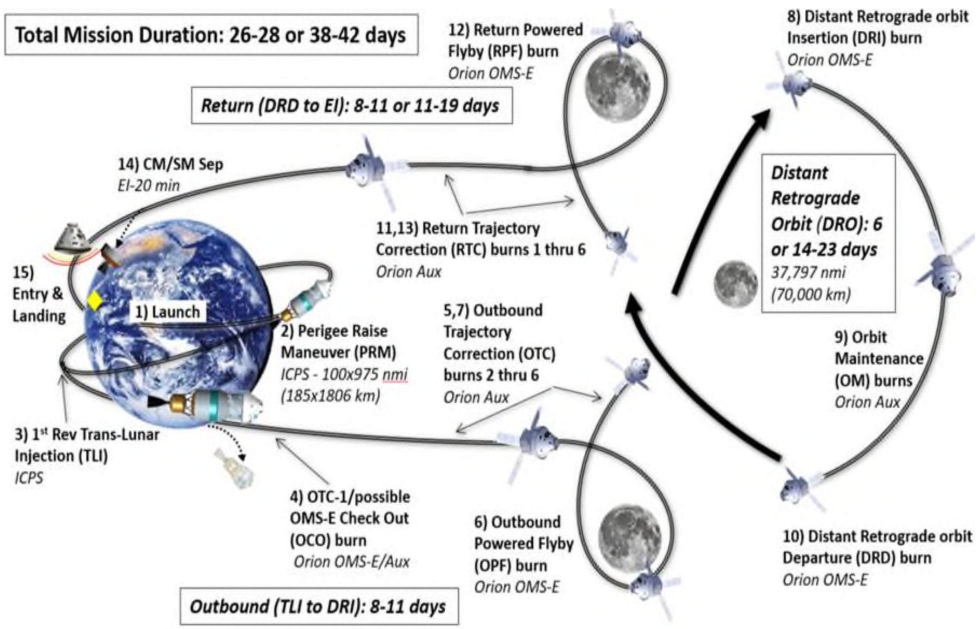
- **Provided by the European Space Agency**
  - Also referred to as EAD Mobile Unit – Orion (MU-O)
- **Based upon the existing ISS EAD MU**
  - ISS EAD system also includes docking station
  - MU-O requires upgraded battery lifetime
  - Additional instances of the EAD MU-O baselined to fly on Orion EM-1 outside of MARE
- **Mass 150 g, volume 6x10x3 cm^3**
- **Thin/Thick Silicon Detector**
- **Instadose®**
- **RadFET**

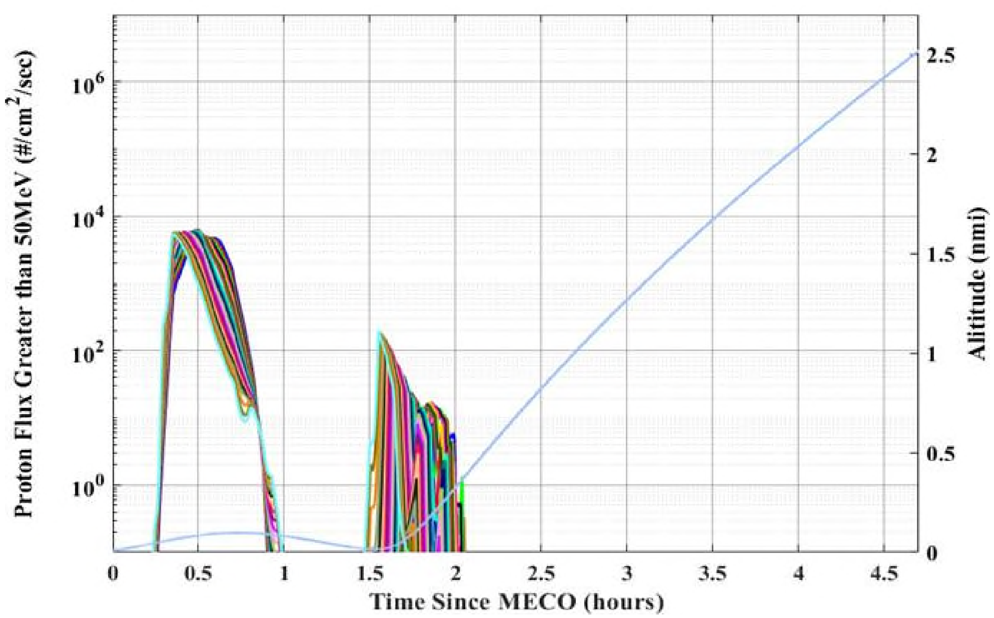
DOSIS 3D PDP

- **Dose Distribution Inside the International Space Station - 3D**
  - DLR lead effort to dose map all the ISS segments (2012 – 2018)
  - Passive Dosimeter Package (PDP) includes TLDs + OSLDs + CR-39 PNTDs
  - Large international participation includes:
    - Technical University Vienna, ATI, Austria
    - Institute of Nuclear Physics, IFJ, Krakow, Poland
    - Centre for Energy Research, MTA EK, Budapest, Hungary
    - Belgian Nuclear Research Center, SCK•CEN, Mol, Belgium
    - Nuclear Physics Institute, NPI, Prague, Czech Republic
    - Oklahoma State University, OSU, Stillwater, USA
    - National Institute of Radiological Sciences, NIRS; Chiba, Japan
    - NASA JSC, Houston, TX, USA

Exploration Mission 1 (EM-1)

- **First Orion test flight beyond Earth orbit scheduled for 2020**
  - Uncrewed flight on Distant Retrograde Lunar Orbit (DRO)
  - Solar minimum: intense GCR, low probability of SPE
  - Van Allen protons useful as SPE surrogate
  - Trajectory through Van Allen belts dependence upon launch date causes ~2x spread in environment (AP-8)

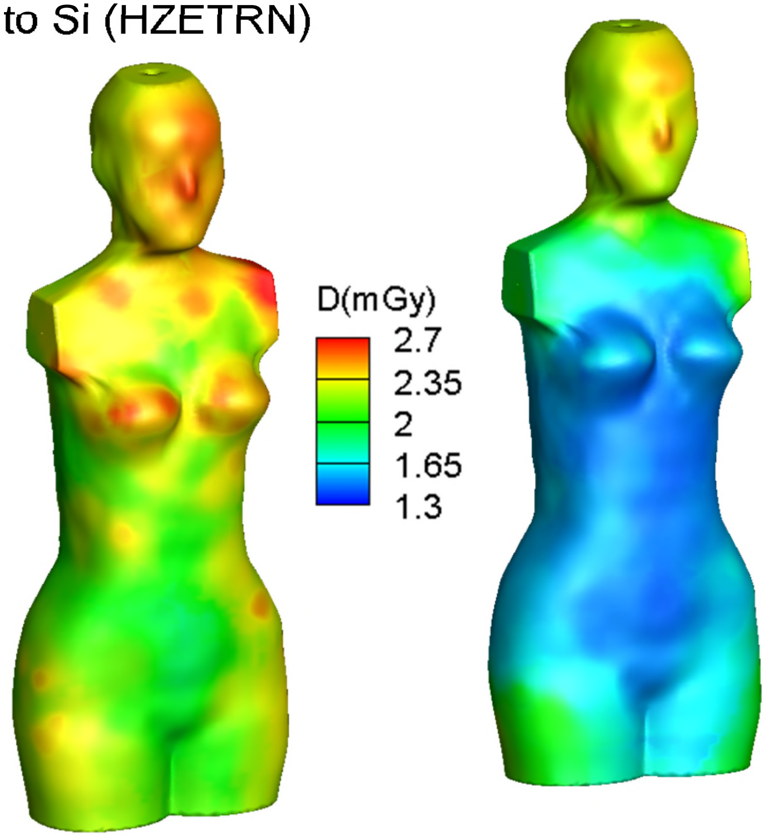




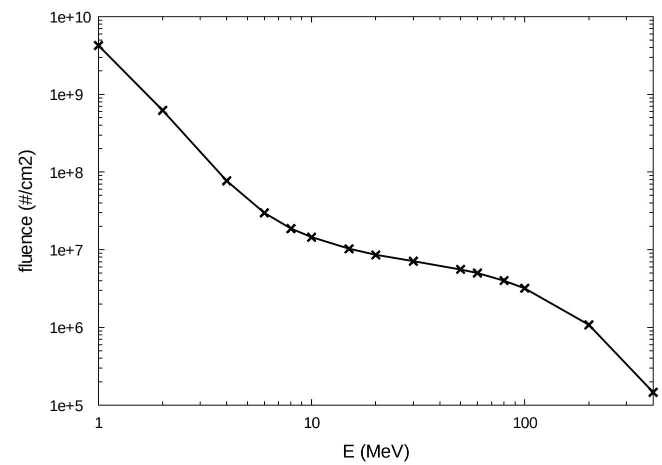
Exploration Mission 1 (EM-1)

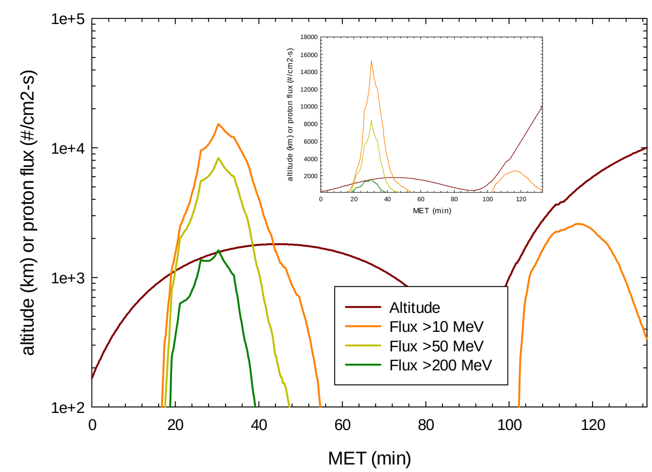
- **Preliminary radiation analysis**
  - Using MARE and Orion EM-1 CAD models
  - Max radiation stressing environment (outbound, AP-8)
  - Dose to Si (HZETRN)

"Helga"
Seat #4
No Vest



"Zohar"
Seat #3
AstroRad
Vest not shown

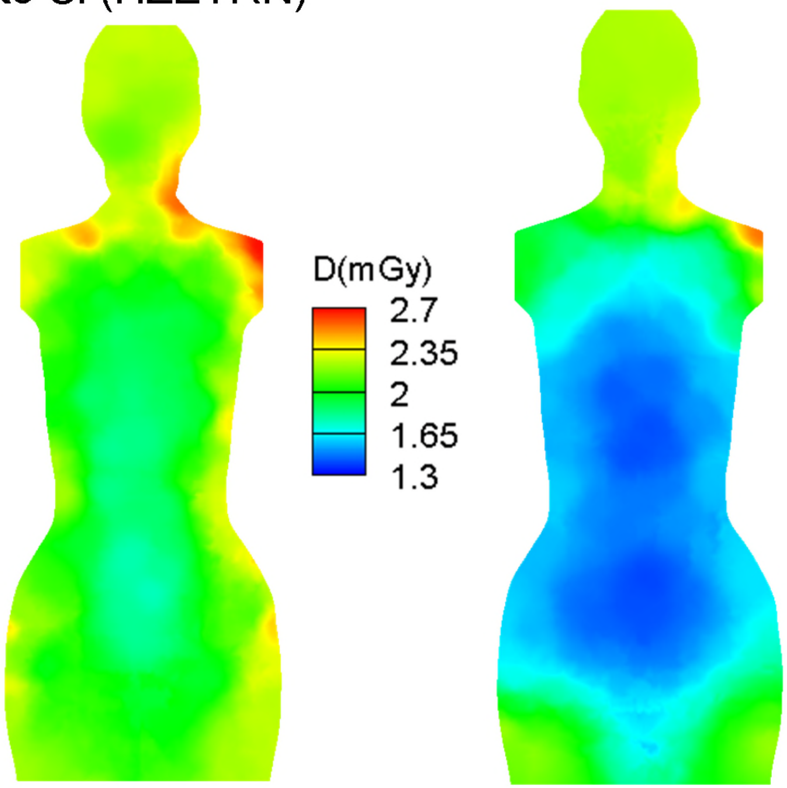




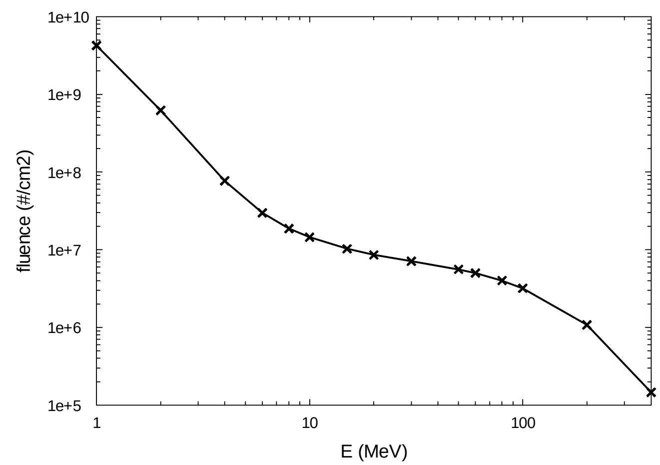
Exploration Mission 1 (EM-1)

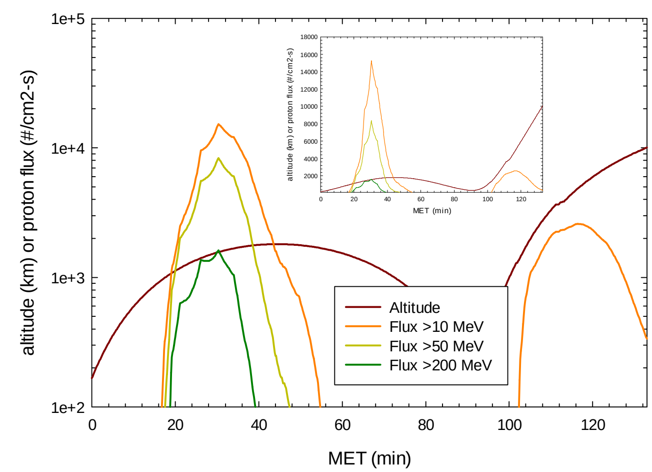
- **Preliminary radiation analysis**
  - Using MARE and Orion EM-1 CAD models
  - Max radiation stressing environment (outbound, AP-8)
  - Dose to Si (HZETRN)

"Helga"
Seat #4
No Vest



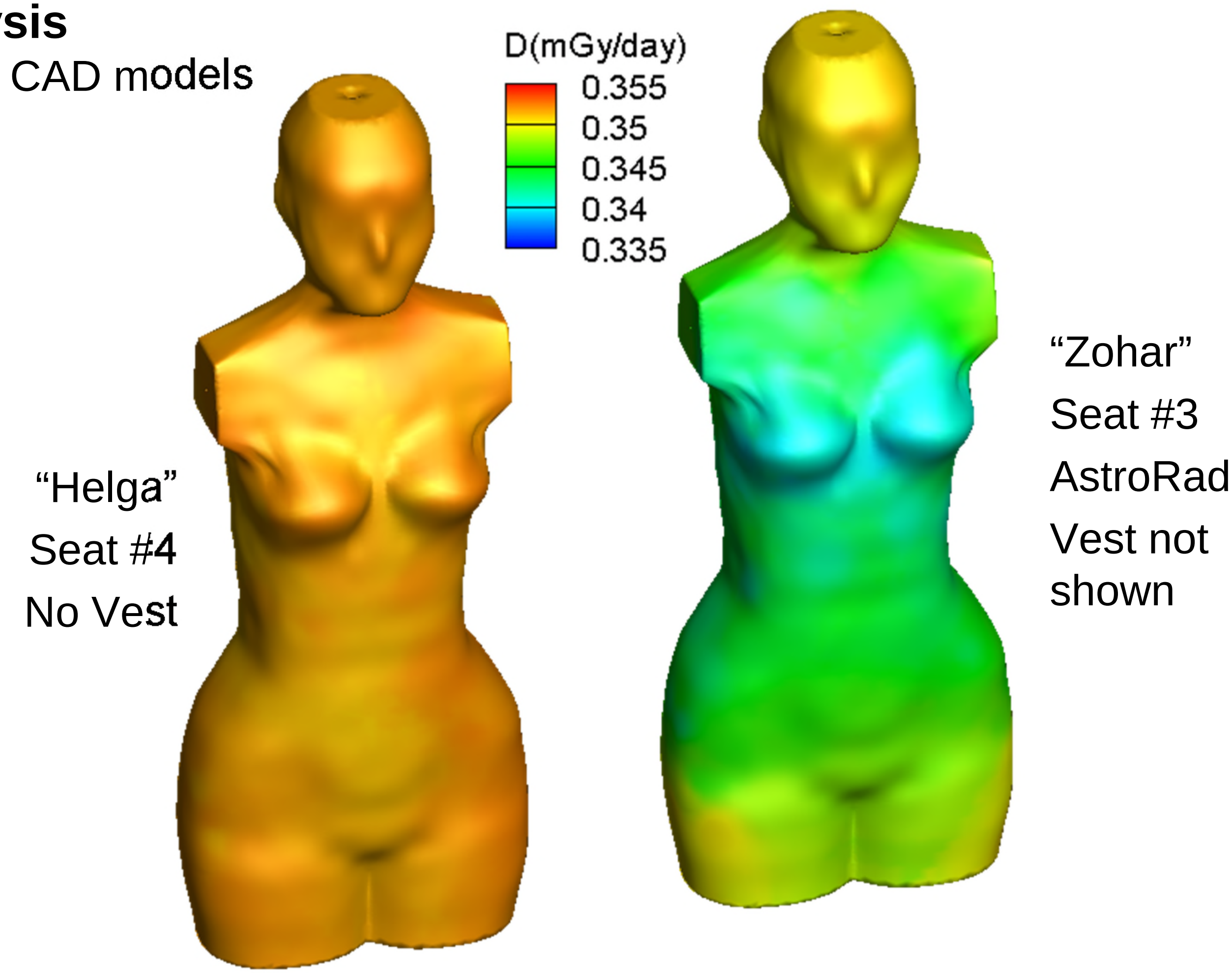
"Zohar"
Seat #3
AstroRad
Vest not shown





Exploration Mission 1 (EM-1)

- **Preliminary radiation analysis**
  - Using MARE and Orion EM-1 CAD models
  - GCR Solar Min (Mar 2009)
  - Daily dose to Si (HZETRN)



Payload Integration Status

- **Successfully completed combined PDR/CDR (Mar 2019)**
  - Structural analysis, Vibration testing
  - Safety certifications ongoing
- **Installation validation in the Orion Structural Test Article**
  - Mass representative mock-ups
- **Science activities**
  - Additional detectors from HERADO / Hellenic space Agency / Thessaloniki University (Greece)
  - Environment and Dose Projection Refinements
- **Late stow vehicle installation**
- **EM-1 Flight (2020)**
- **Post-flight data processing, consolidation and publication**
  - AstroRad vest improvements

Conclusion

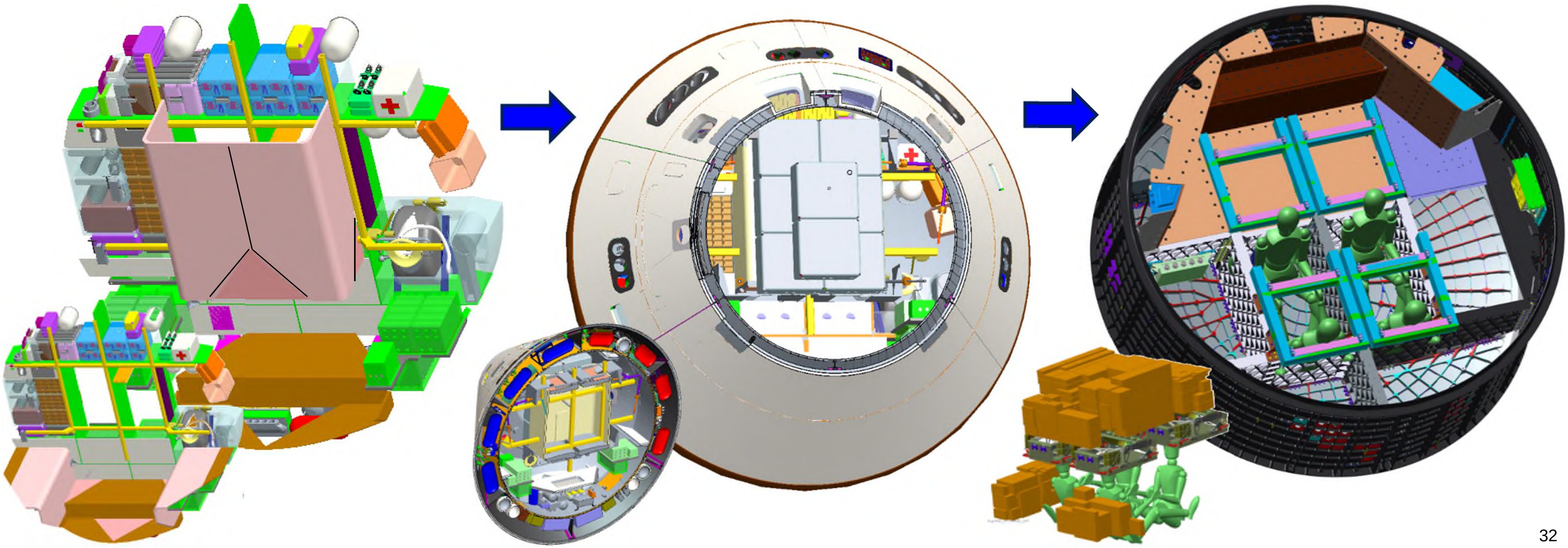
- **Orion is the first Exploration architecture component**
  - MARE is among the first Orion payloads
- **International collaboration is critical to successful space exploration**
- **MARE as example of upcoming science research opportunities**

Our goal is to improve astronaut safety and enable Exploration

Backup

Orion Design for Crew Radiation Protection

- **Matured throughout the vehicle design**
  - Early in the program the Master Equipment List included 254 lbm of Polyethylene radiation shield
  - Dedicated shielding mass was progressively reduced and ultimately eliminated
  - Current baseline relies on design and operational reconfiguration of cabin in case of SPE



Radiation Shelter Evaluation

- **2016 Human In The Loop testing in the NASA JSC Orion med-fidelity mockup**

https://www.youtube.com/watch?v=70GrihLXmSs

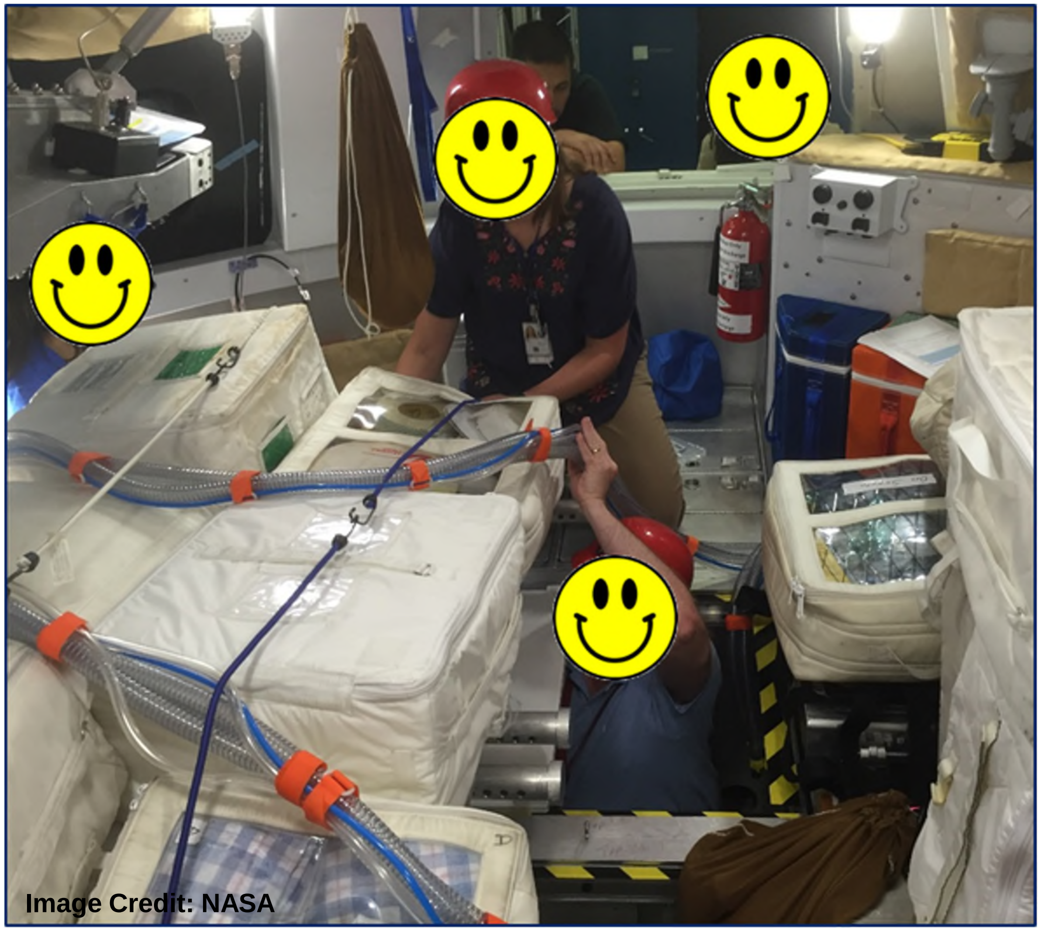
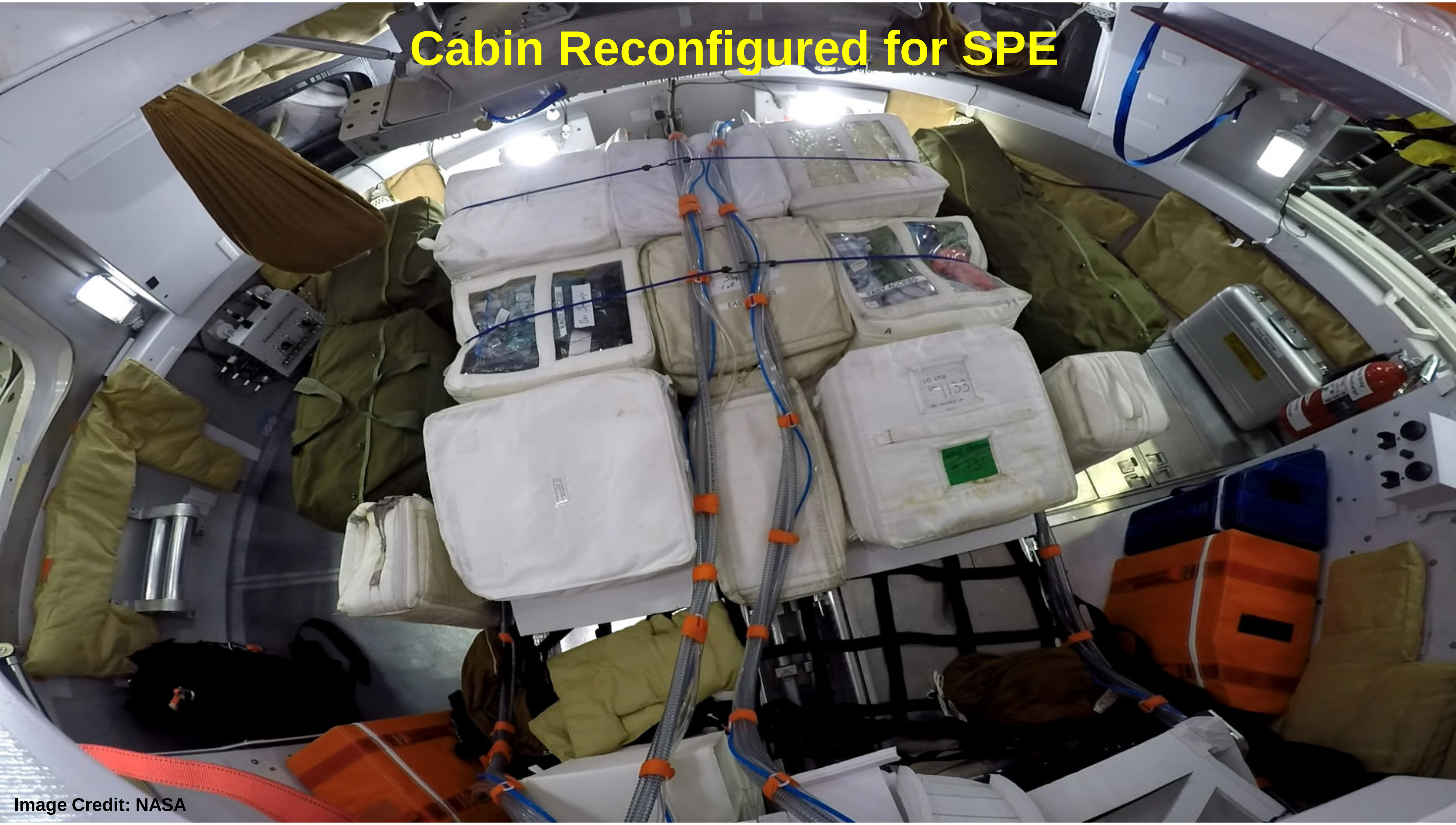


Image Credit: NASA

Image Credit: NASA

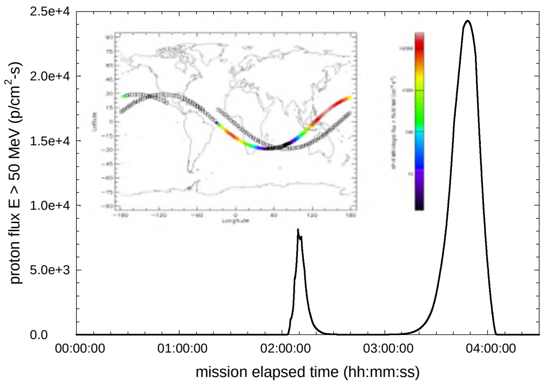
Nominal Cabin Configuration

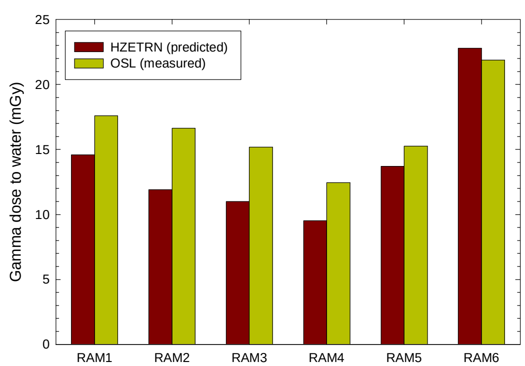
Image Credit: NASA

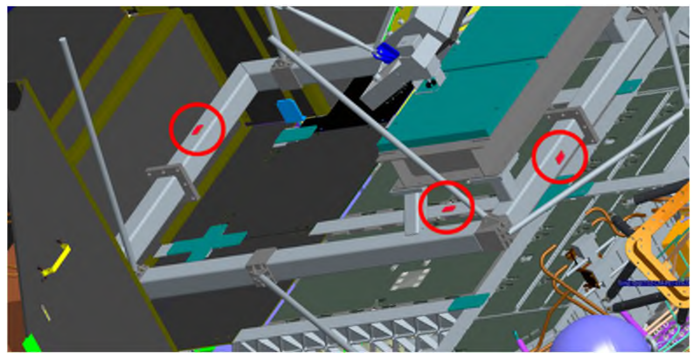

Cabin Reconfigured for SPE
Image Credit: NASA

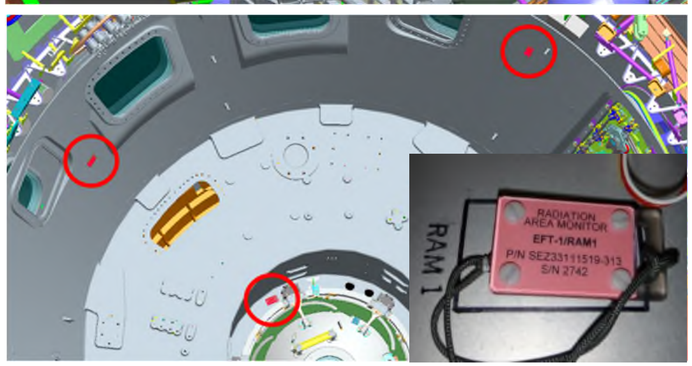
Radiation Analysis Verification by Measurement

- **Exploration Flight Test 1 (EFT-1) opportunity to validate radiation analysis**
  – High energy re-entry trajectory traversed the core of the Van Allen belts
  – Passive (RAMs, OSLDs) and active (BIRD) on-board radiation detectors
  – Measurements correlate well with predictions based on planned trajectory and AP-8 model





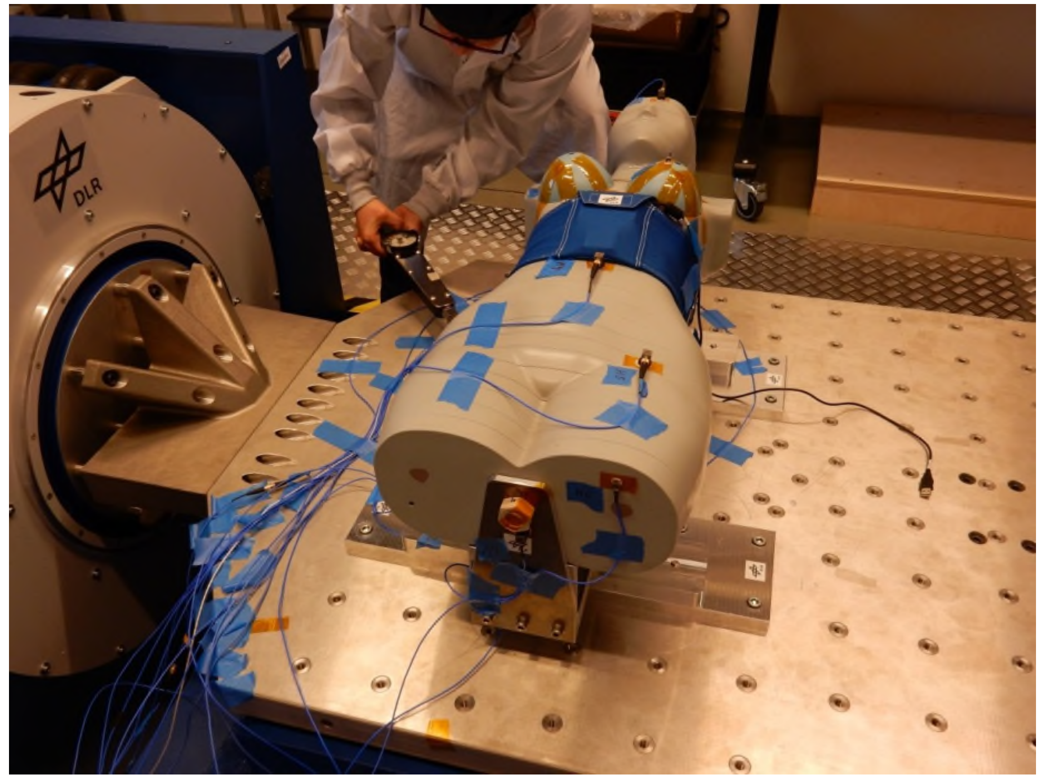




- Dynamic radiation environment
- Radiation transport modeling
- Detector efficiency vs Z/LET
- Body self-shielding
- Internal body dose mapping
- Biological Z/LET susceptibility
- Biological endpoints

Analysis validation continues on future flights toward improved astronaut safety

Vibration Test



Structural Analysis