International Science Aboard Orion EM-1: The Matroshka AstroRad Radiation Experiment (MARE) Payload

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COSPAR 2018

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Presentation Outline

- **Orion background, radiation requirements, and design for ALARA**
- **AstroRad individual radiation shield**
- **Matroshka AstroRad Radiation Experiment (MARE)**

Orion MPCV

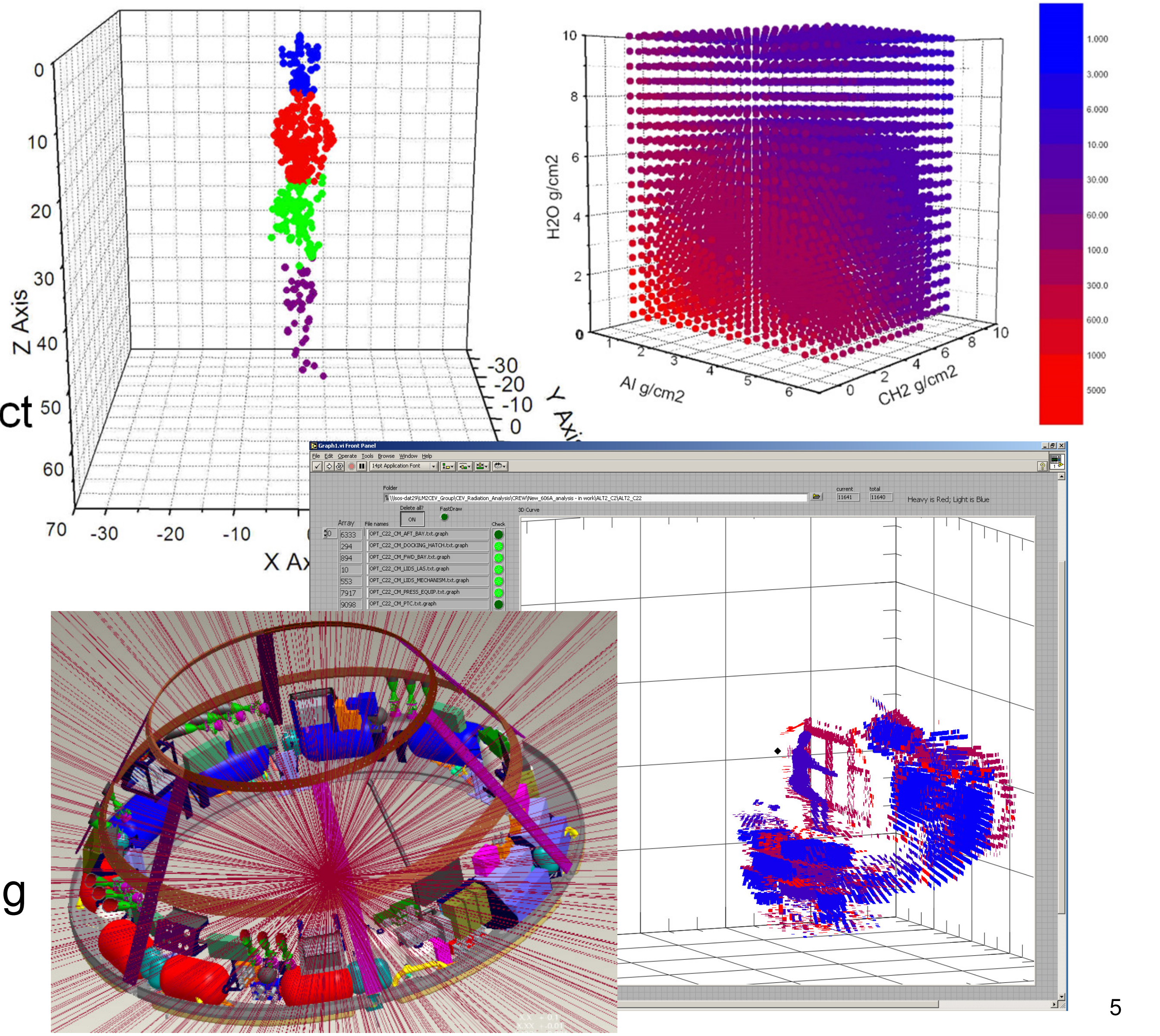
- **The Orion Multipurpose Crew Vehicle (MPCV) is NASA's next generation spacecraft for human exploration of the solar system**
- **Exploration Flight Test 1 (EFT-1) successfully executed December 2014**
  – High eccentricity high altitude orbit to 3600 mi
- **Exploration Mission 1 (EM-1) scheduled 2019**
  – 21-42 days mission to Cis-lunar space
- **Exploration Mission 2 (EM-2) first crewed flight scheduled 2022**
  – Gateway elements (Power and Propulsion Element PPE) will begin launching in 2022

Orion Radiation Requirements

- **Hardware radiation protection (survivability)**
  - "Orion shall meet its functional, performance, and reliability requirements during and after exposure to the mission radiation environment" (Systems Requirements Document SRD)
  - Further decomposed in the Ionizing Radiation Control Plan (IRCP)
- **Crew radiation protection**
  - First NASA spacecraft on which Crew radiation protection is levied as a design driving requirement
  - Human Systems Integration Requirements, Design Specification for Natural Environments
  - Spacecraft design "shall provide radiation protection consistent with ALARA and not to exceed crew exposure of E = 150 mSv for design reference environment"
    - Aug 1972 Solar Particle Event (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

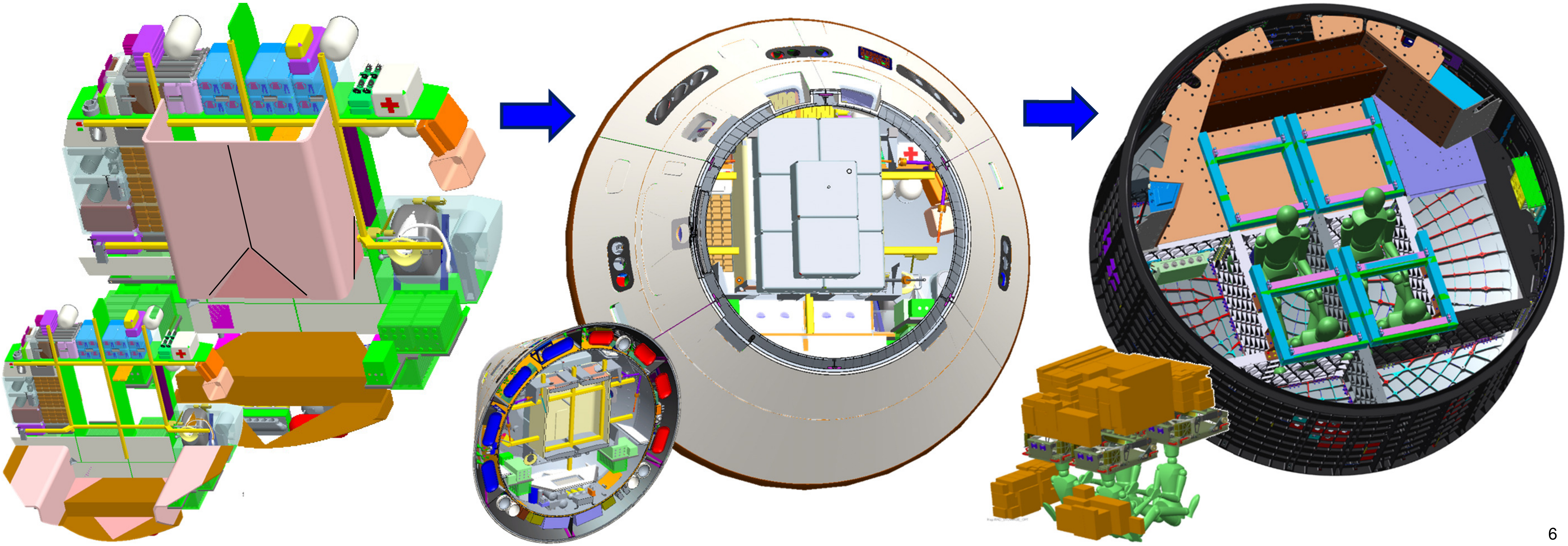
Orion Requirement Verification

- **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)



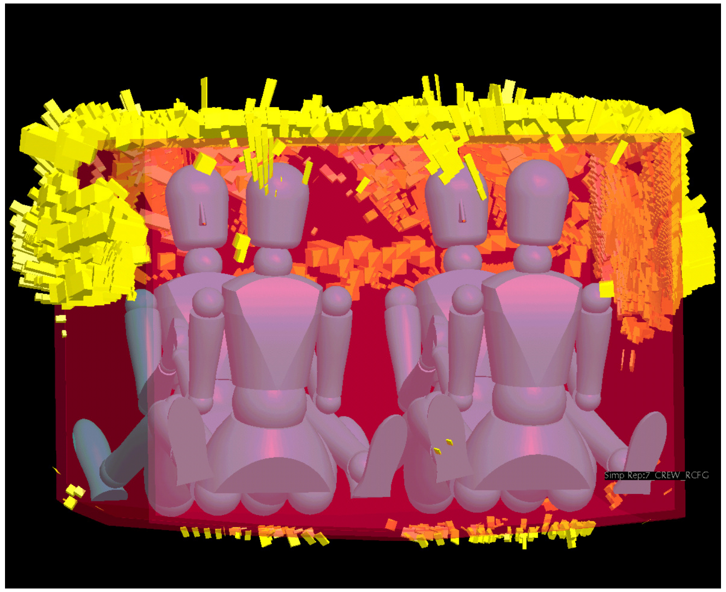
Orion Design for Crew Radiation Protection

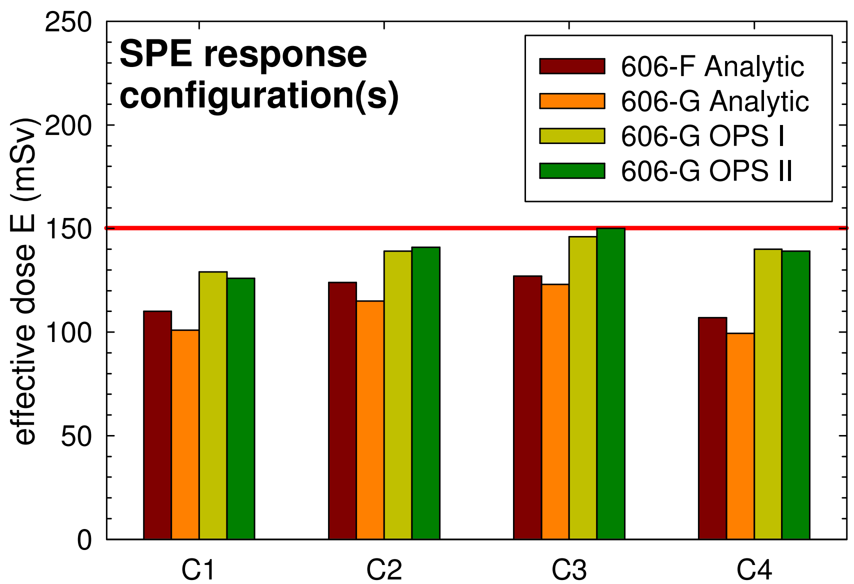
- **Matured throughout the vehicle design**
  - Early in the program MEL included 254 lbm of HDPE radiation shield
  - Dedicated shielding mass was progressively reduced and ultimately eliminated
  - Current baseline relies on operational reconfiguration of cabin in case of SPE

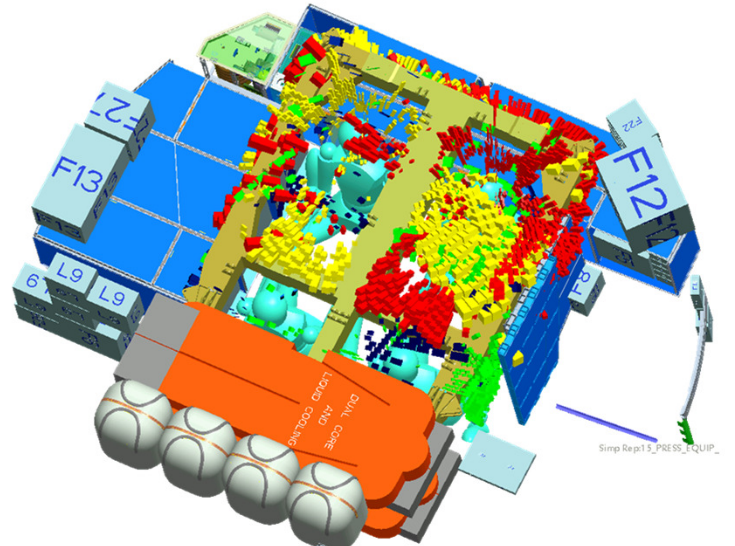


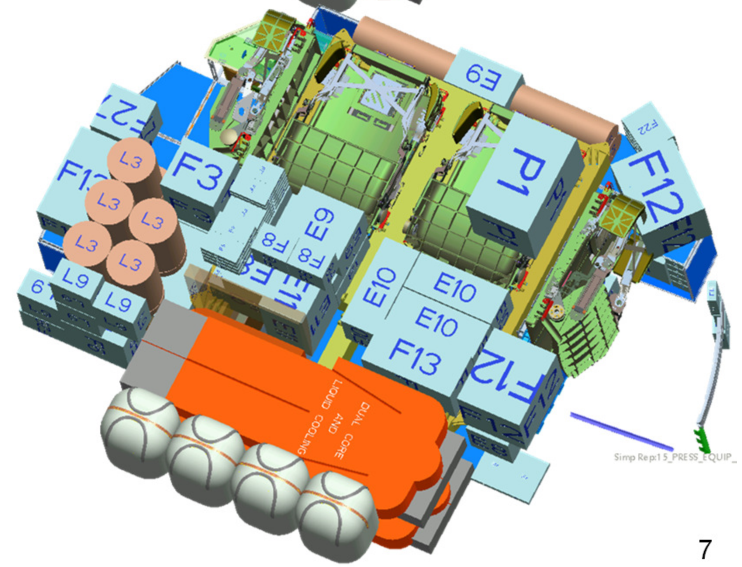
Cabin Configuration Optimization

- **Definition of cabin reconfiguration that maximizes crew radiation protection**
  - 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 Shelter Evaluation

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

Image Credit: NASA

Image Credit: NASA

Cabin Reconfiguration for SPE (nominal)

Image Credit: NASA

Cabin Reconfiguration for SPE (reconfigured)

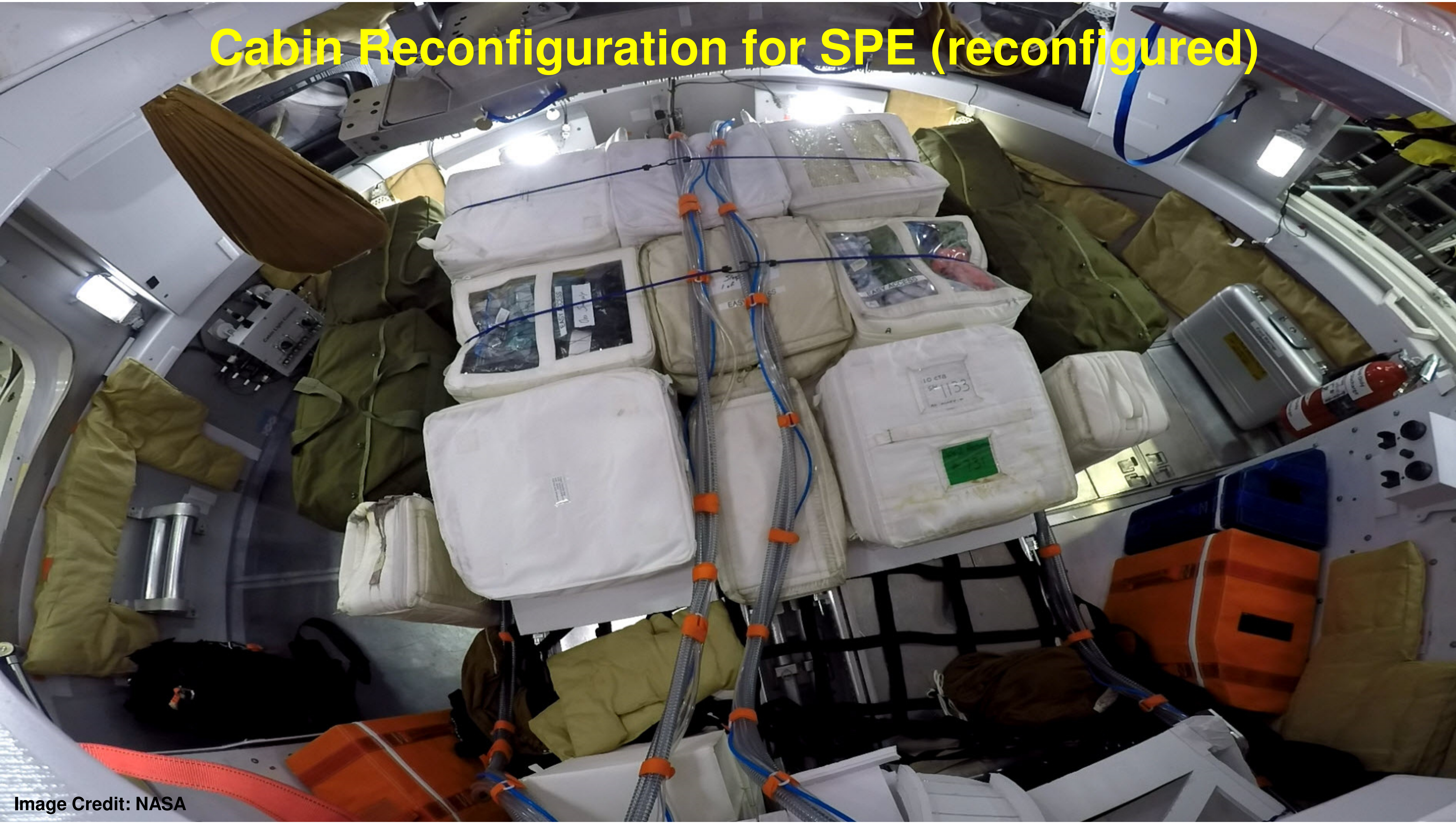
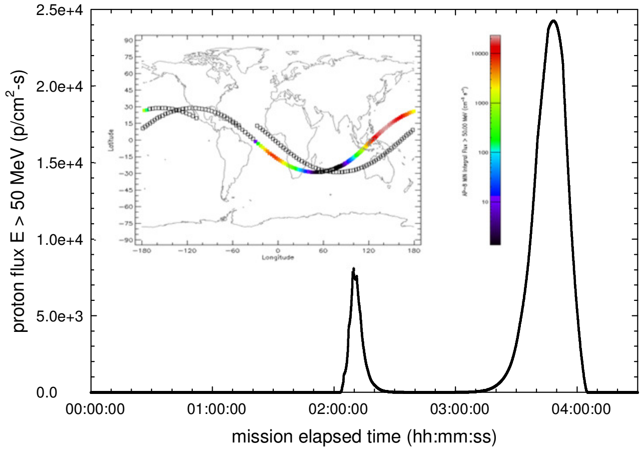
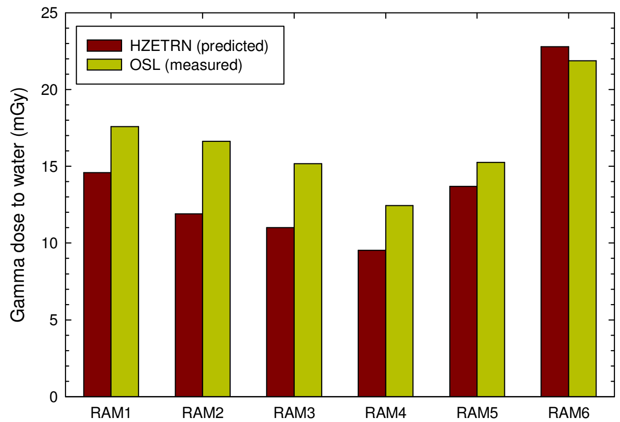


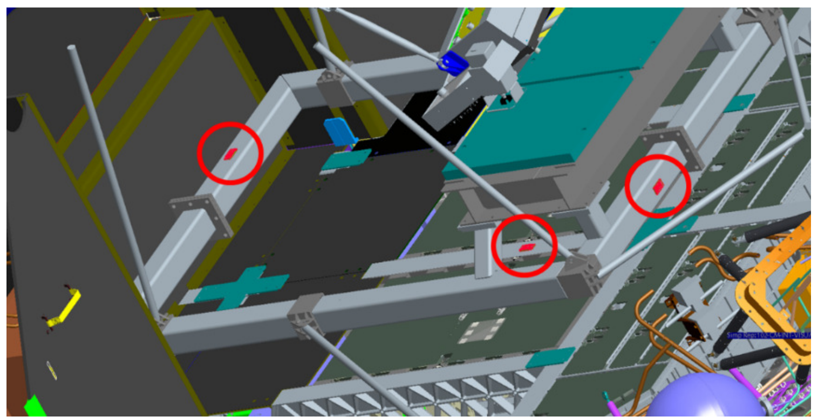
Image Credit: NASA

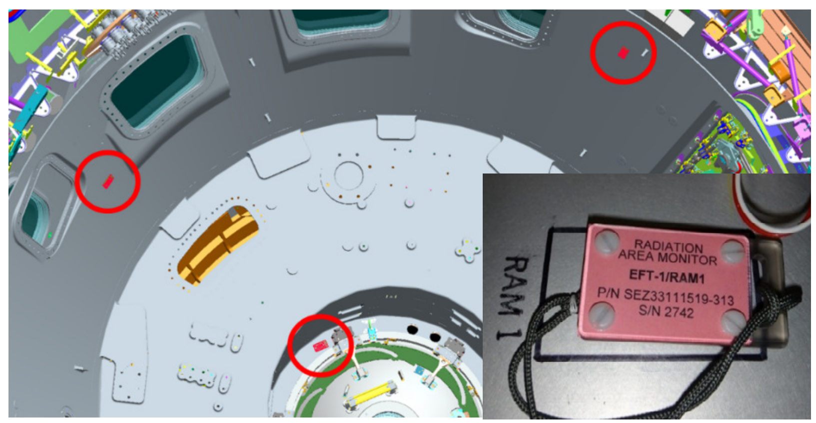
Radiation Analysis Verification by Measurement

- **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 (GFE RAMs, EDC OSLDs) and active (GFE 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

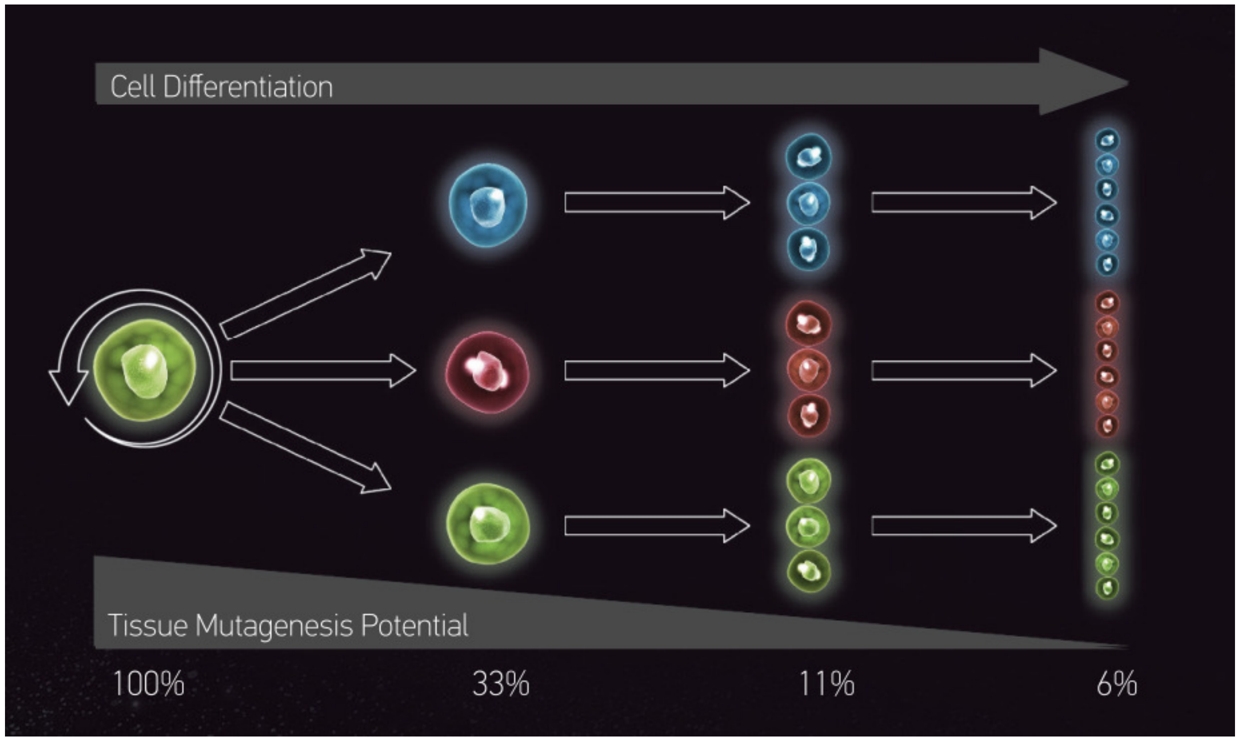
Analysis validation continues on future flights toward improved astronaut safety

Radiation Vest for Astronauts: AstroRad

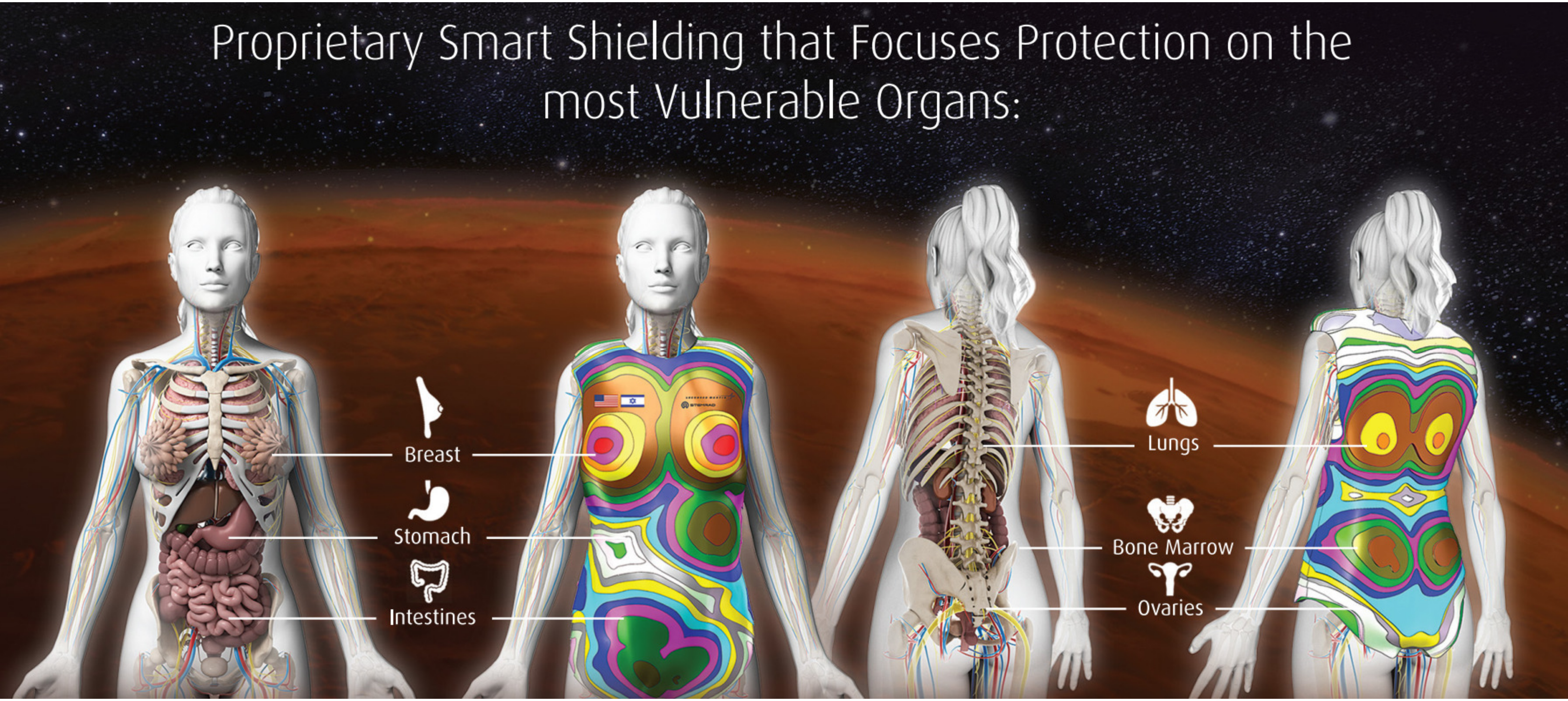
SPACE FLORIDA

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 planned aboard International Space Station

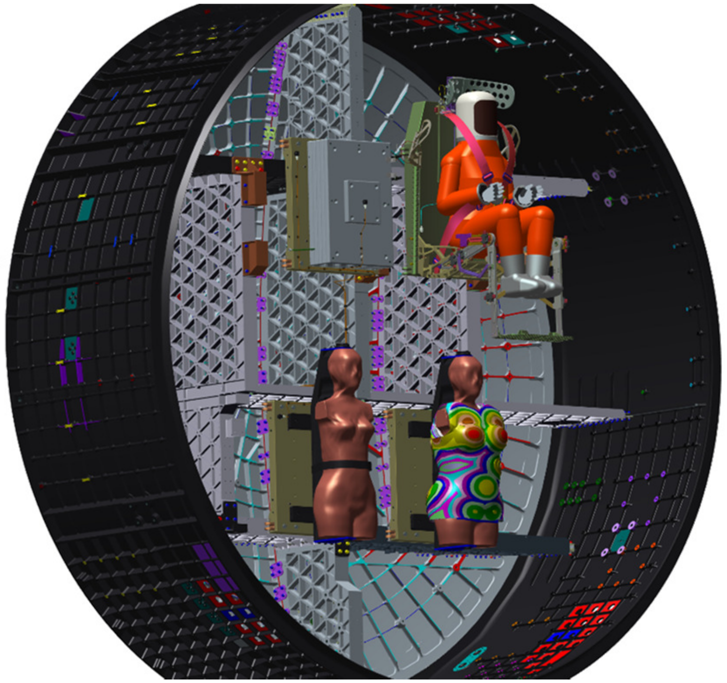


AstroRad


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

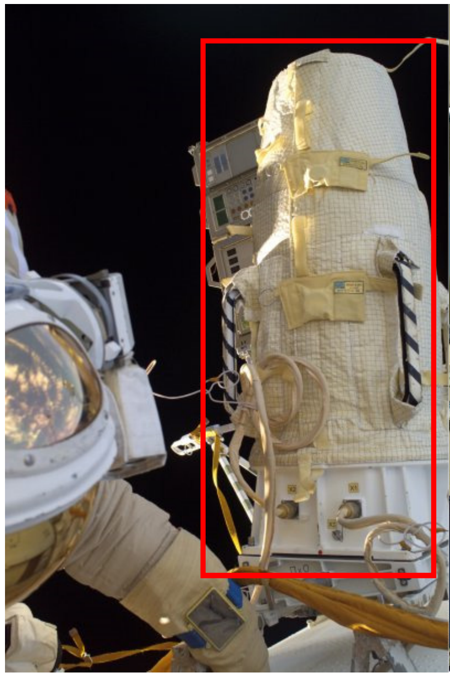
Matroshka AstroRad Radiation Experiment (MARE)

- **Lockheed Martin invited feedback as part of Orion radiation protection efforts**
  - Interest was expressed in continuation & scope expansion of the ISS MATROSHKA experiment on board the Orion vehicle
  - Resulted in the Israel Space Agency (ISA) and the German Aerospace Center (DLR) proposing the Matroshka AstroRad Radiation Experiment (MARE)
  - MARE has been approved by NASA in May 2017 and is currently manifested as an international science payload aboard the EM-1 flight.
  - MARE consists of two tissue-equivalent radiation phantoms
  - Positioned inside the Orion cabin at seat 3 & 4 locations
  - One phantom is fitted with the StemRad-manufactured AstroRad vest
  - Both phantoms are fitted with both active and passive radiation detectors
  - 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 Orion's vehicle

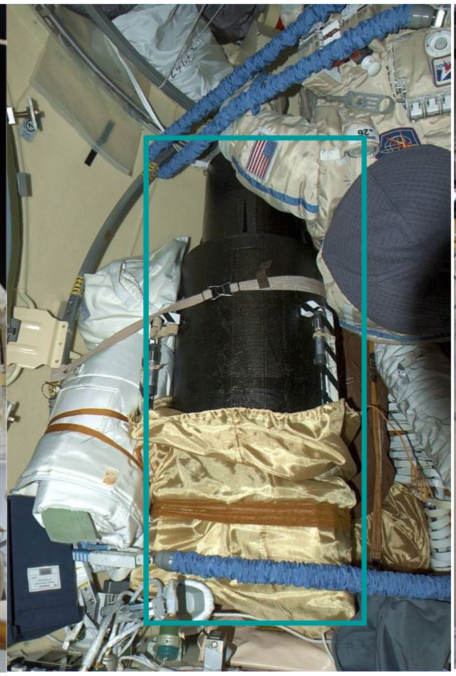


ISS Matroshka

- **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.



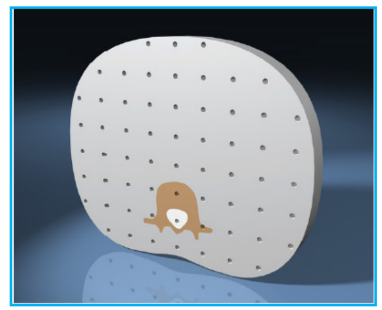
MTR-1 539 days (2004–05)



MTR-2A 337 days (2006)

MTR-2B 518 days (2007–09)

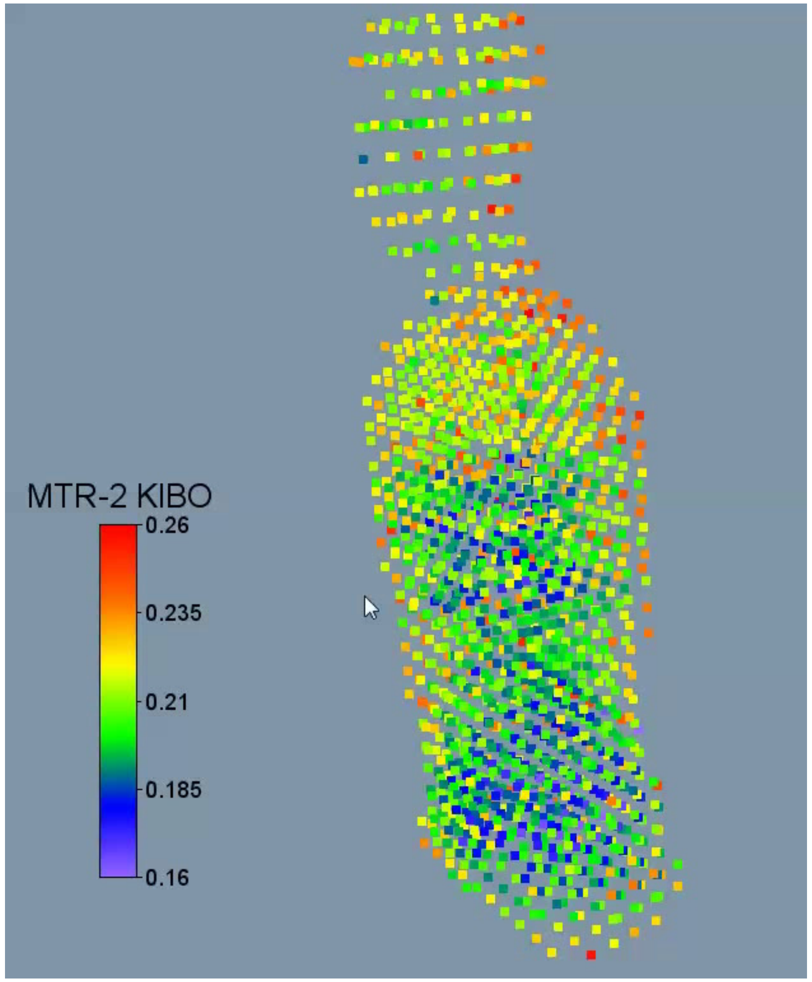
MTR-2 KIBO 310 days (2010–11)

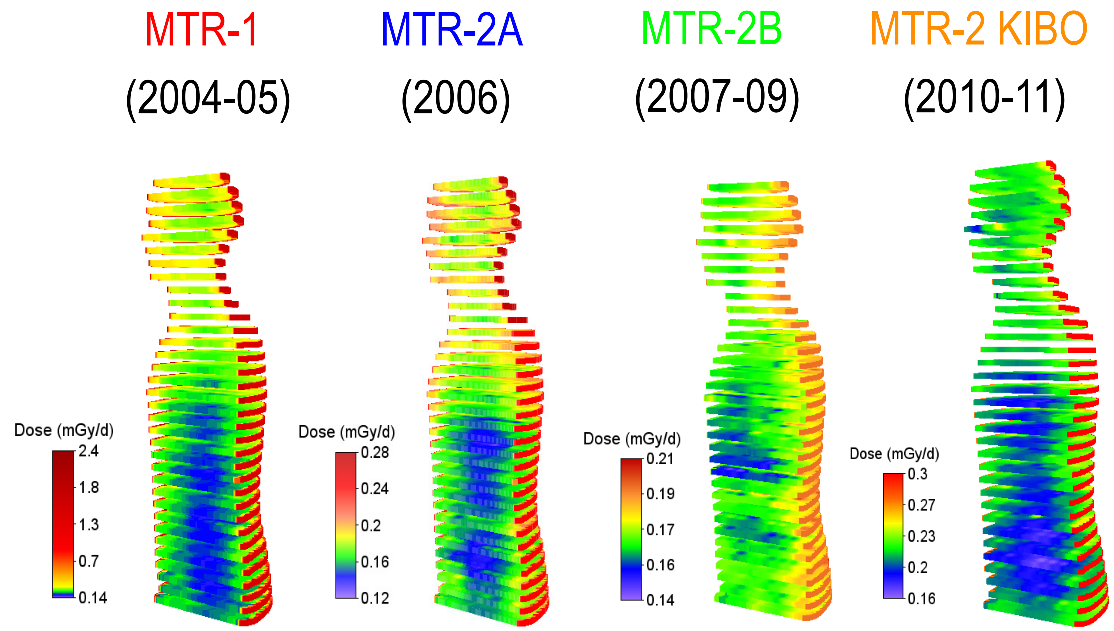


http://www.cirsinc.com/file/Products/701_706/701%20706%20ATOM%20PB%20050418.pdf

DLR

ISS Matroshka





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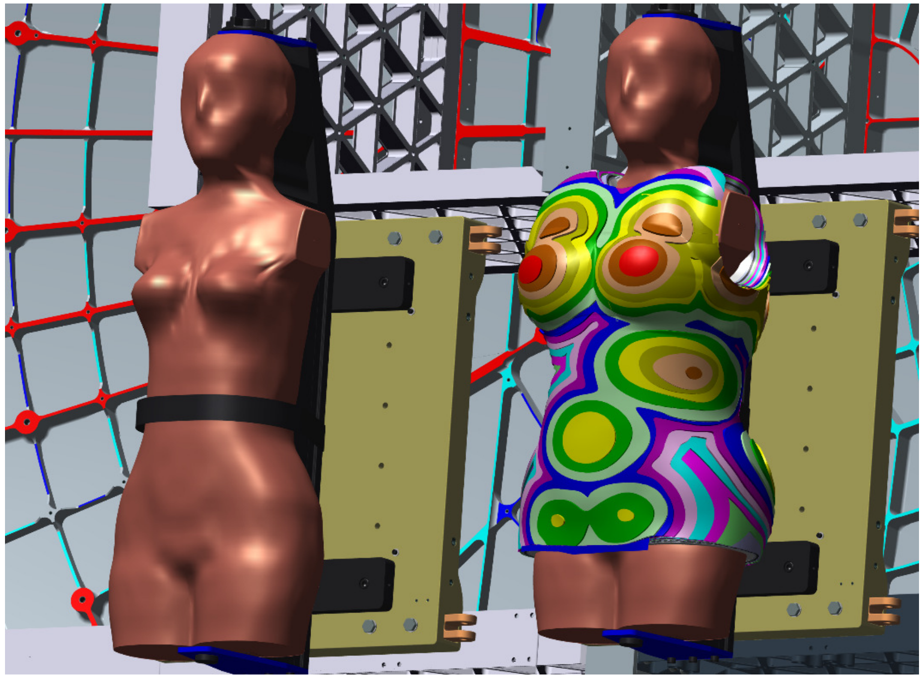
- Zhou, D., Semones, E., O'Sullivan, D., Zapp, N., Weyland, M., Reitz, G., Berger, T., Benton, E.R. Radiation measured for MATROSHKA-1 experiment with passive dosimeters. Acta Astronautica (2010), 66, 301 – 308
- Reitz, T. Berger *et al*., Astronaut's organ doses inferred from measurements in a human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

MARE Aims and International Participation

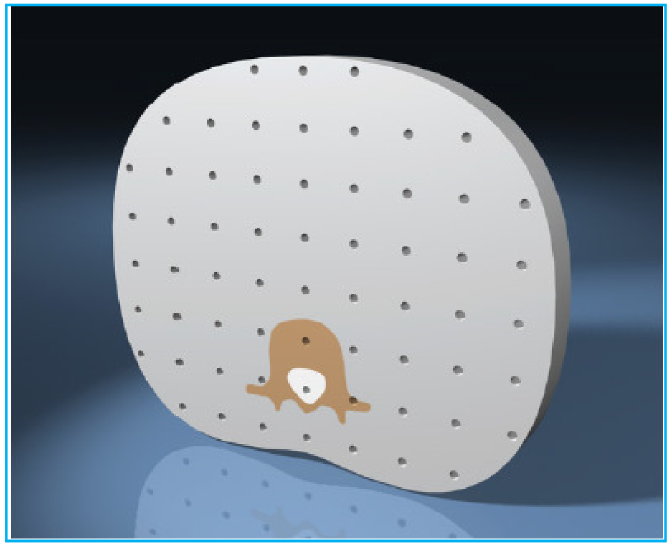
- **Experiment Aims:**
  - To perform radiation measurements that help refine risk projections
    - Skin- and internal body organs dosimetry
    - During Van Allen belt transit & in cis-lunar space
    - Intravehicular environment specific to Orion
  - To validate the protection provided by AstroRad
  - To expand the ISS MATROSHKA international participation
  - Demonstration of science opportunities aboard Orion

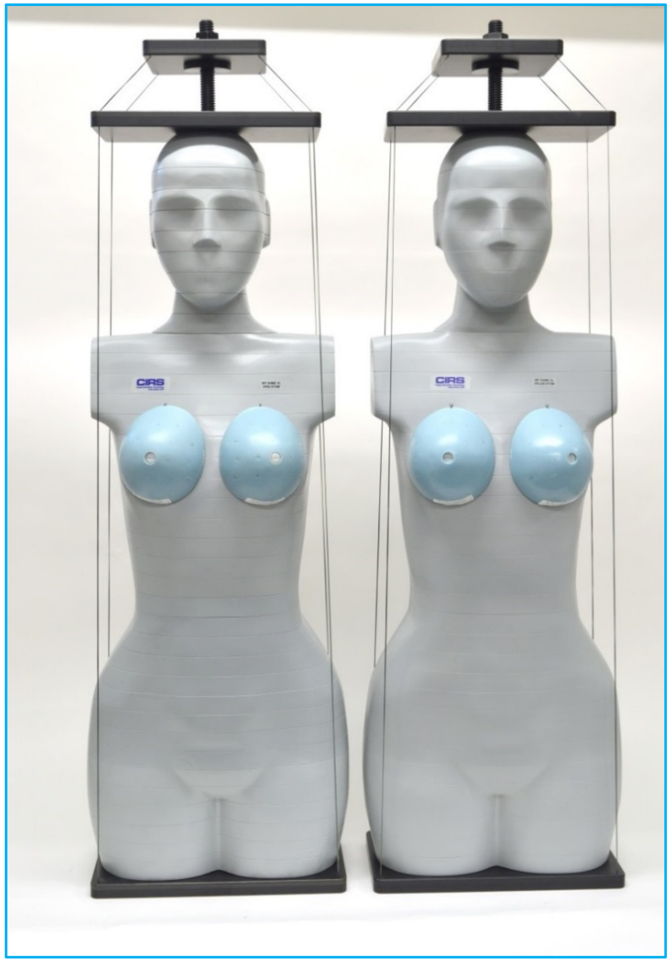


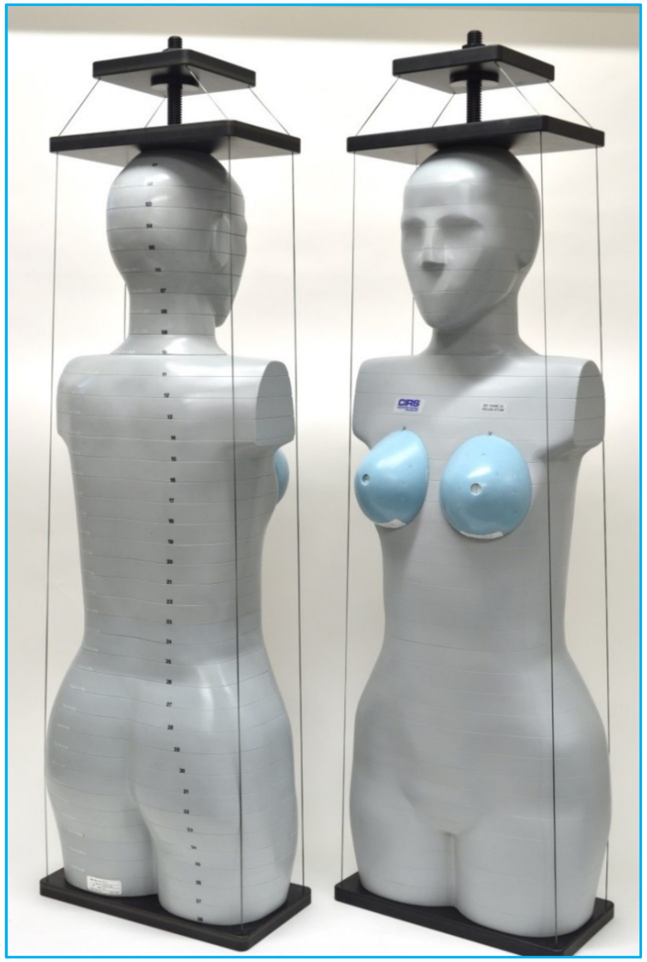
- **International Participation:**
  - One phantom provided by DLR, one by ISA.
    - AstroRad provided by ISA
    - Installation bracketry provided by DLR
  - Most radiation detectors are provided by DLR and NASA
  - Additional baselined detectors by DOSIS 3D community and the European Space Agency
  - Exploring addition of detectors from the Canadian Space Agency / BTI, and Thessaloniki University Greece

MARE: CIRS Phantoms

- **ATOM® 702 Female model**
  - Avis 36.42 kg / Helga 36.48 kg
  - Tissue equivalent material
  - Artificial bone
  - 38 slices with TLD/OSLD holes
    - 3 cm custom grid



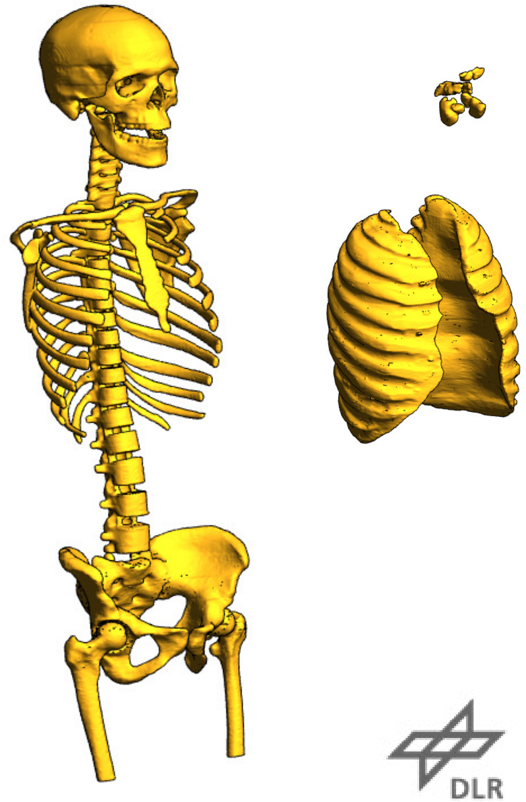


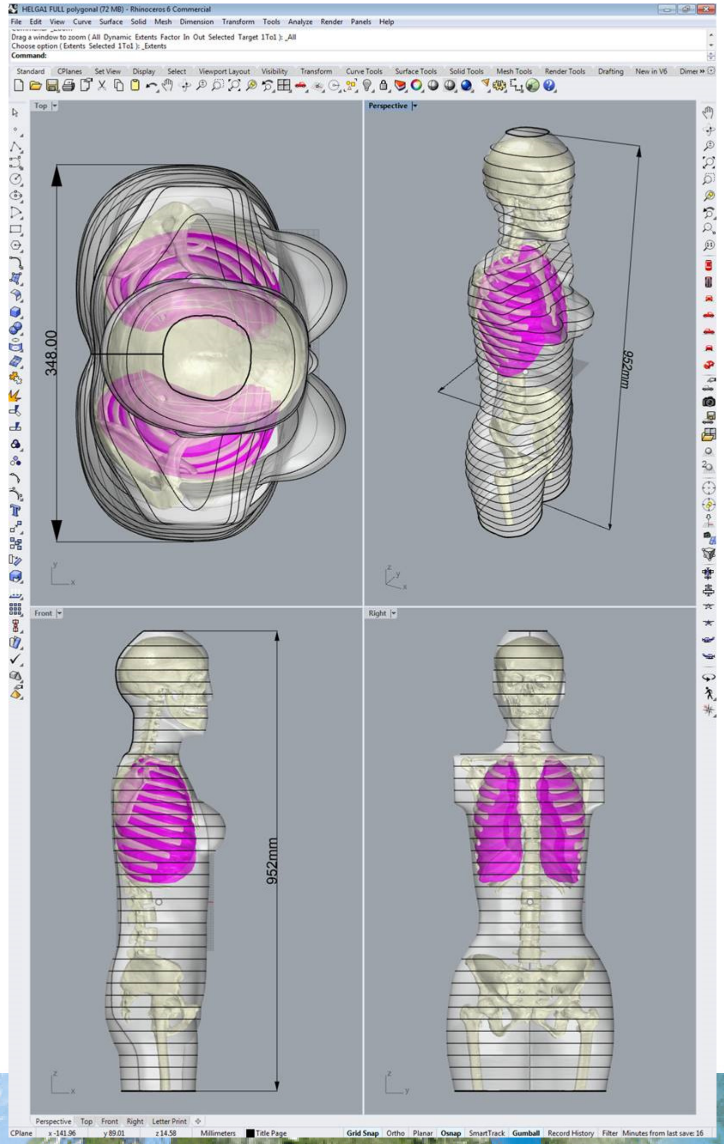


http://www.cirsinc.com/products/modality/33/atom-dosimetry-verification-phantoms

MARE: CIRS Phantoms Internal

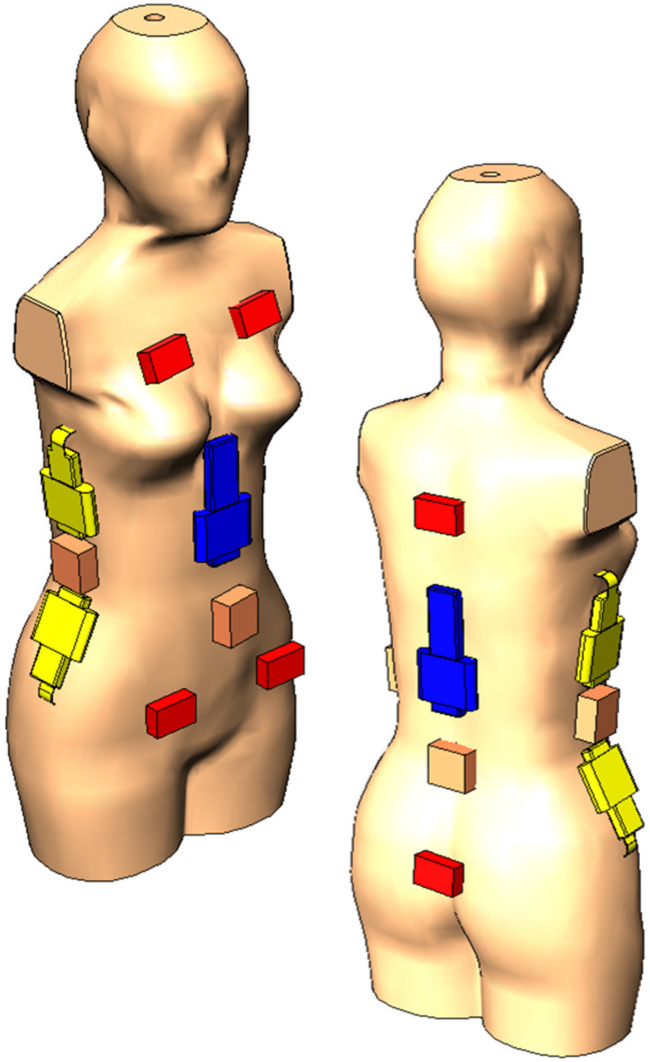
- **CT scan performed on each phantom**
- **CT scan data are used to generate CAD models**
- **CAD models are used for AstroRad vest customization and radiation analysis**



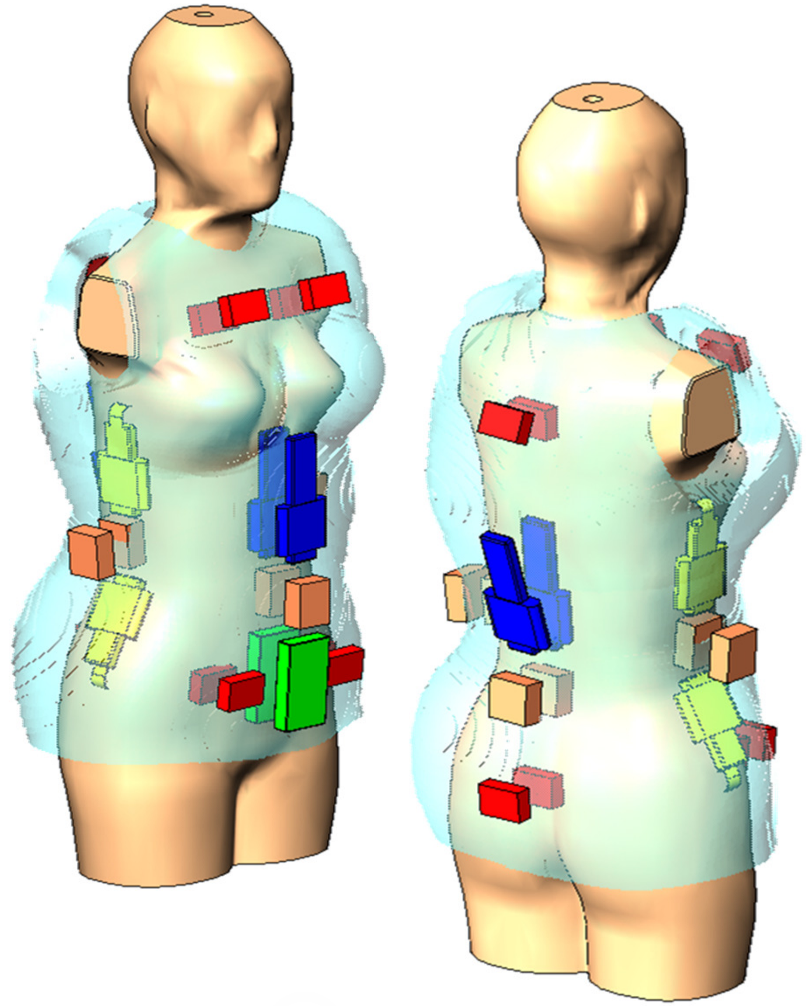


MARE Baselined Radiation Detectors

- **Radiation Detectors Overview: Actives & PDP**



# 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

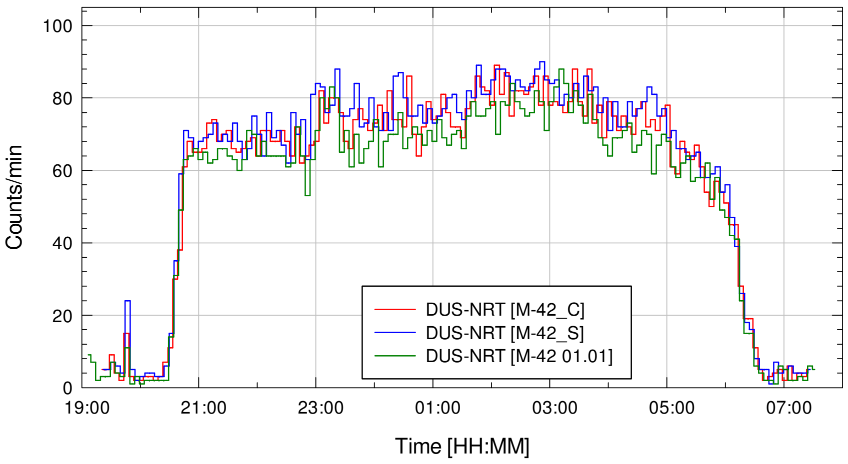


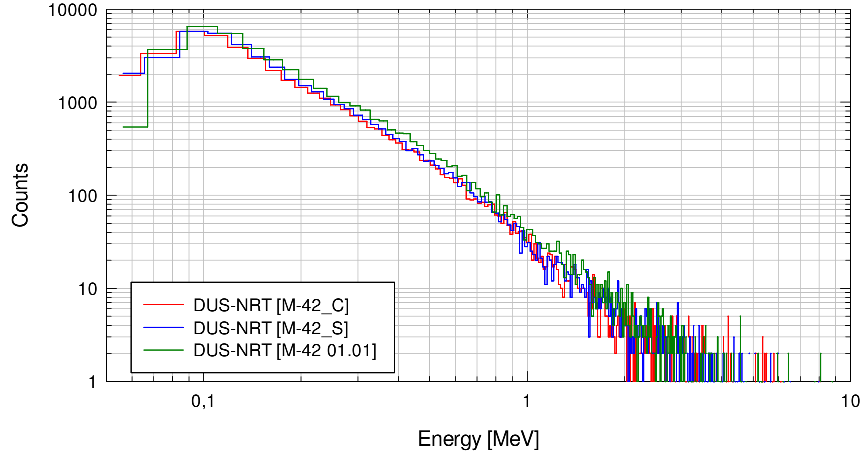
DLR M42

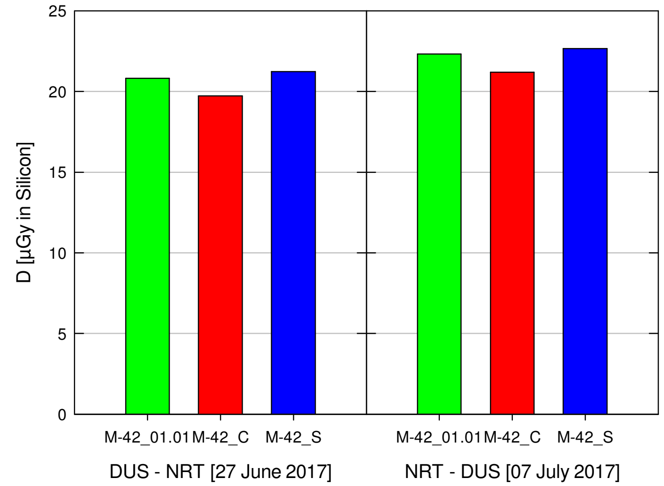
- **Silicon Detector**
- **Mass: 108-120 g**
- **1 cm^2 area, 300 µm thickness**
- **Energy range 0.06-20 MeV (Si)**
- **1024 channels**
- **Autonomous operation**
  - Launch detection (accelerometer)
  - Run time > 42 days
- **Two versions**
  - Compact
  - Split

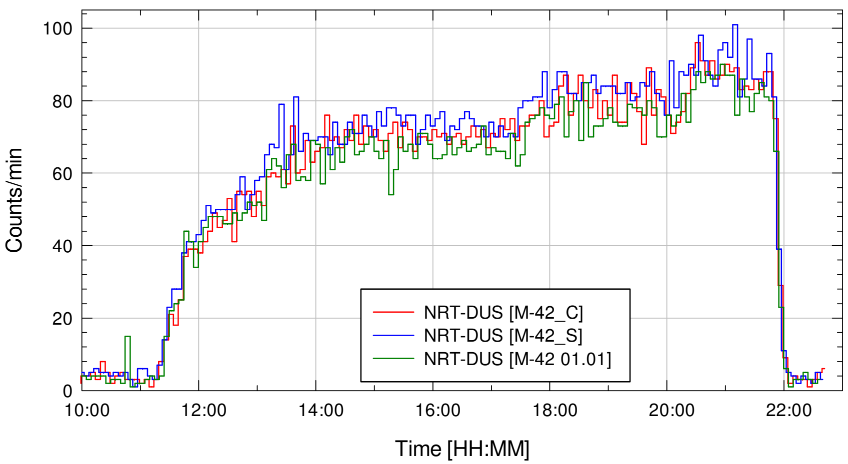
DLR

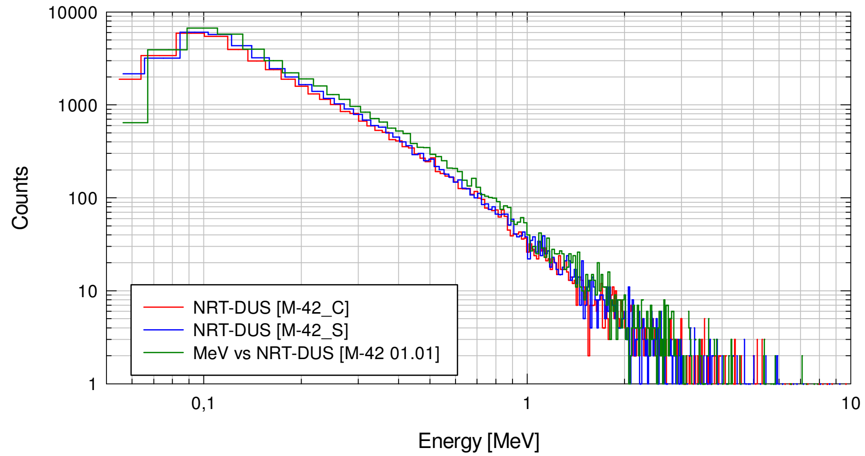
DLR M42 DUS-NRT and return







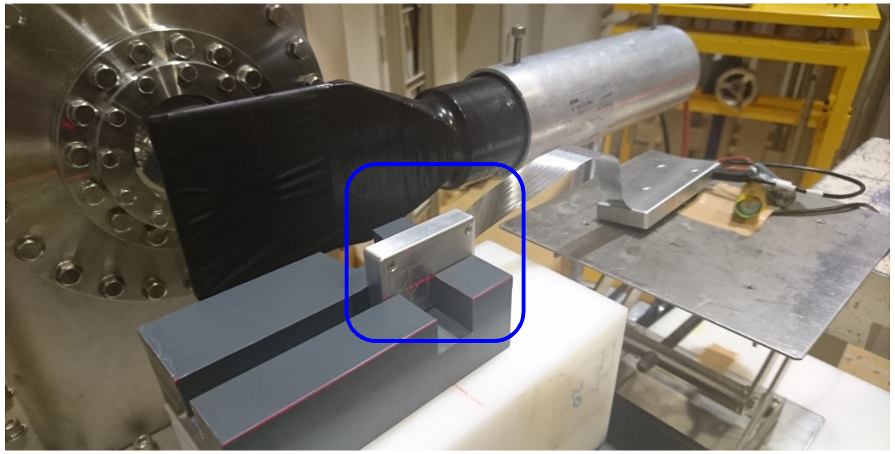


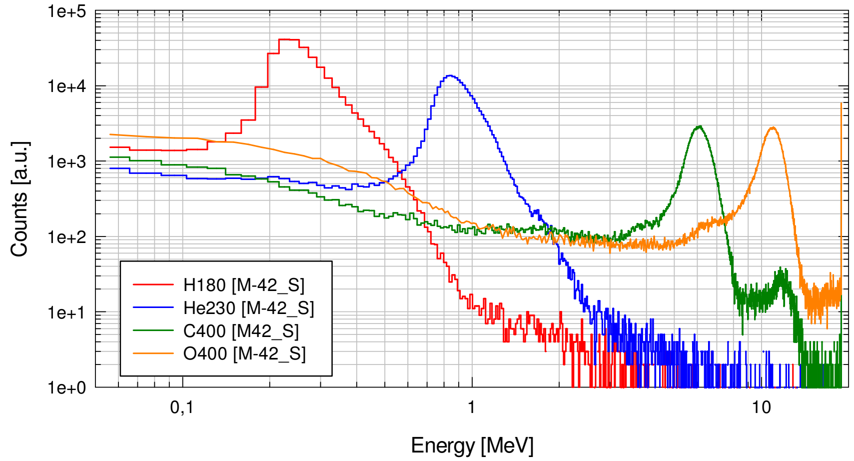


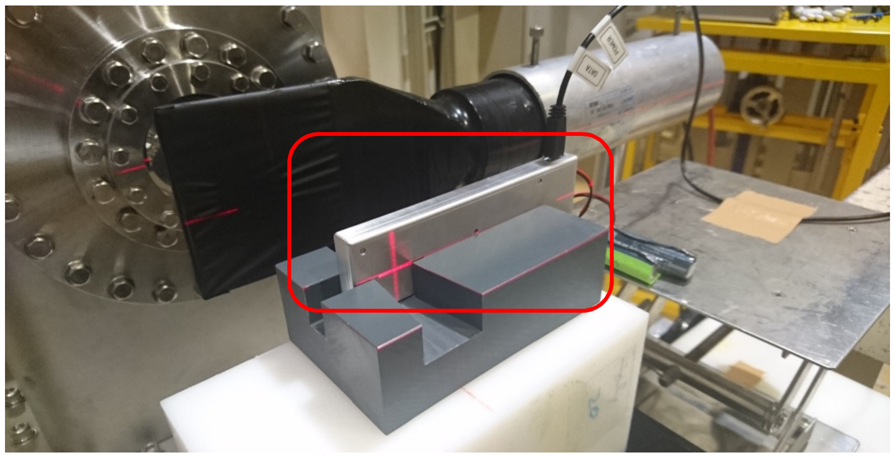
DUS-NRT: 20.56 ± 0.78 µGy in Si
NRT-DUS: 22.07 ± 0.77 µGy in Si

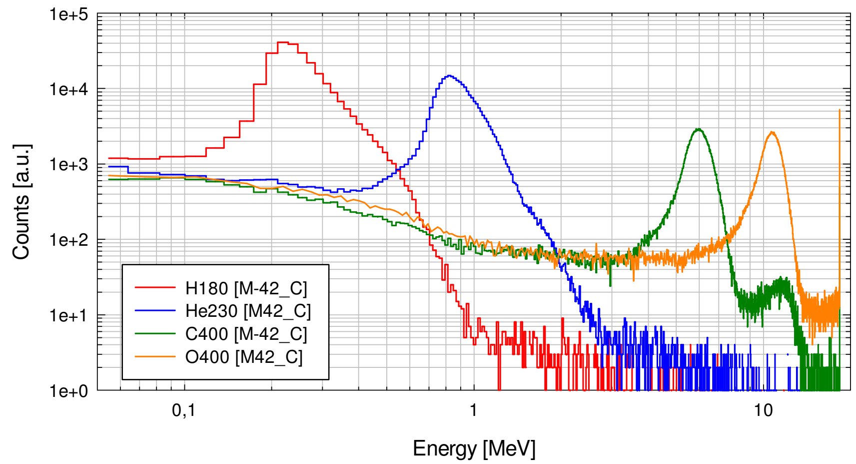
DLR M42 HIMAC Exposure

HIMAC Research Project 17H374



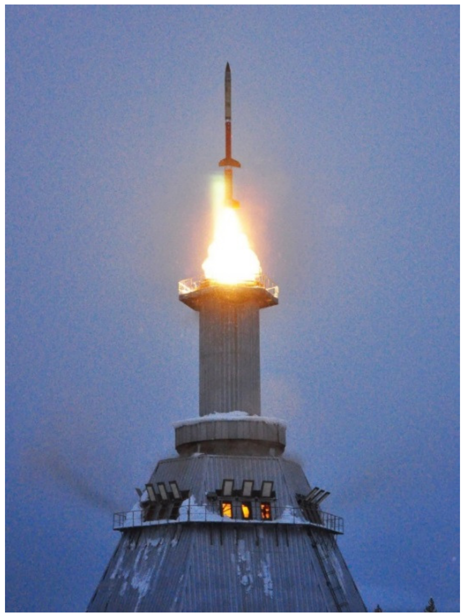


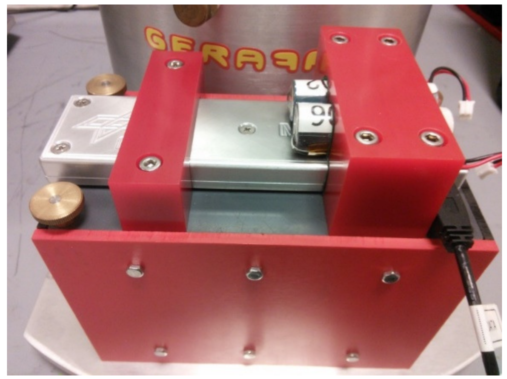


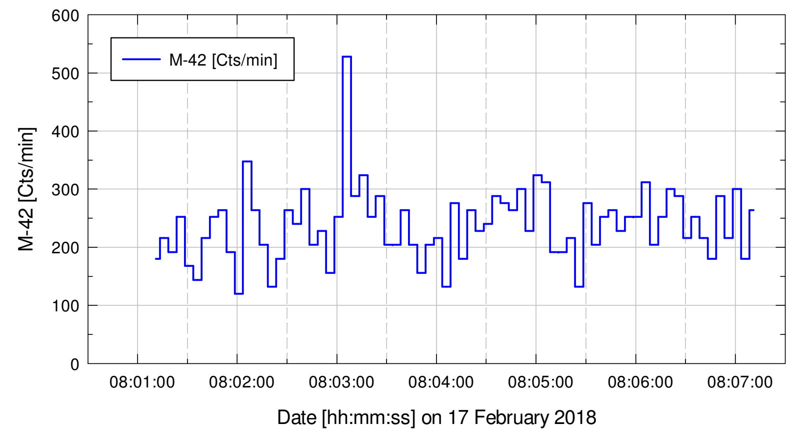


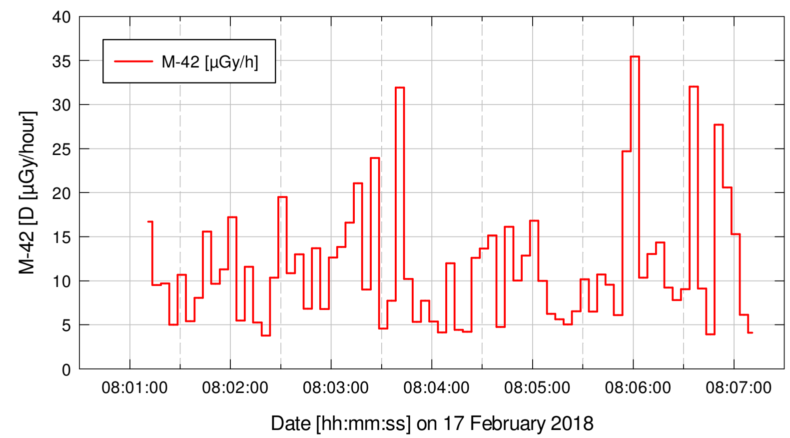
DLR M42 MAPHEUS testing

- **MAPHEUS is a 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









DLR

NASA CPAD

- **Crew Personal Active Detector**
- **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**
- **Variable storage rate, no load detector needed**
- **ISS Tech Demo currently in progress**

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

DLR

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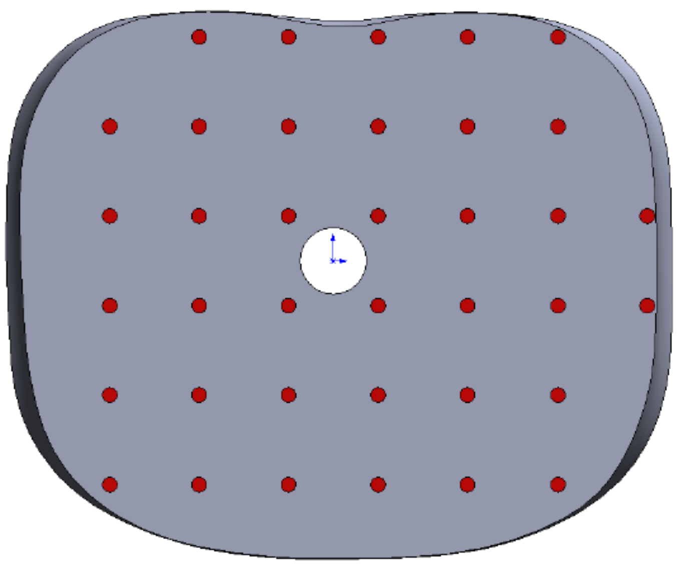
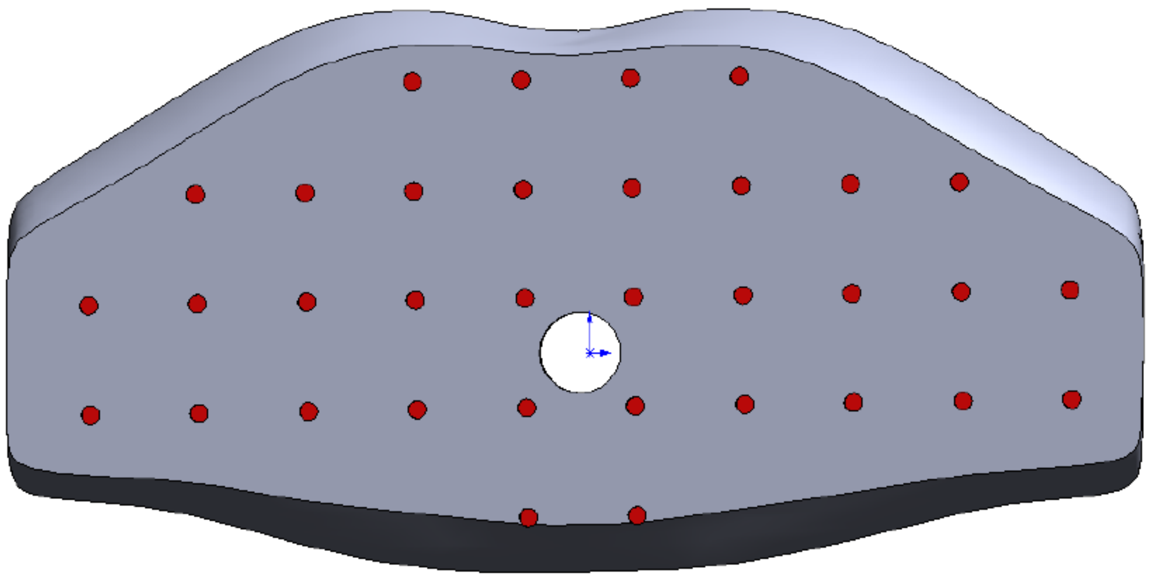
SCK•CEN
Nuclear Physics Institute of the CAS public research institution
OKLAHOMA STATE UNIVERSITY
NIRS
NASA

Phantom Embedded Dosimeters

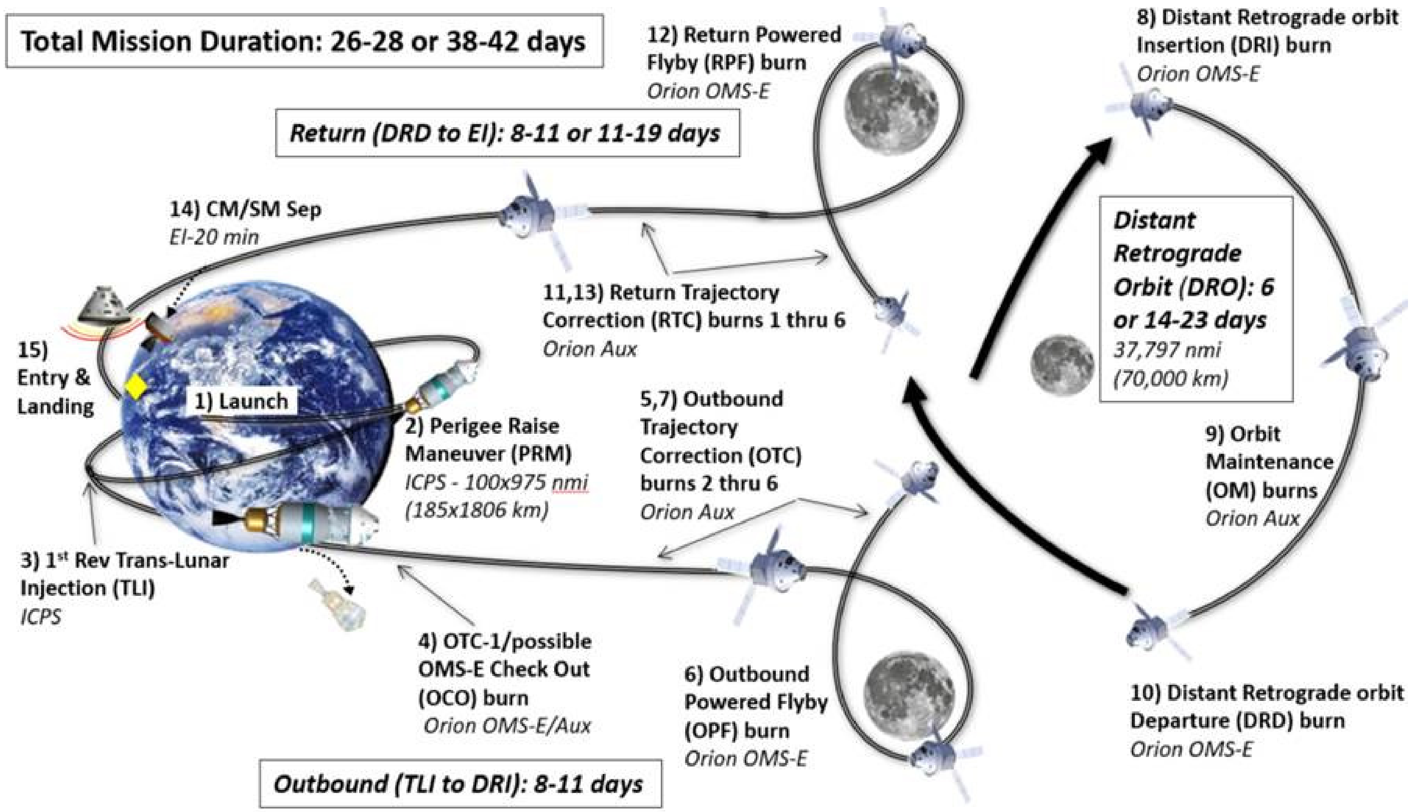
- **Passive dosimeters located on the phantoms grid**
  - 6000 TLDs provided by DLR (750 measurement points/phantom, 4 TLDs/measurement point
  - 2000-3000 TLDs/OSLDs provided by NASA JSC (1000-1500 /phantom)
  - 10 organ point passive dosimeter packages provided by DLR (5 /phantom)
    - Containing TLDs and CR-39 PNTDs

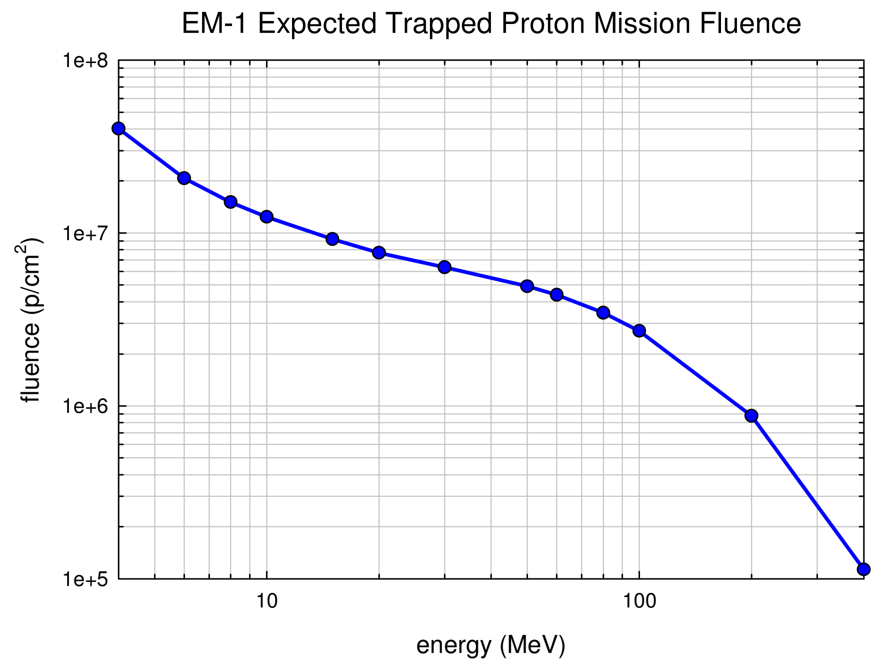




Exploration Mission 1 (EM-1)

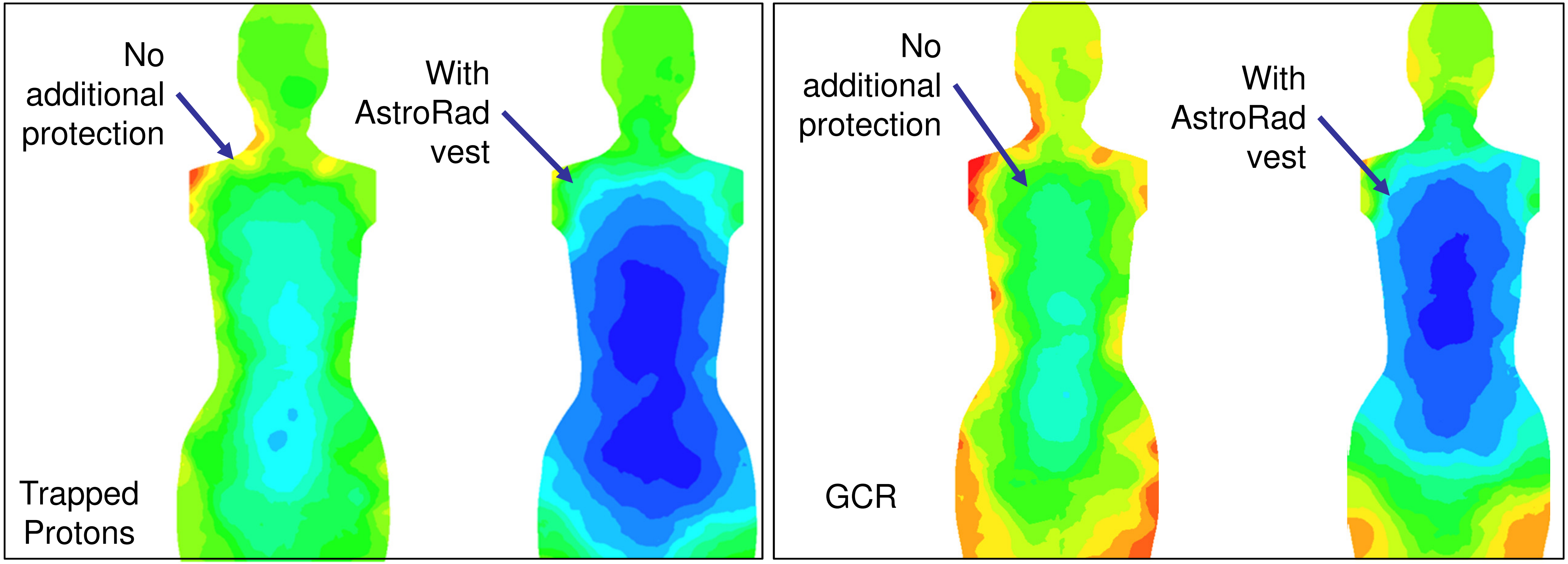
- **First Orion test flight beyond Earth orbit scheduled for 2020**
  - Uncrewed flight on Distant Retrograde Lunar Orbit (DRO)
  - Trapped protons, GCR, possibly SPE





Preliminary MARE exposure projections

- **MARE at relevant locations inside Orion vehicle. Limitations:**
  - Conceptual Flight Profile
  - Solid phantom of constant density / material
  - Preliminary AstroRad design
  - Time resolved measurements from active detectors to separate environment contributions



Path Forward

- **International collaboration framework**
- **MARE System Requirements Review**
  - Validation of design requirements
- **Payload integration design and verification efforts**
  - Safety certification
  - Design reviews
- **Dose projections refinement**
- **Late stow vehicle installation**
- **Post-flight data processing, consolidation and publication**

Conclusion

- **MARE is among the first Orion payloads**
- **Benefits from large international collaboration support**
- **Example of science research opportunities on board Orion as the first Exploration architecture component**

Our goal is to improve astronaut safety and enable Exploration