Orion Artemis 1 Internal Environment Characterization: The Matroshka AstroRad Radiation Experiment

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2019 WRMISS

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Presentation Outline

- **Orion**
- **AstroRad**
- **ISS Matroshka**

- **Matroshka AstroRad Radiation Experiment (MARE) on Artemis 1**

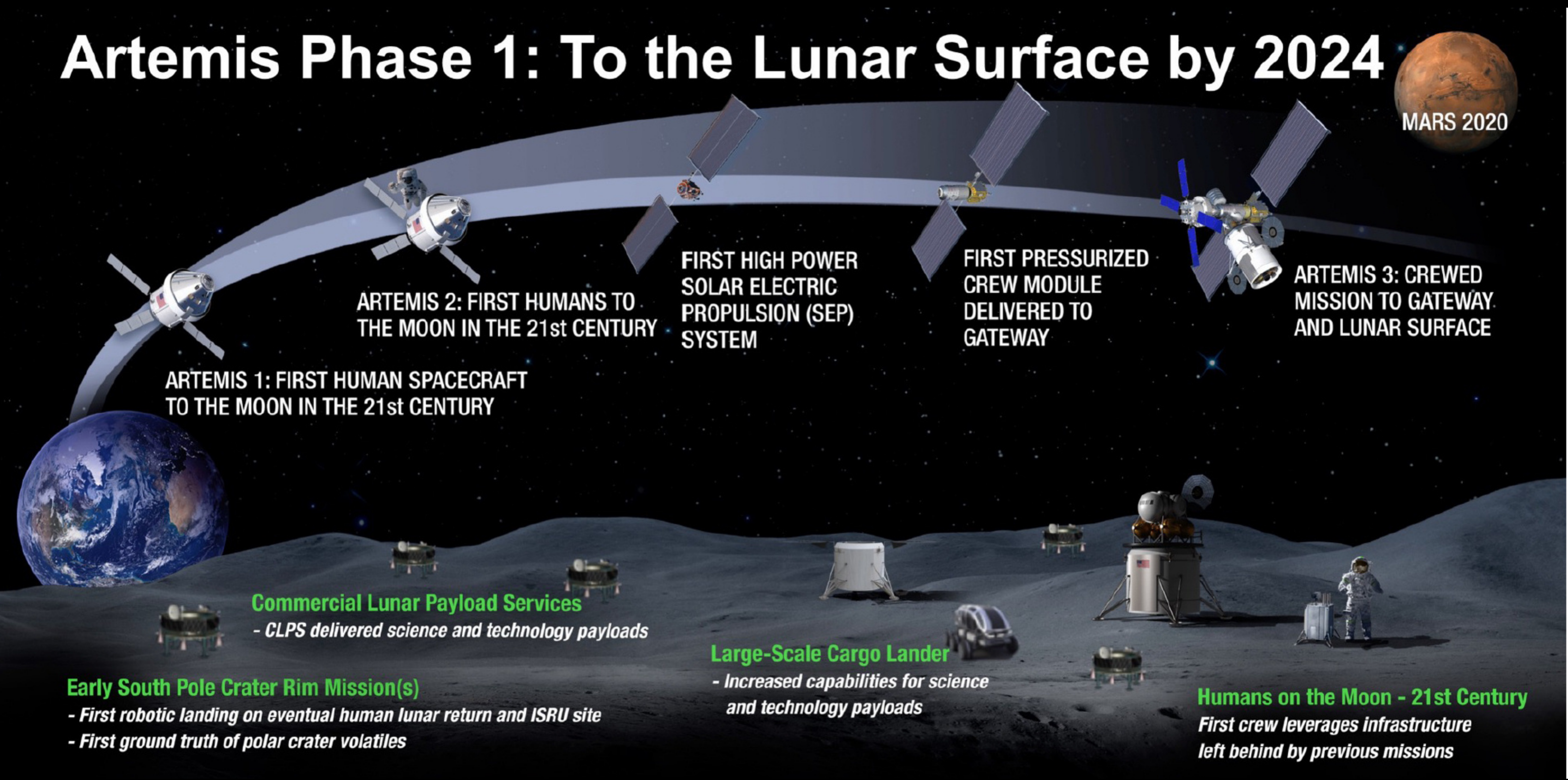
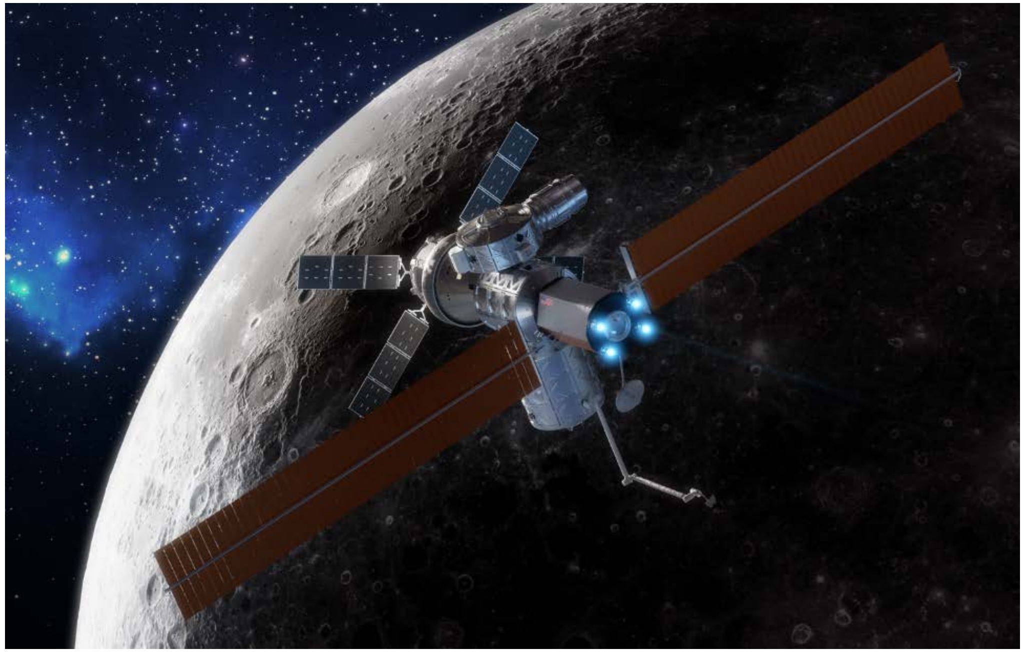


Image credit: NASA

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
- **Artemis 1 is scheduled for 2020**
  – Formerly referred to as Exploration Mission 1 (EM-1)
  – 21-42 days mission to Cis-lunar space
- **Artemis 2 is scheduled for 2022**
  – First crewed flight
- **First Gateway element also scheduled for 2022**
  - Power and Propulsion Element PPE
- **Artemis 3 is scheduled for 2024**
  – First crewed mission to the lunar surface

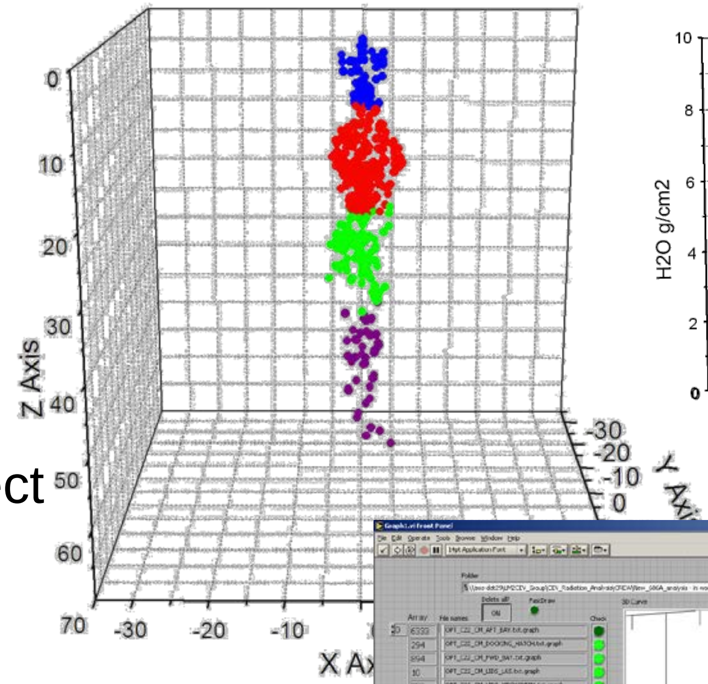


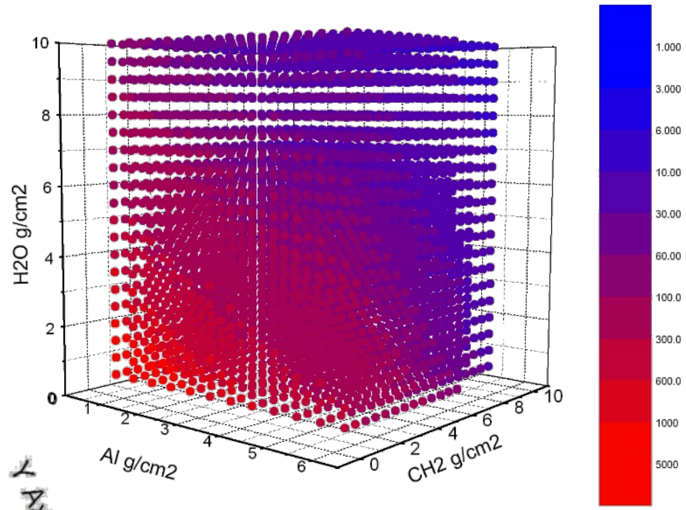
Orion Ionizing Radiation

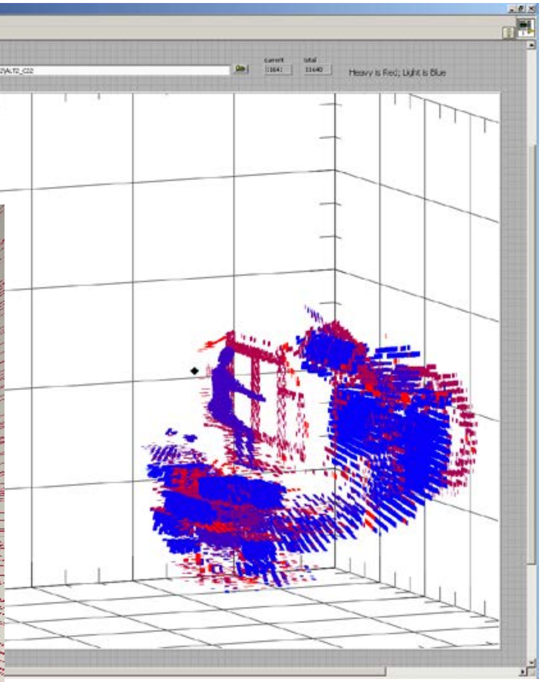
- **Orion spacecraft design requirements address both electronic systems (e.g., avionics) and crew protection**
  - First NASA human spacecraft to implement an Ionizing Radiation Control Plan (IRCP)
    - Systematic decomposition of SRD high level requirement “Orion shall meet its functional, performance, 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

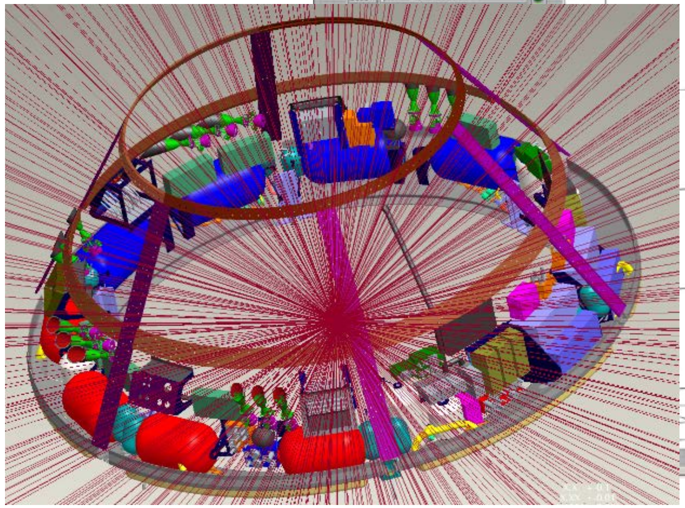
Orion Requirement Verification

- **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)



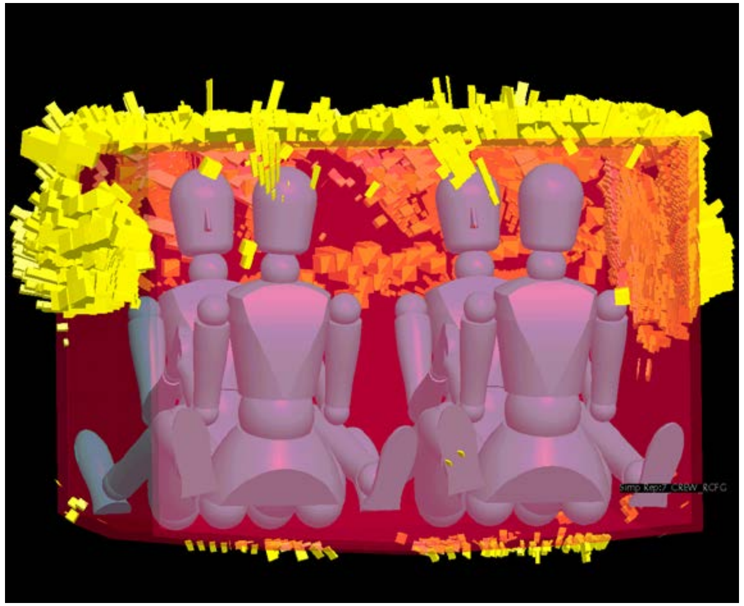


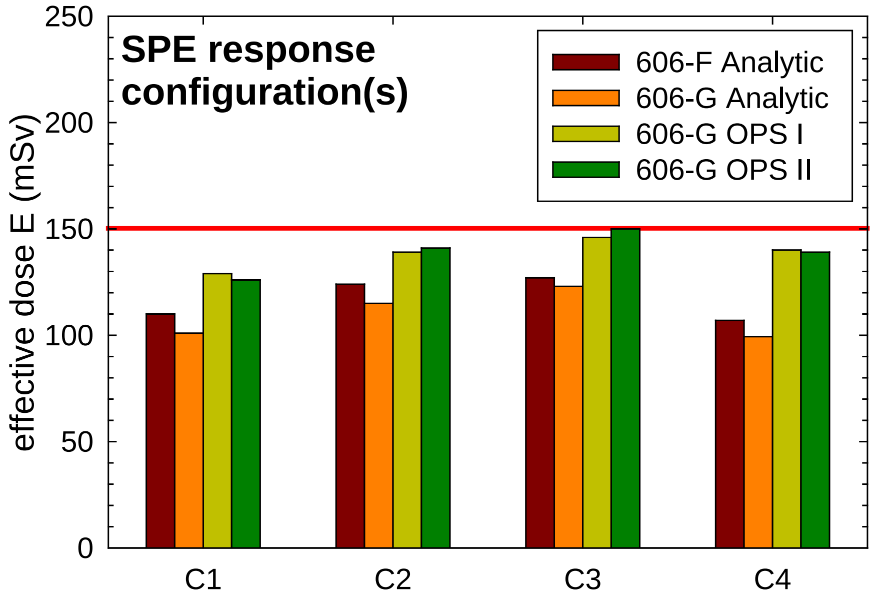


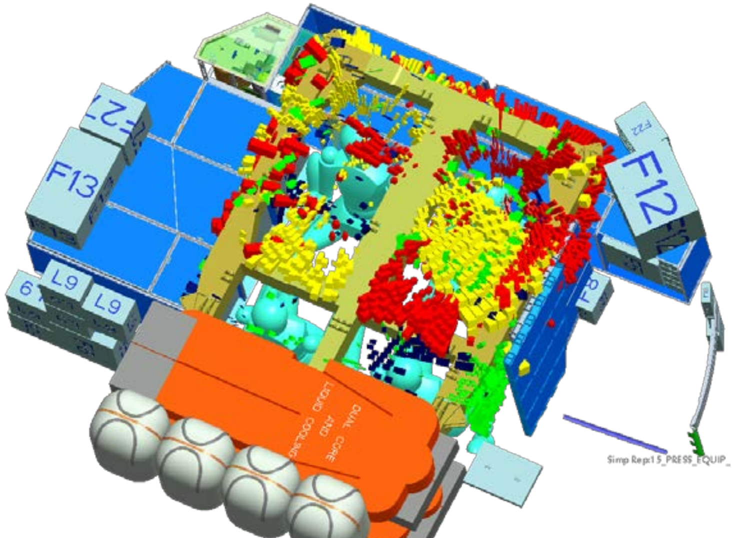


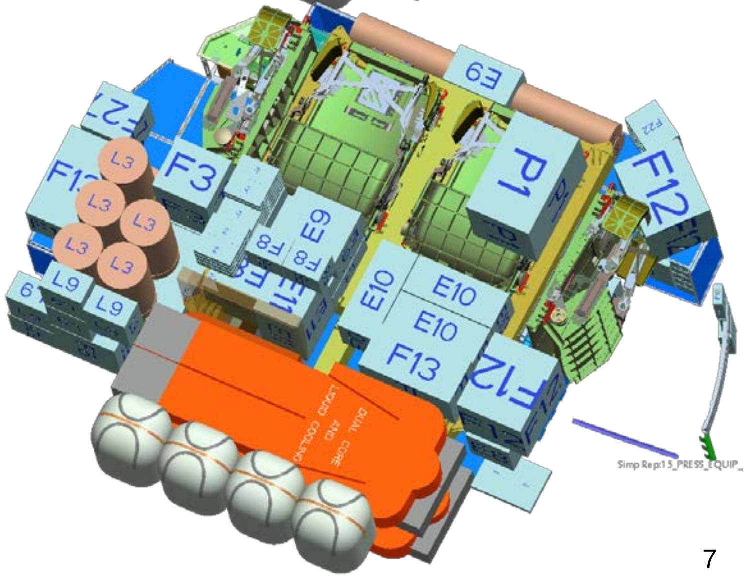
Cabin Configuration Optimization

- **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



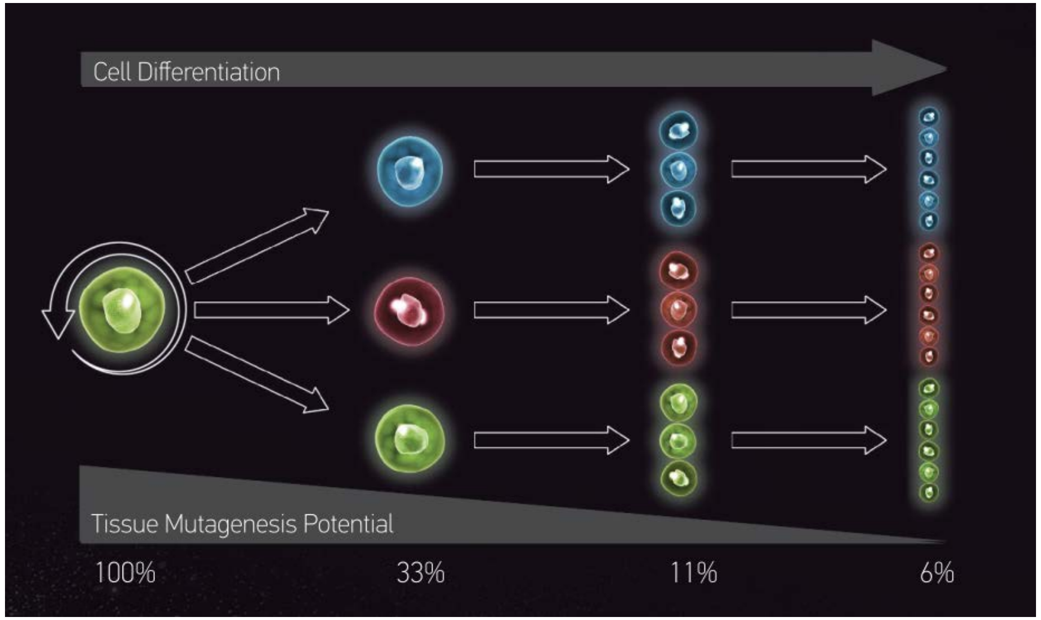






Radiation Vest for Astronauts: AstroRad

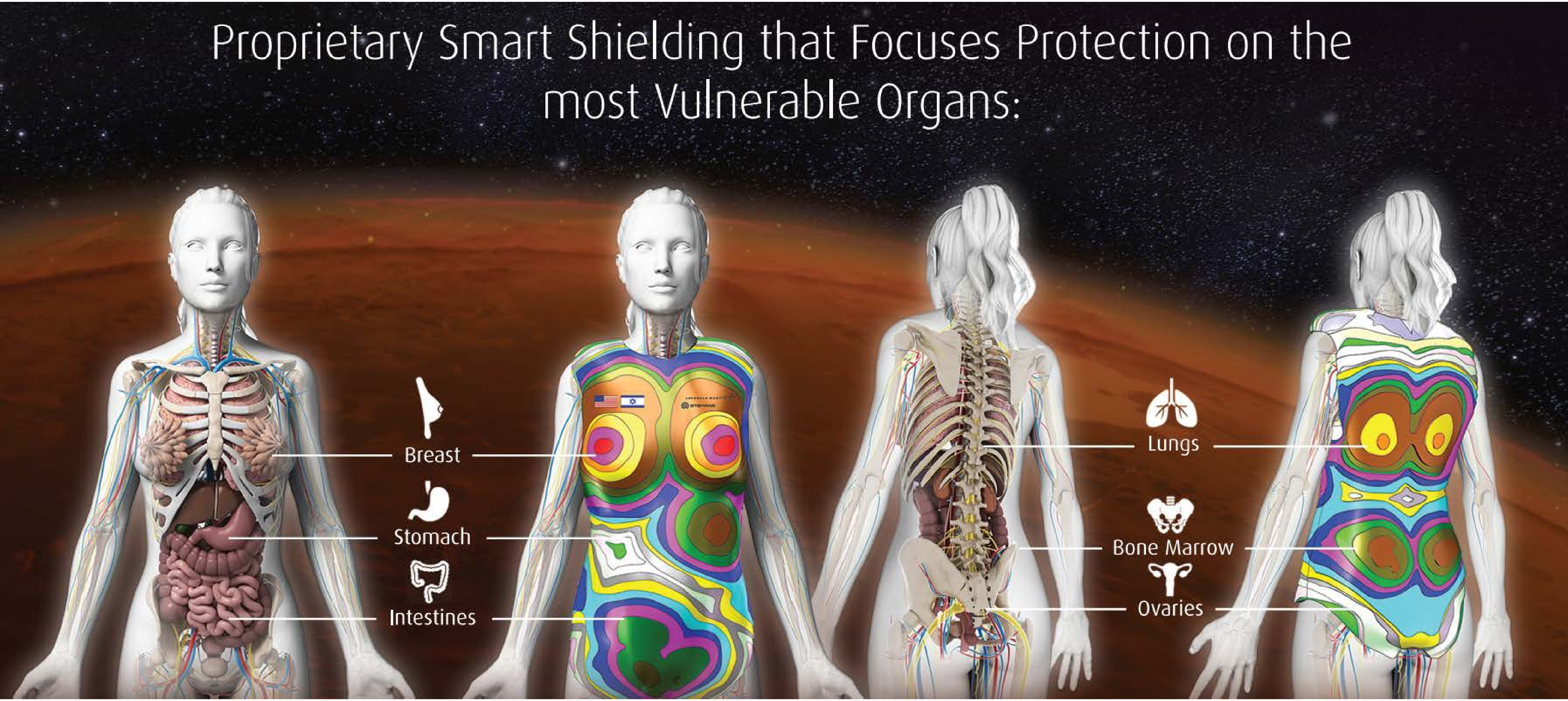
- **Collaboration between Lockheed Martin Space and StemRad Israel**
  - Portable radiation protection for astronauts
  - Provides preferential protection to stem cell rich organs and tissues
  - Designed for flexibility and ergonomics
  - Ergonomic evaluation aboard the International Space Station pending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



SPACE FLORIDA

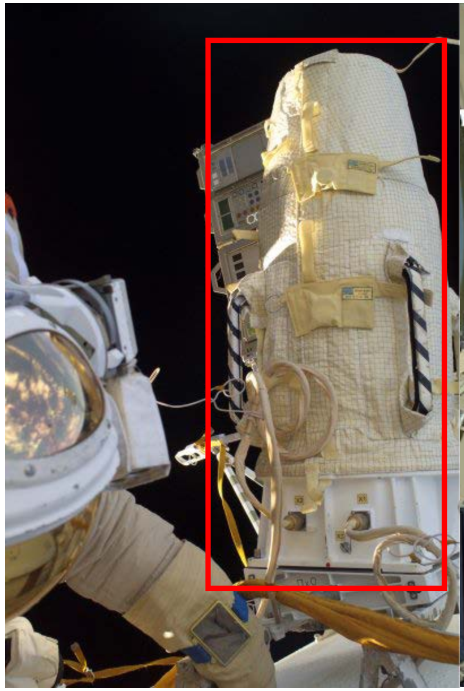
רשות החדשנות
Israel Innovation
Authority

AstroRad

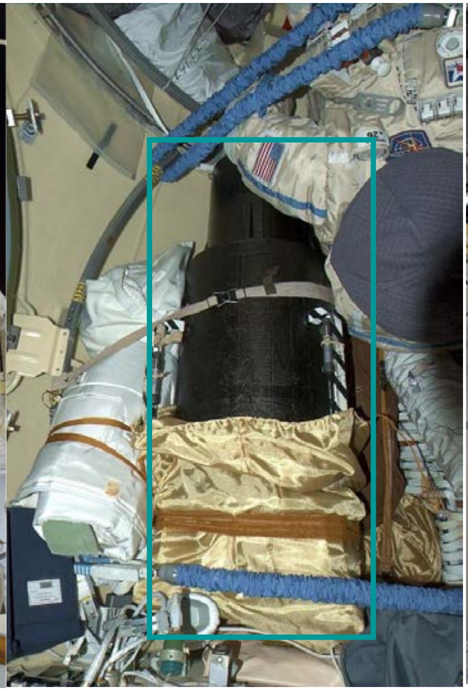

Proprietary Smart Shielding that Focuses Protection on the most Vulnerable Organs:
Breast
Stomach
Intestines
Lungs
Bone Marrow
Ovaries

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)

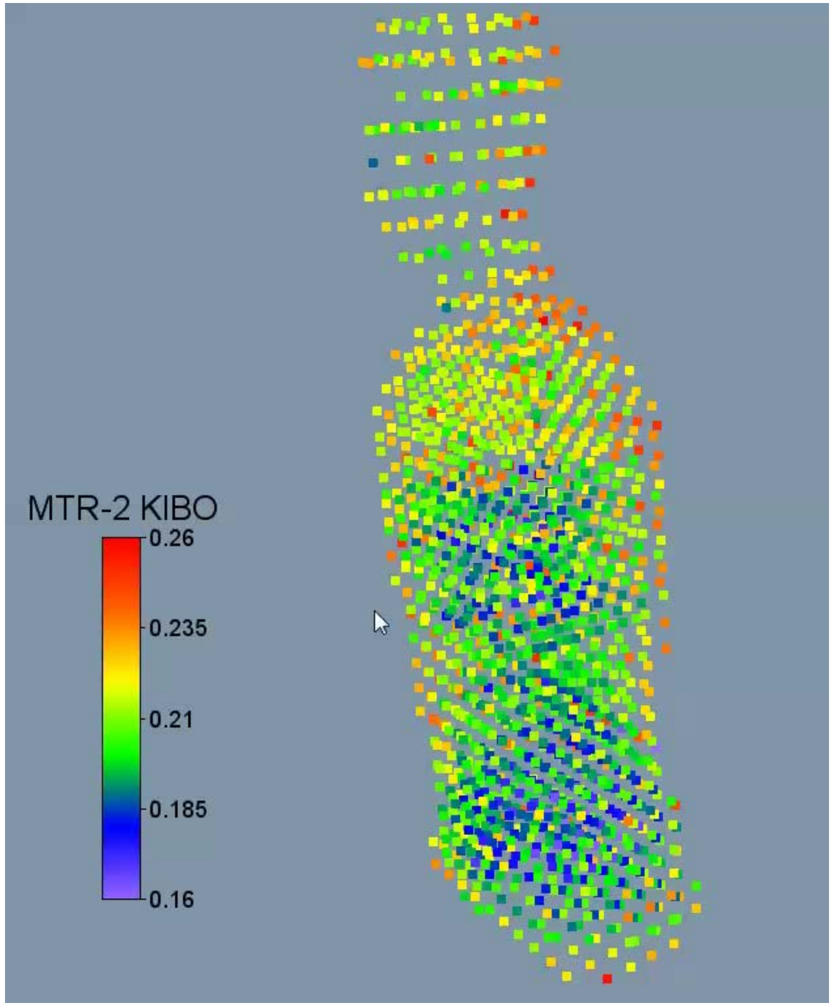
MTR-2B 518 days
(2007–09)

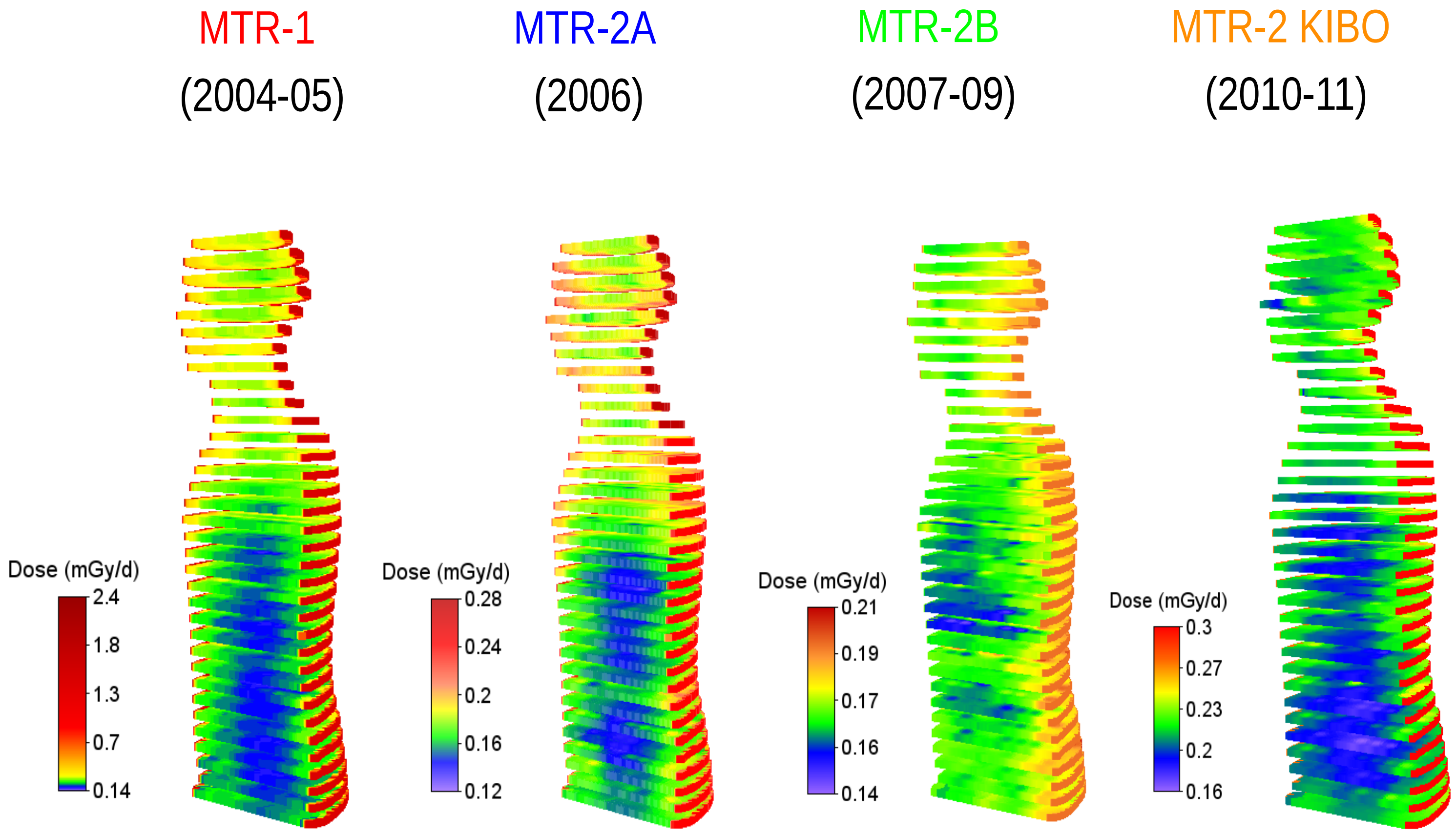
MTR-2 KIBO 310 days
(2010–11)

https://www.fp7-hamlet.eu

DLR

ISS Matroshka





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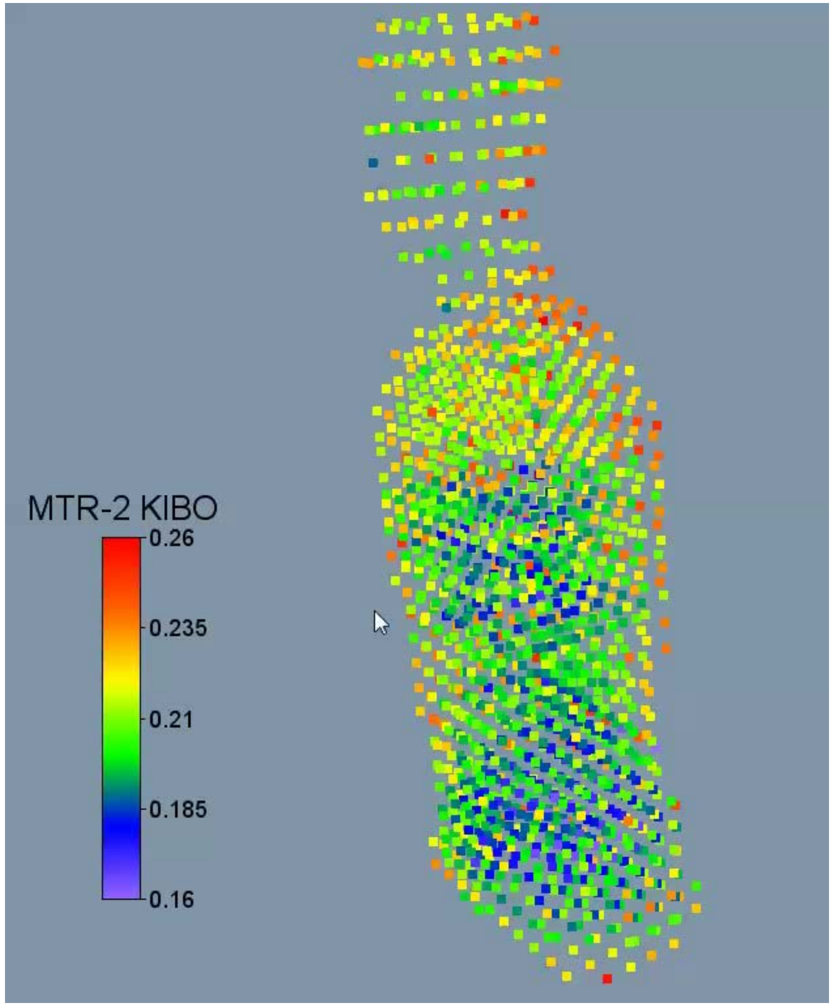
ISS Matroshka



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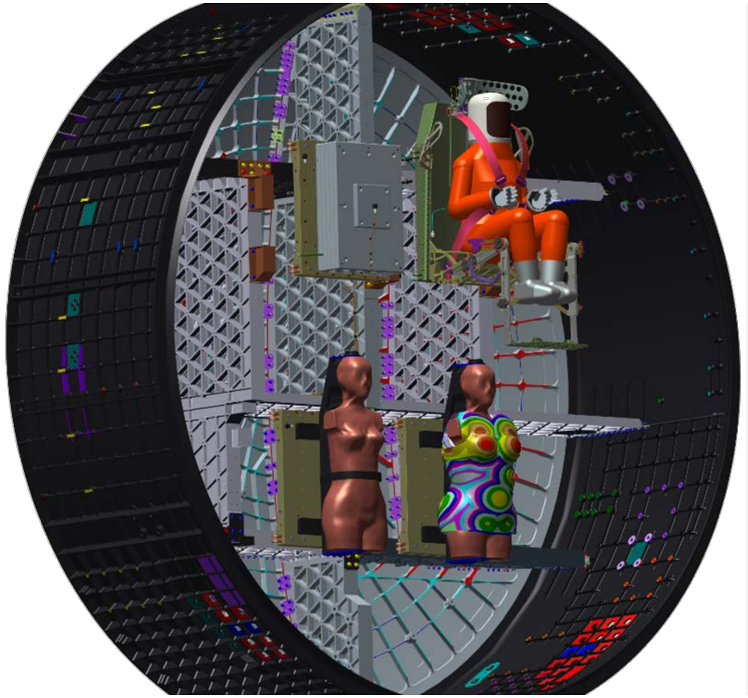
ATOMINSTITUT

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

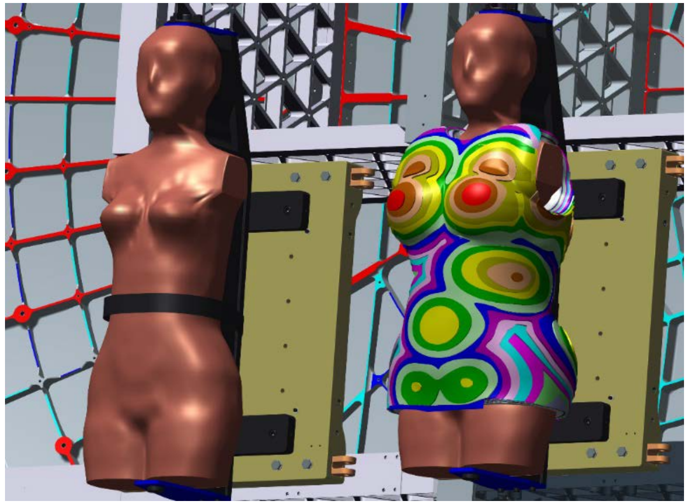
DLR

Matroshka AstroRad Radiation Experiment (MARE)



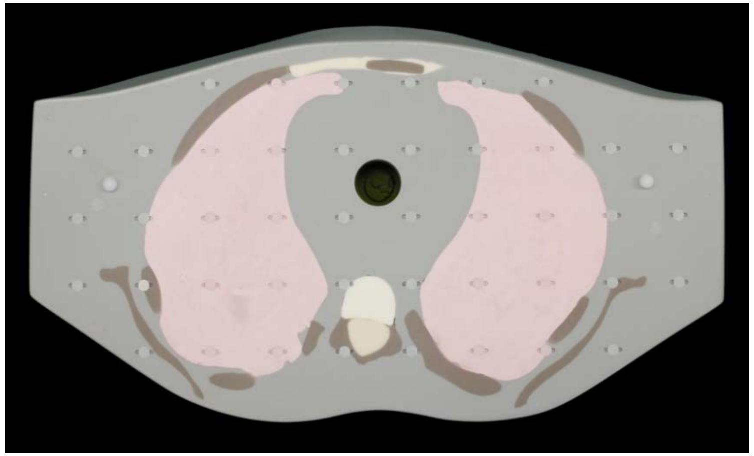
- Lockheed Martin invited feedback as part of Orion radiation protection efforts
- Israel Space Agency (**ISA**) and the German Aerospace Center (**DLR**) proposed MARE as an international science payload
- **NASA** approved the proposal in May 2017 and manifested it aboard the EM-1 (now Artemis 1) flight.

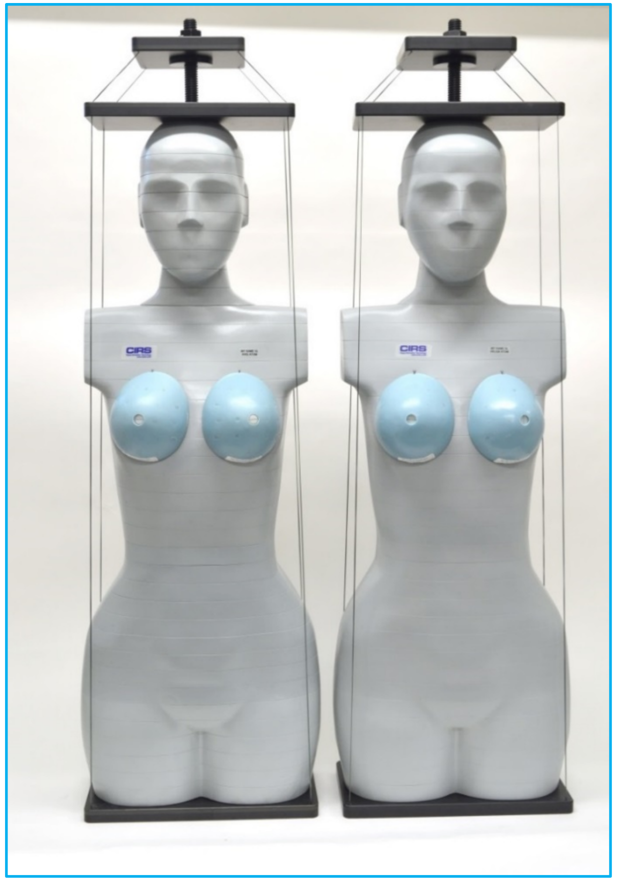
- MARE description
  - Two tissue-equivalent radiation phantoms inside the Orion cabin
  - Fitted with active and passive radiation detectors
  - One phantom fitted with the StemRad-manufactured AstroRad vest
- MARE is managed by DLR and ISA, with NASA as a co-PI
  - Lockheed Martin personnel co-located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



MARE: CIRS Phantoms

- **ATOM® 702 Female model**
  - Radiation phantom materials: Soft tissue, bone, cartilage, lungs, brain, breast, spinal disk, and spinal cord
  - 38 slices with custom 3-cm TLD/OSLD grid
  - Identical within manufacturing tolerances: Zohar 35.88 kg / Helga 35.99 kg
  - Artificial bone

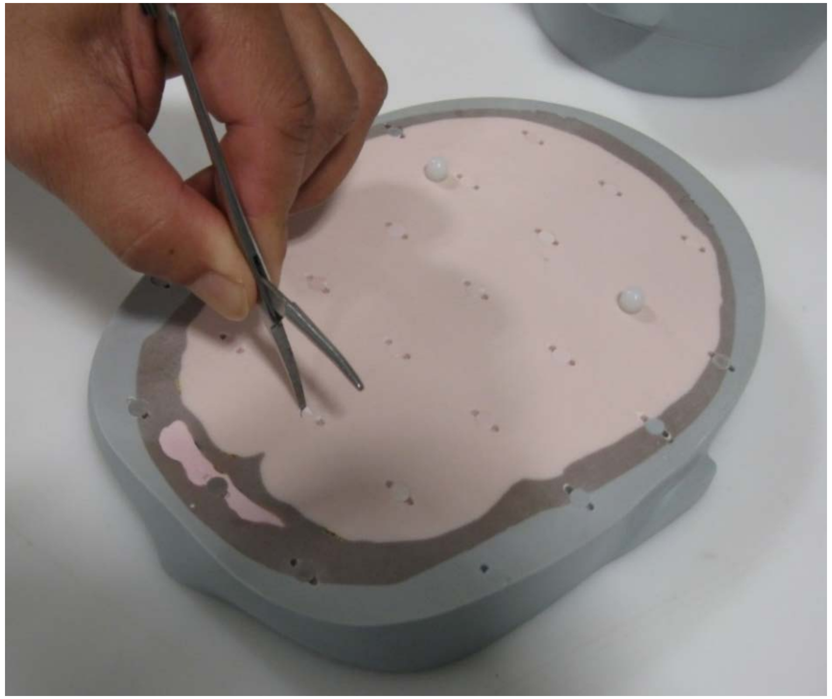


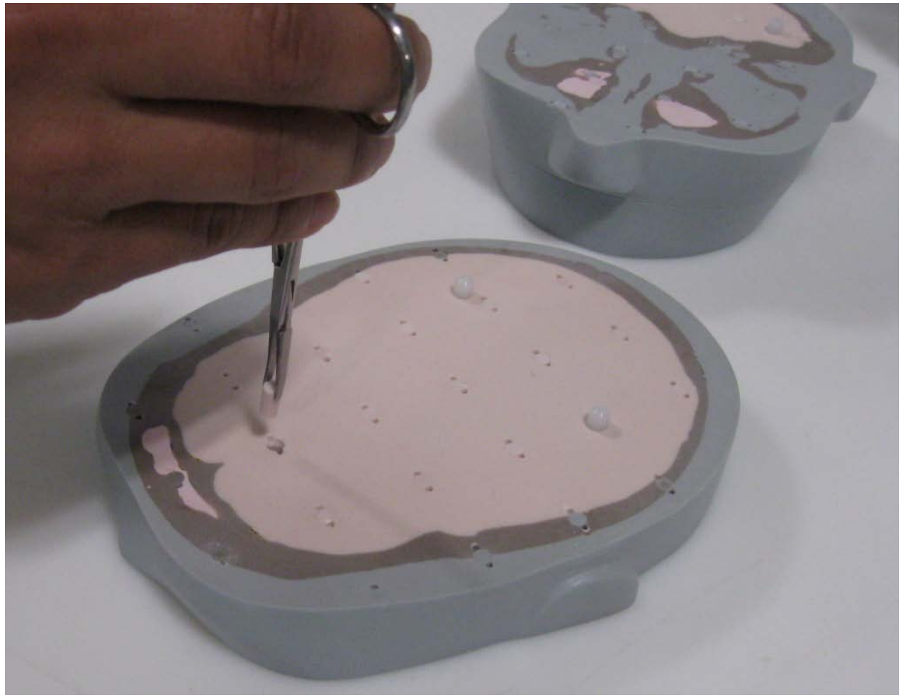


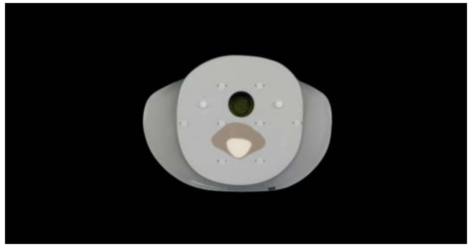
http://www.cirsinc.com/products/modality/33/atom-dosimetry-verification-phantoms

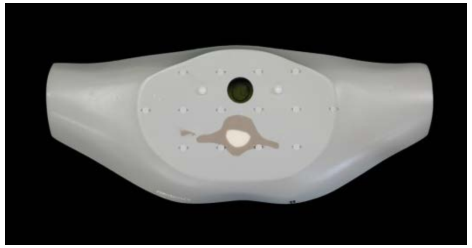
Helga TLD Positions

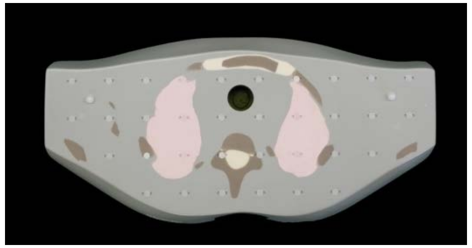
Helga: 1392, Zohar: 1383 (DLR: 6000 TLDs, NASA: 2-3000 TLDs/OSLDs)

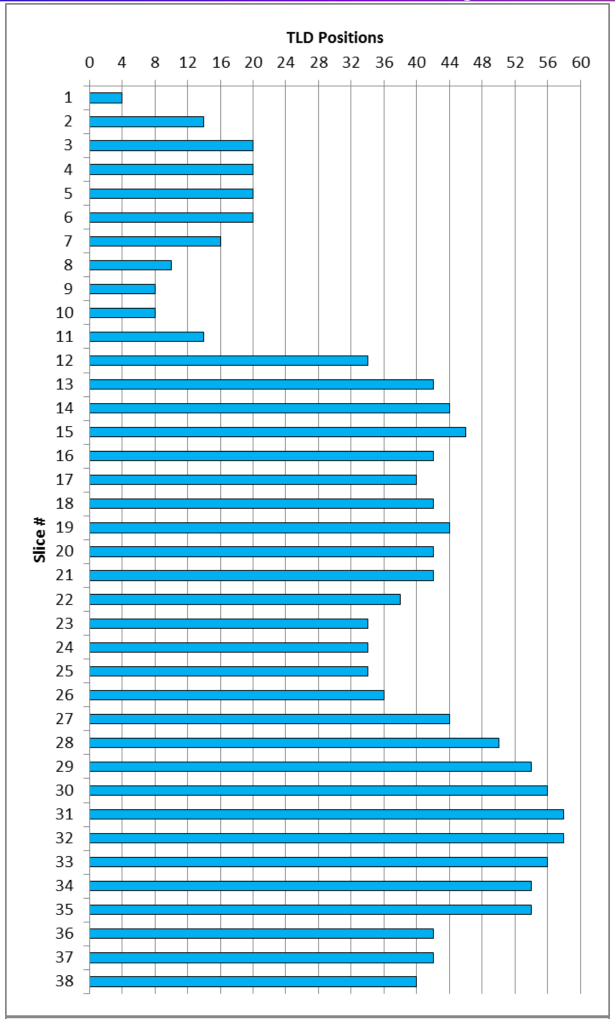


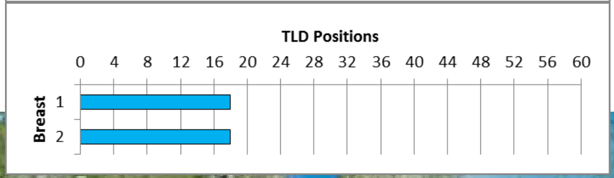








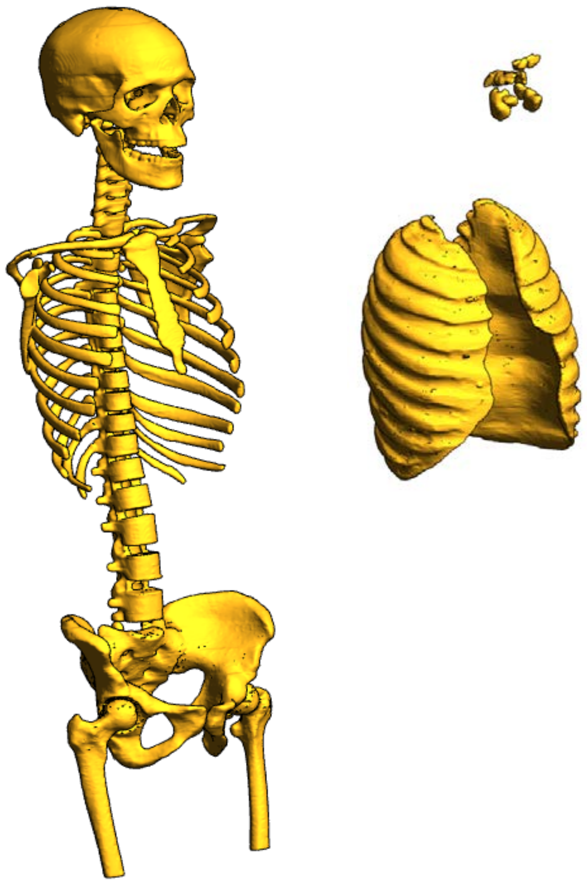


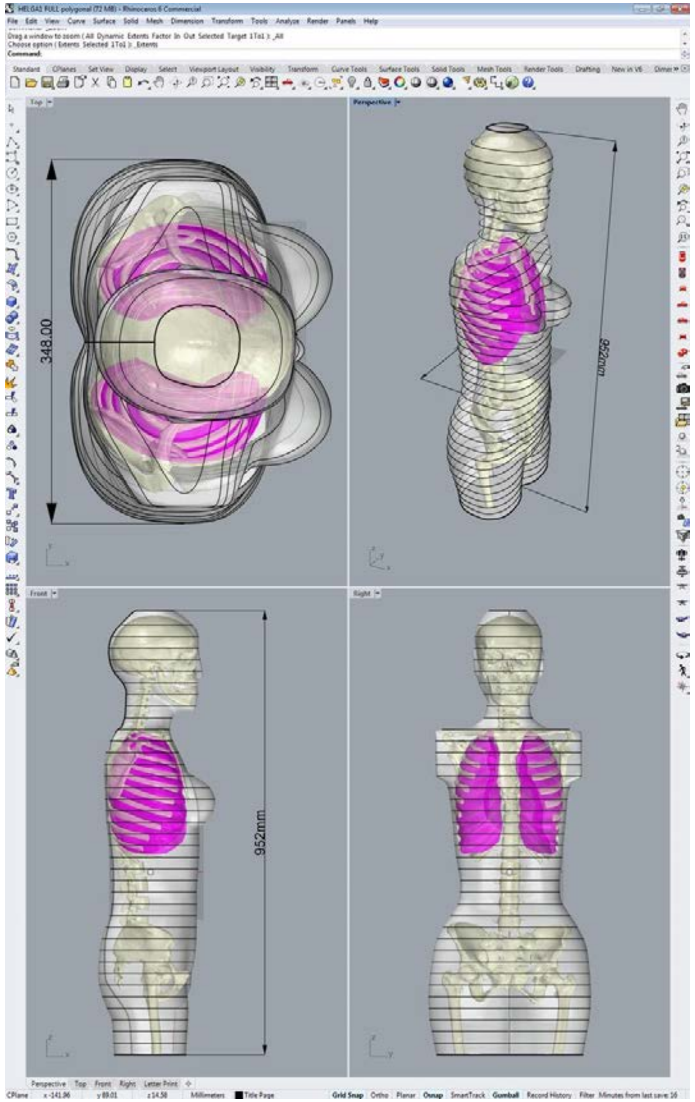


DLR

MARE: CIRS Phantoms

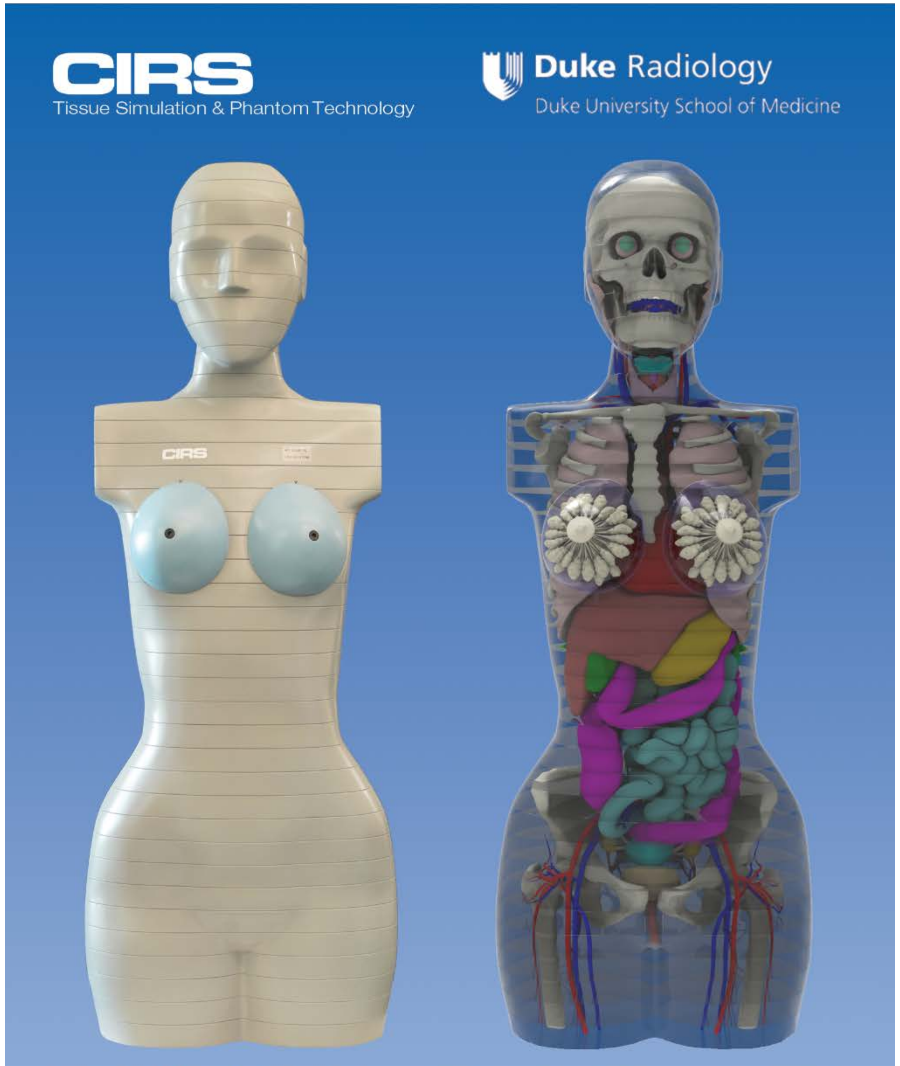
- CT scan performed on each phantom
- CT scan data are used to generate CAD models
- CAD models are used for AstroRad vest customization and radiation analysis





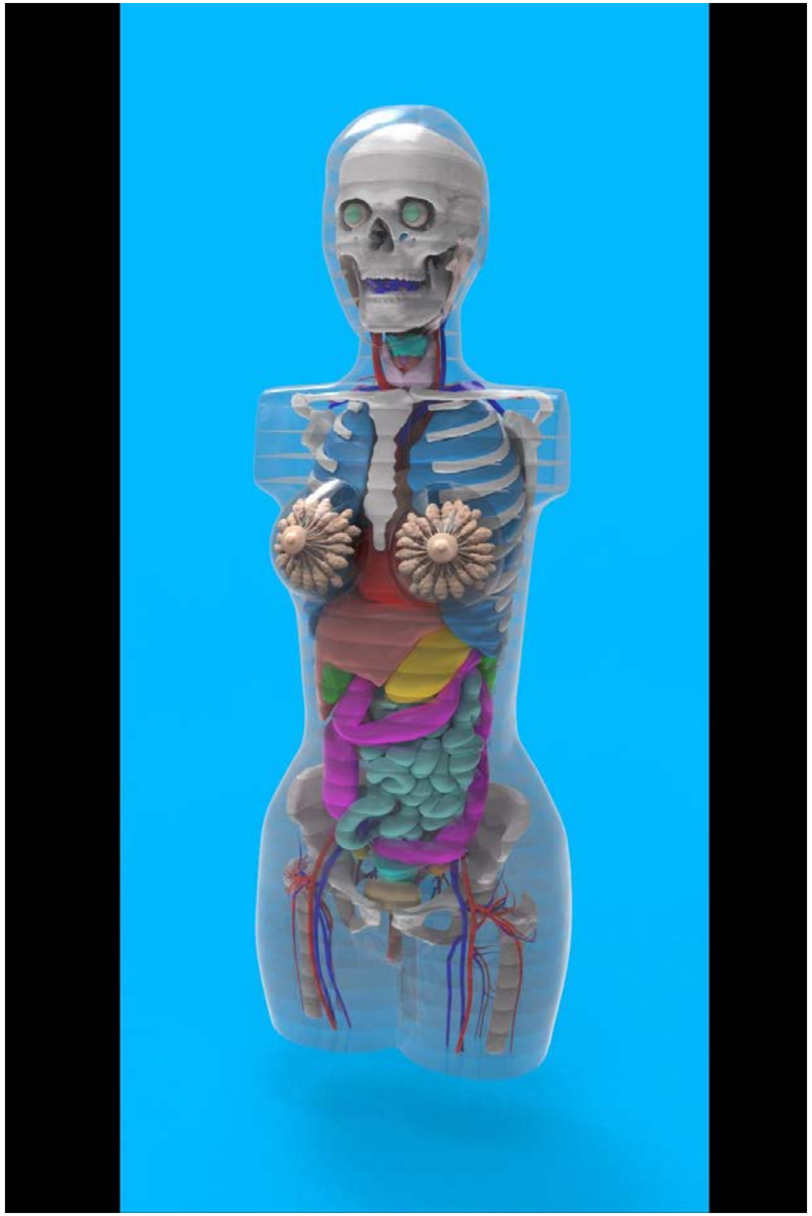
MARE: Bio-modeling

H. Hussein and T. Berger for the MARE team
2019 WRMISS, Athens, Greece



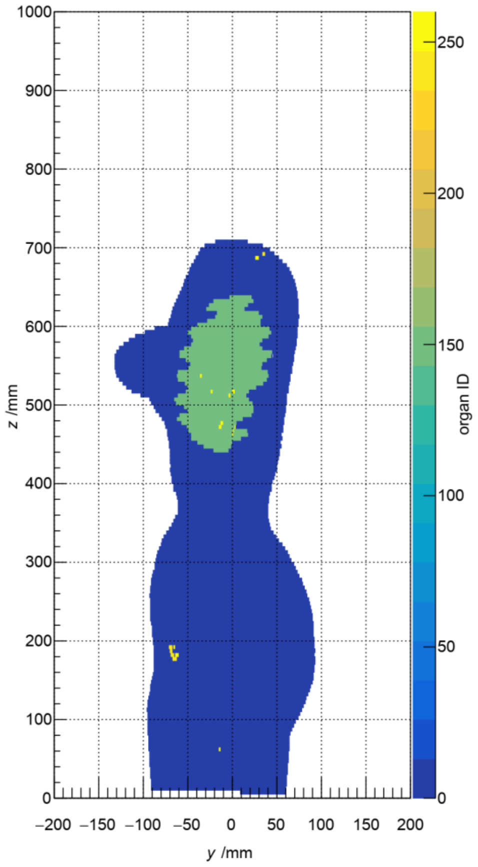
CIRS Inc. 702 Adult female (left) ATOM anthropomorphic phantom for investigating organ dosimetry. Individual organs are not physically defined in the phantom other than average tissues for soft tissue, bones, cartilage, lungs, brain, breast, spinal disc and spinal cord. The Carl E. Ravin Advanced Imaging Laboratories at Duke University developed digital computational models for over 170 anatomical constructs (right). These three dimensional organ maps are used to assign thermo luminescent radiation detectors according to the various tissues of interest.

- **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)

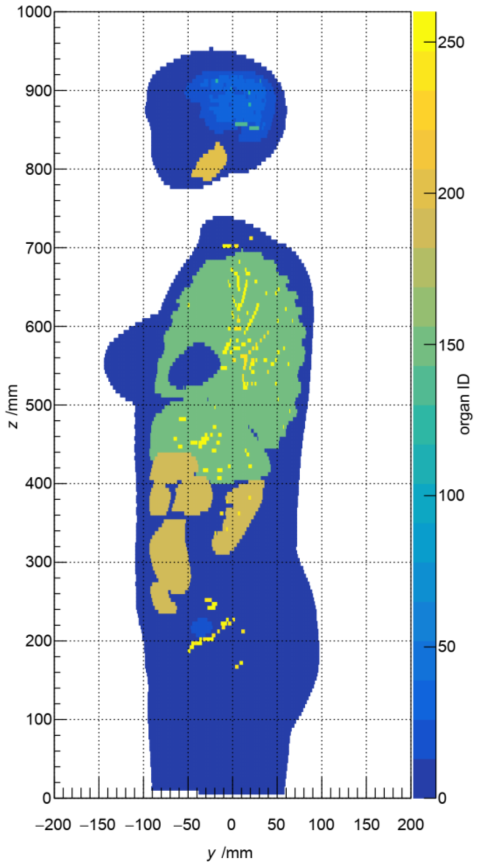


MARE: DLR Voxel Model

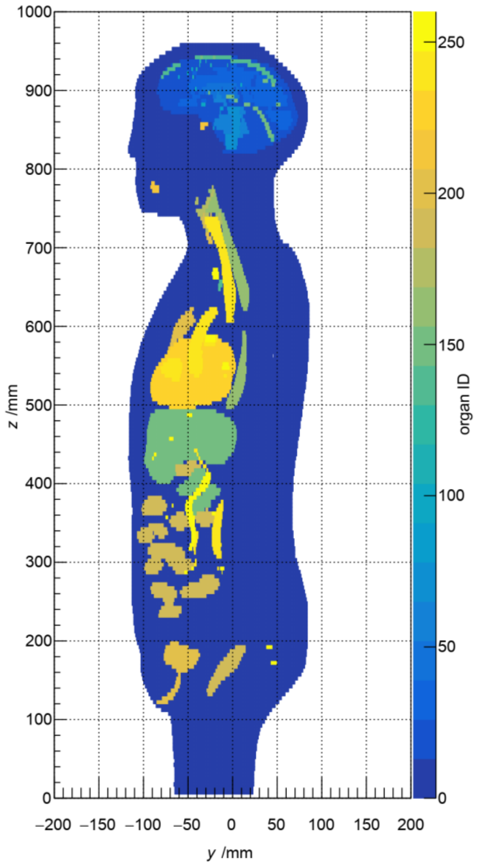
HELGA, zy projection, 99 < x/mm < 100



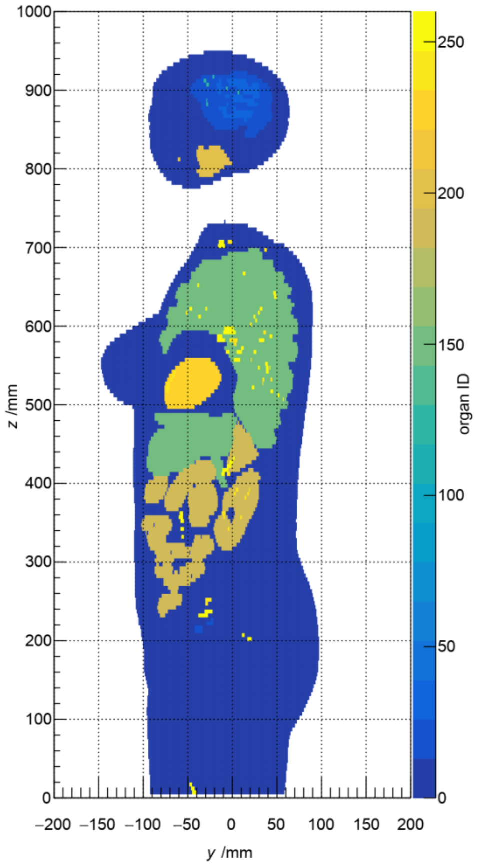
HELGA, zy projection, 149 < x/mm < 150



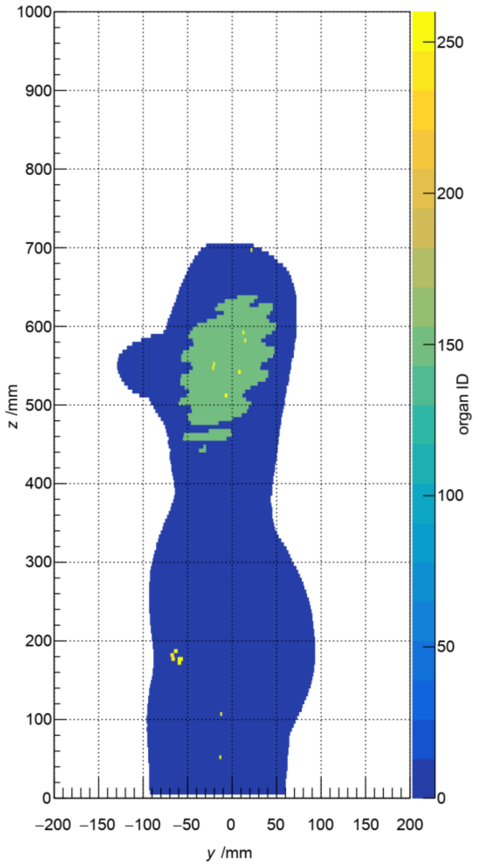
HELGA, zy projection, 199 < x/mm < 200



HELGA, zy projection, 249 < x/mm < 250

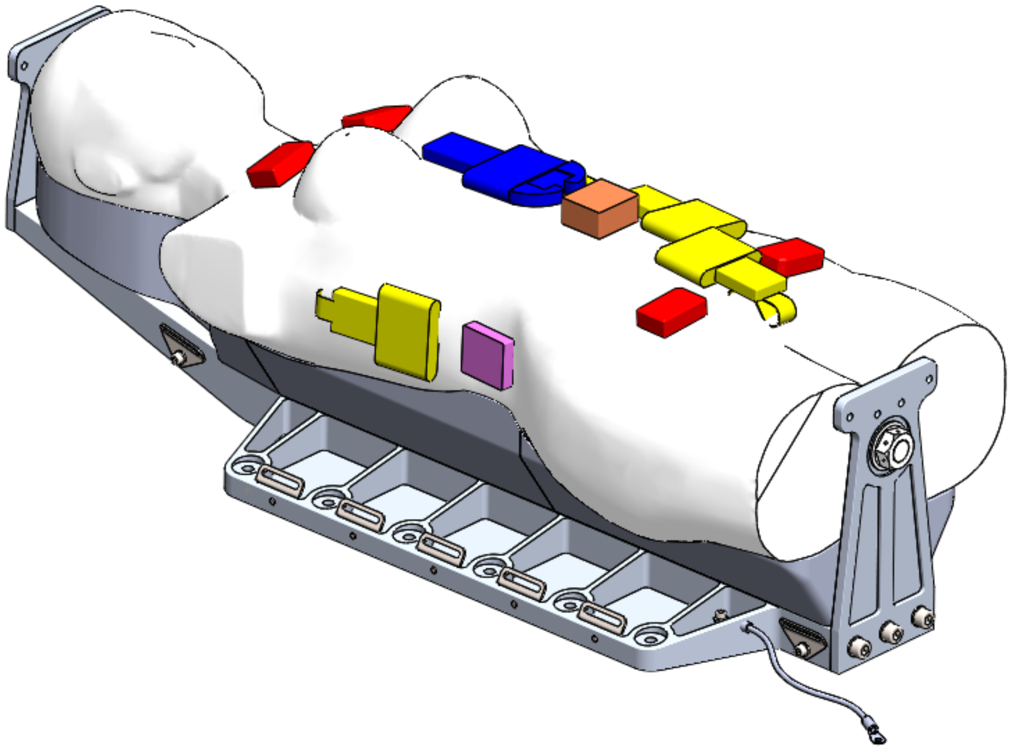


HELGA, zy projection, 299 < x/mm < 300

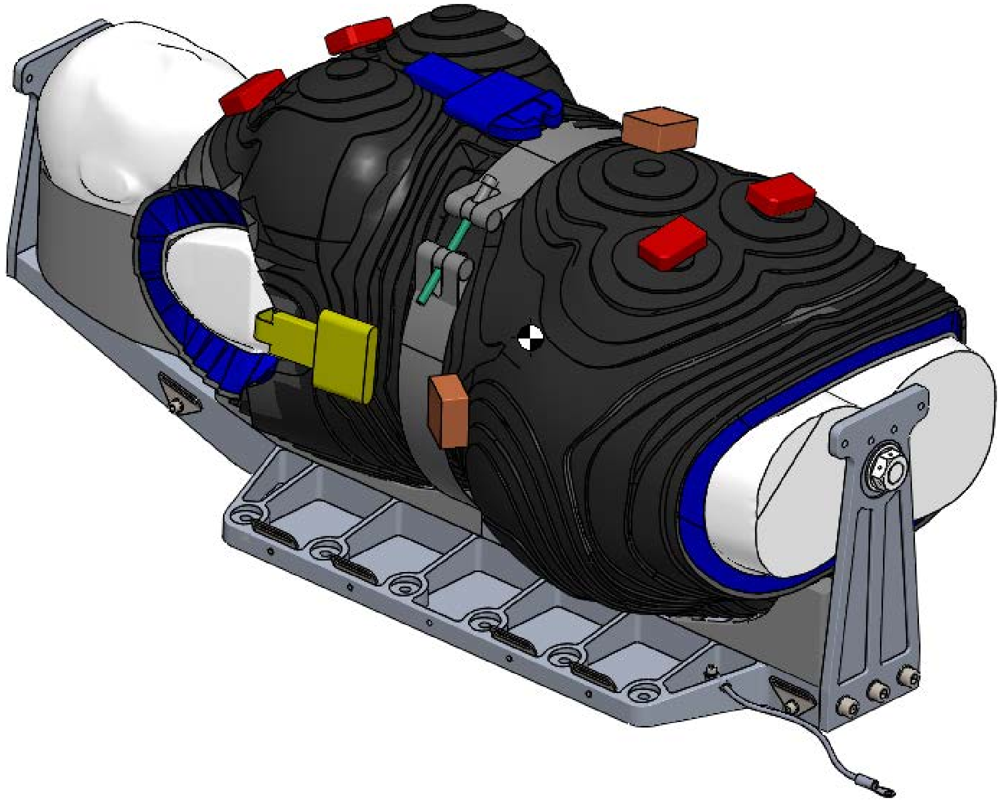


MARE: Orion configuration

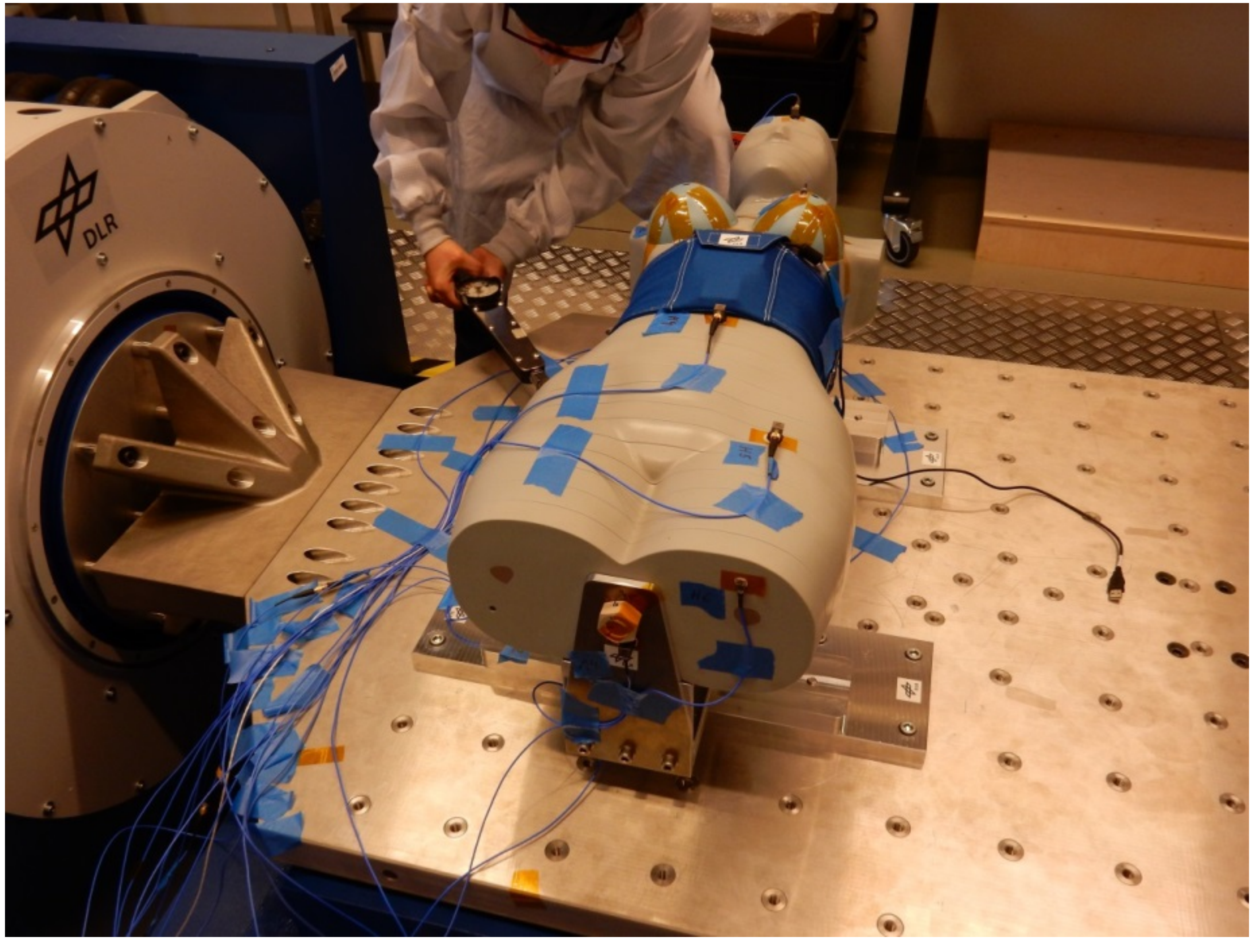
Helga



Zohar

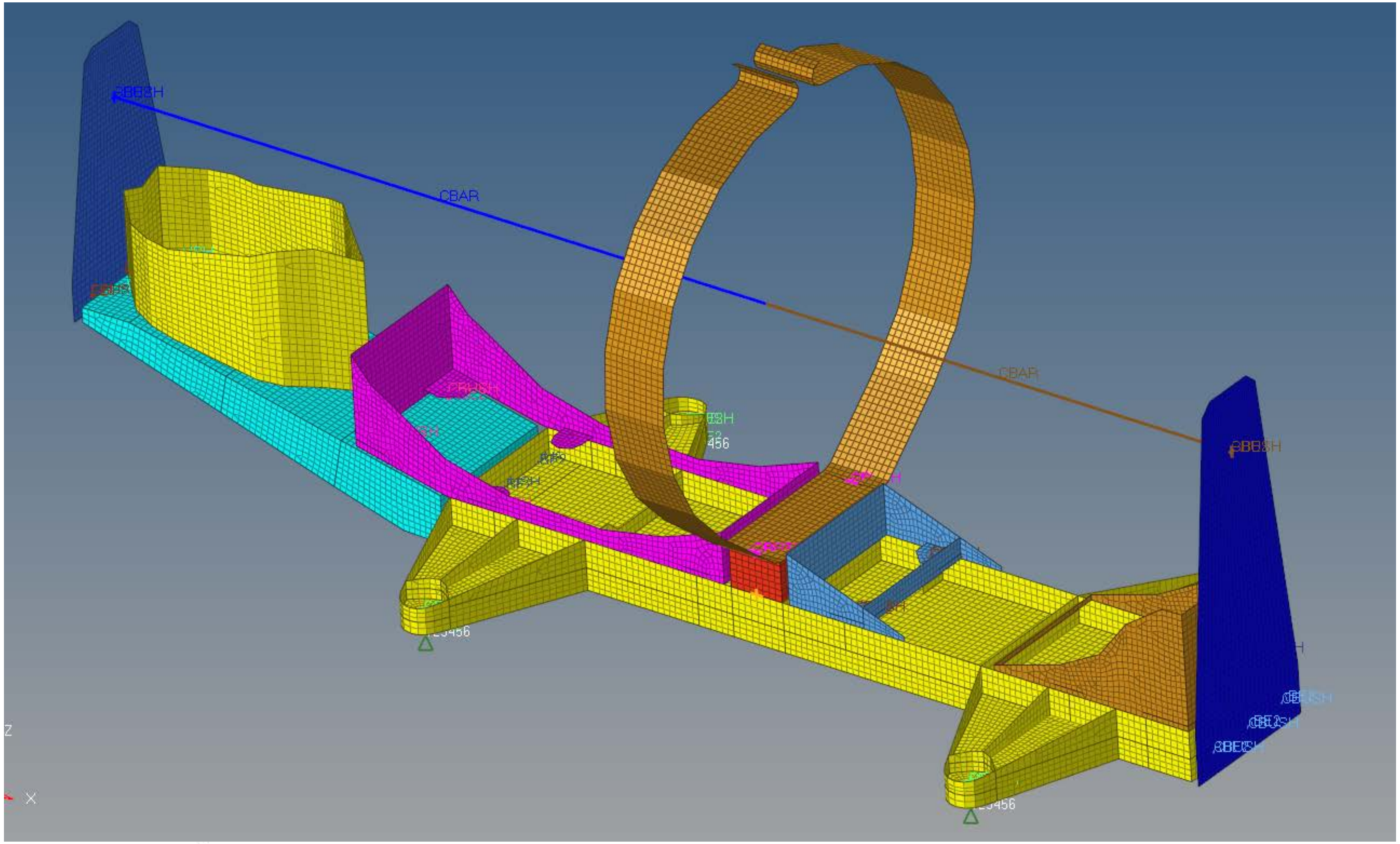


MARE: Vibration Test

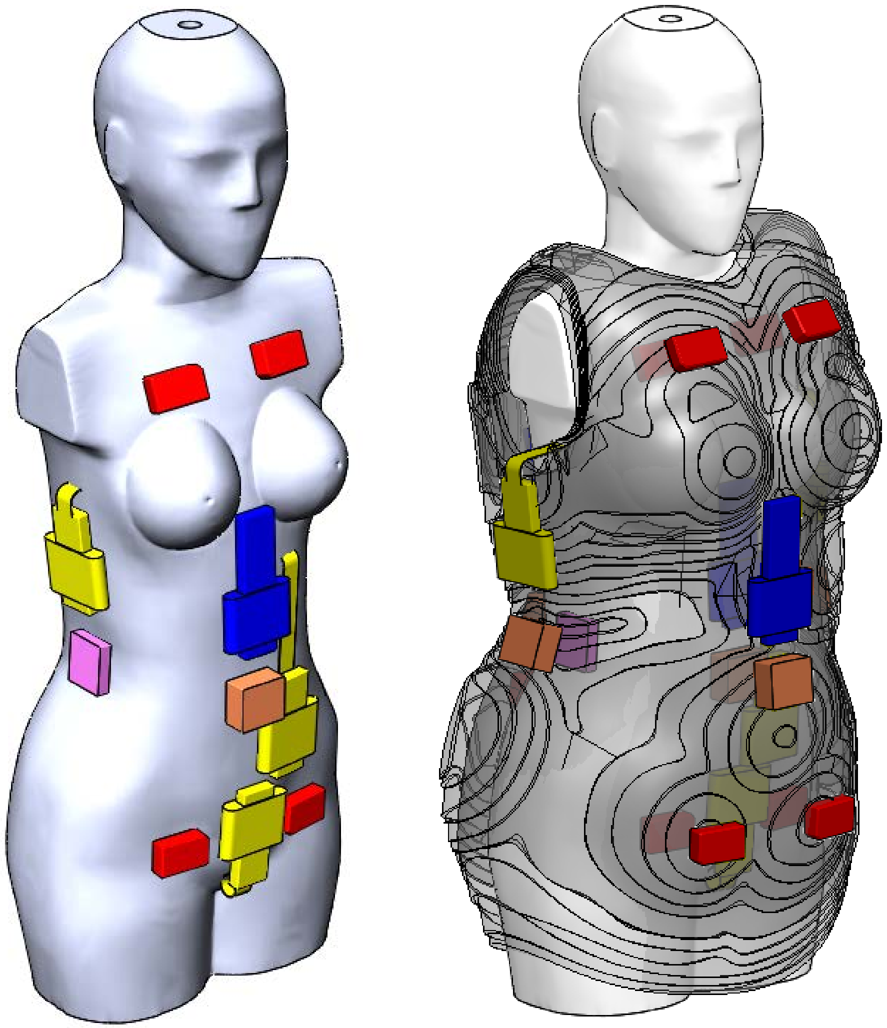


DLR

MARE: Structural Analysis



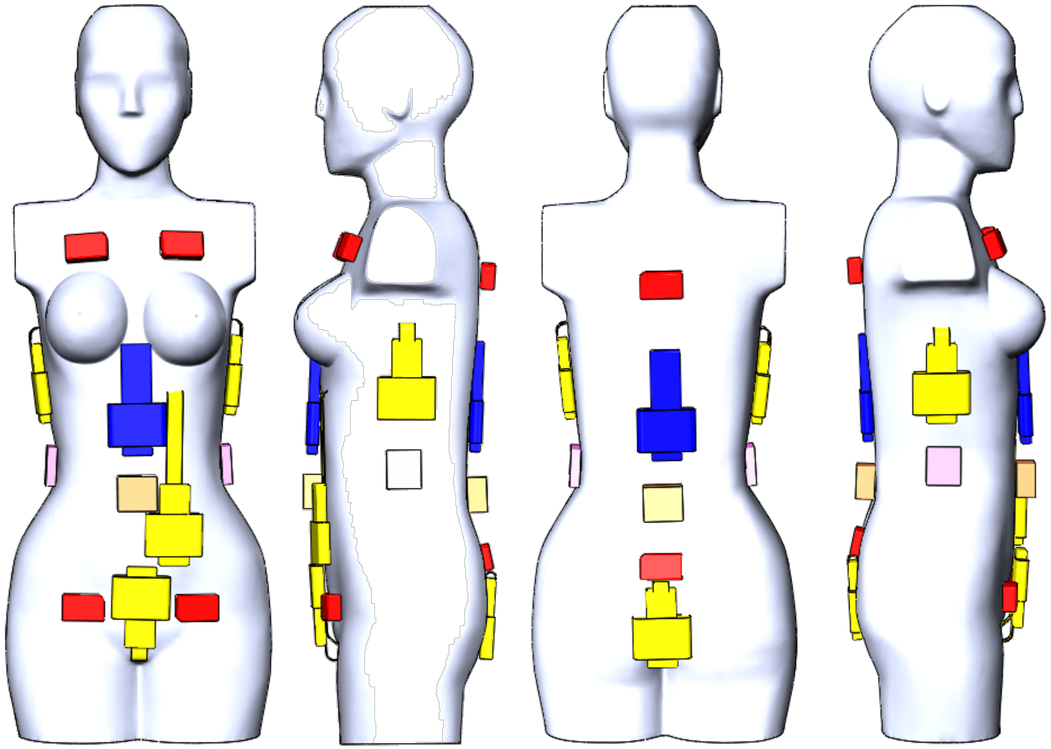
Location Radiation Detectors



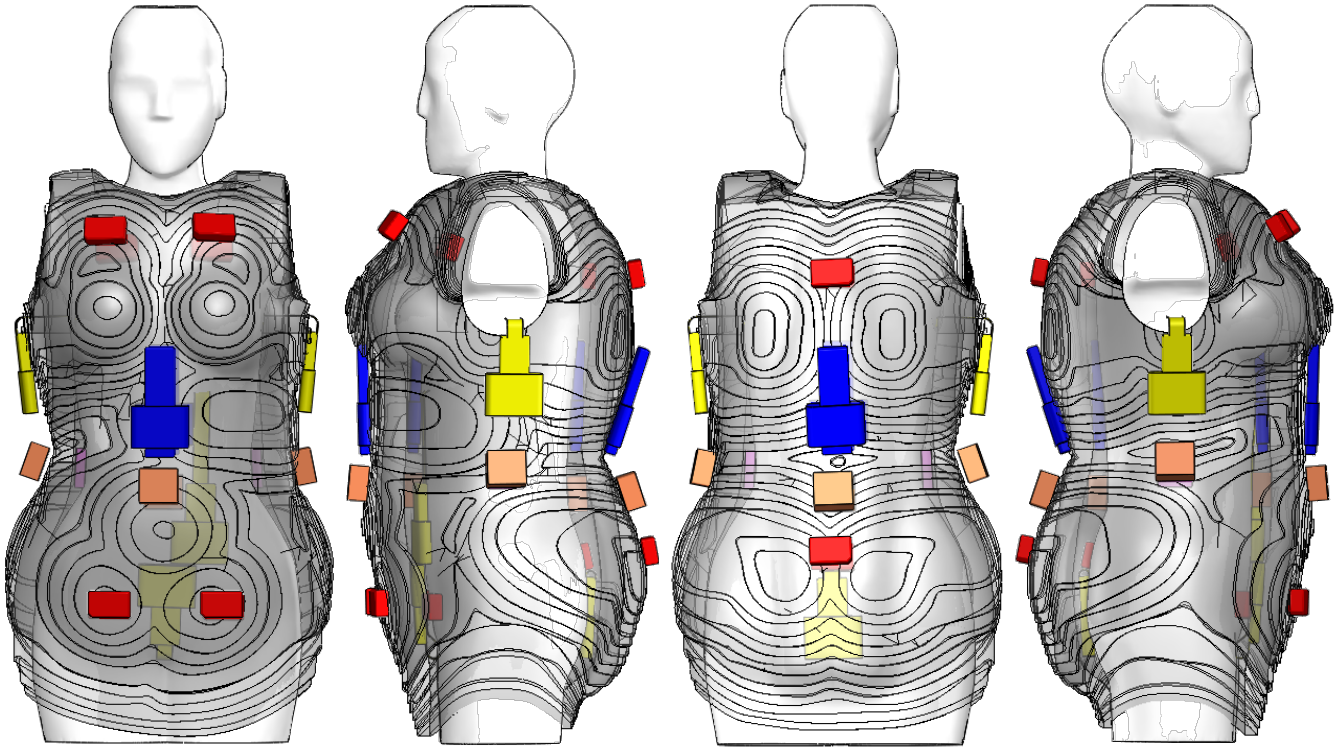
M-42 Compact SAFT Batteries	*DLR*
M-42 Split SAFT Batteries	*DLR*
CPAD Coin Cell	*NASA*
DOSIS PDP Passive	*DLR*
ALMAR Coin Cell	*Herado*

Location Radiation Detectors

Helga



Zohar



M-42 Compact	DLR
M-42 Split	DLR
CAD	NASA
DOSIS PDP	DLR
ALMAR	Herado

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

Berger et al. (2019) *The DLR M-42 radiation detector – a new development for applications in mixed radiation fields.* Review of Scientific Instruments (Under Review)

DLR M42 DUS-NRT and return

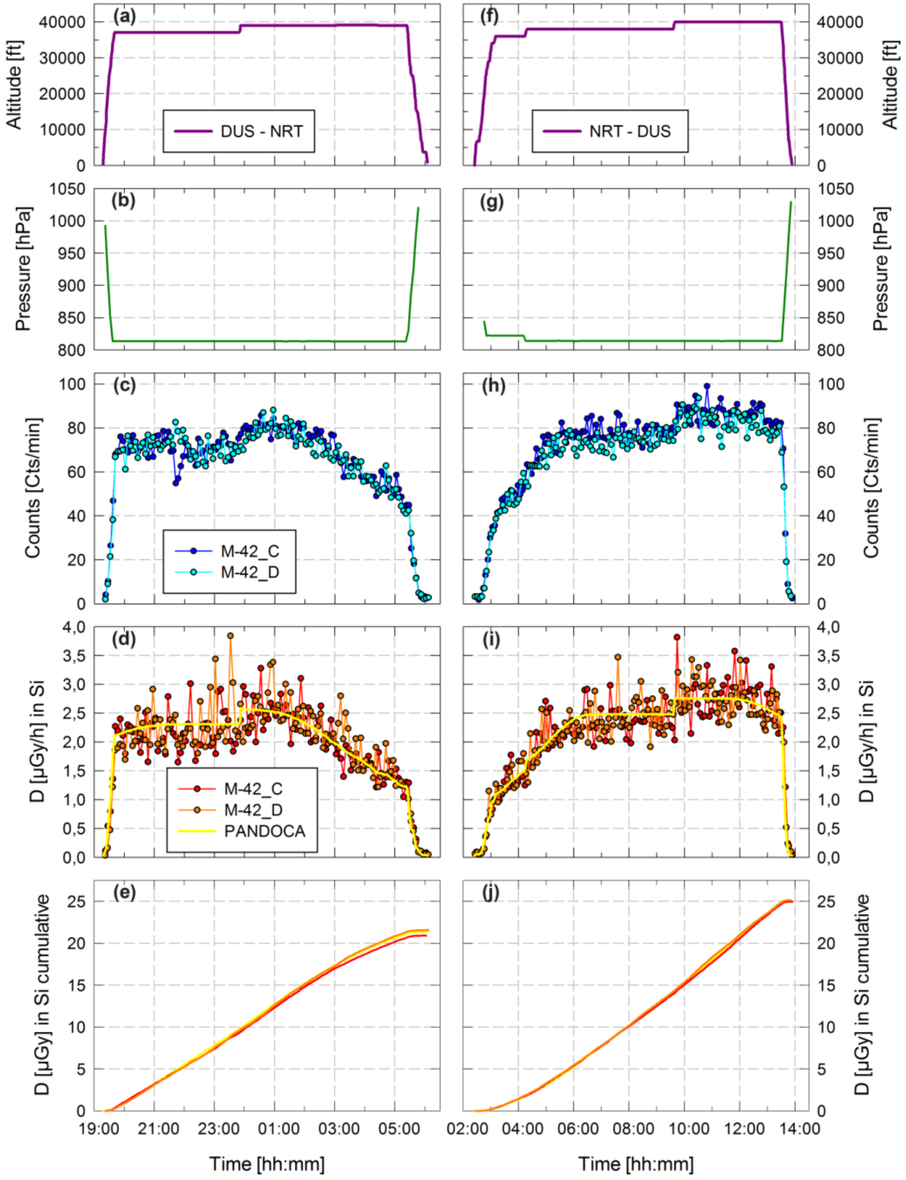


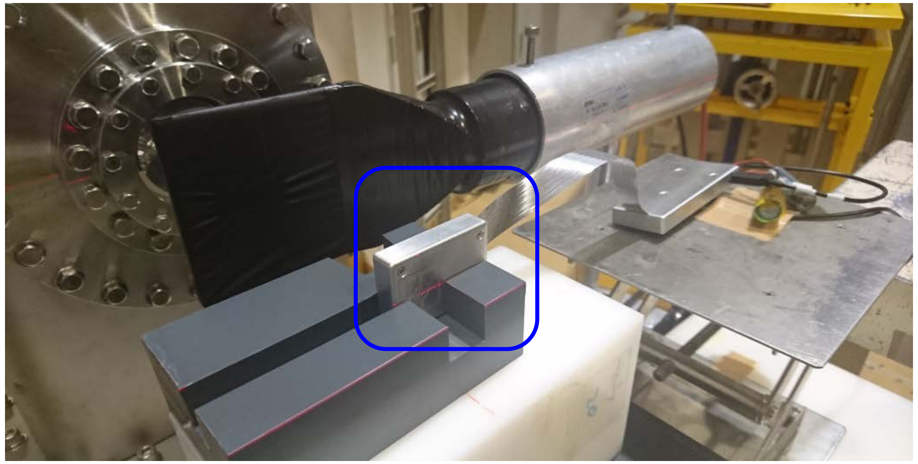
TABLE III: Results of the measurements of the total flight absorbed dose in Si compared with the DLR PANDOCA calculations.

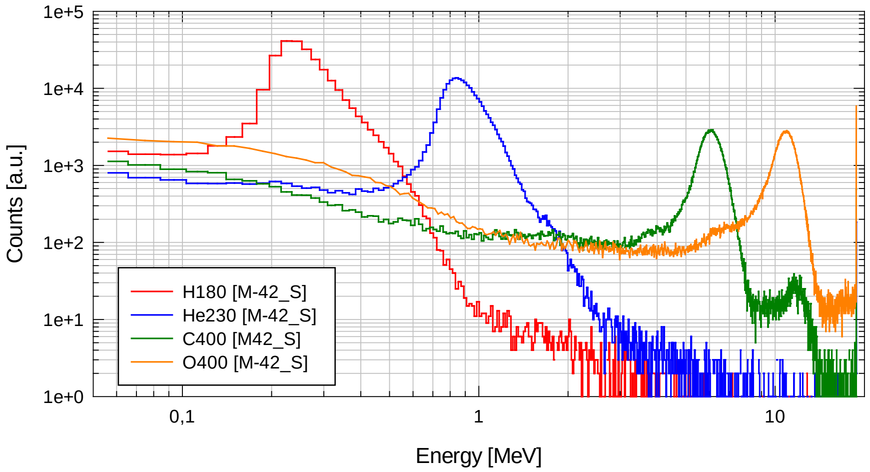
	M-42_C	M-42_D	PANDOCA
		[µGy] in Si	
DUS-NRT	20.94	21.55	21.34
NRT-DUS	24.99	25.12	24.97

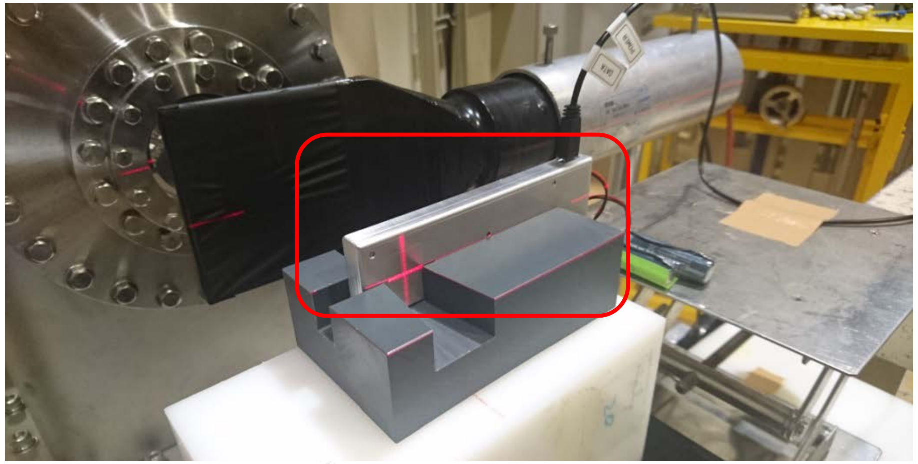
FIG. 14. (a) and (f) Flight level for the flight from Düsseldorf (DUS), Germany to Tokyo Narita (NRT), Japan and from NRT to DUS; (b) and (g) measured pressure for the flights; (c) and (h) count rates; (d) and (i) absorbed dose rates in Si as well as the absorbed dose rate in Si calculated with the DLR PANDOCA model; (e) and (j) cumulative dose for the data given in (d) and (i).

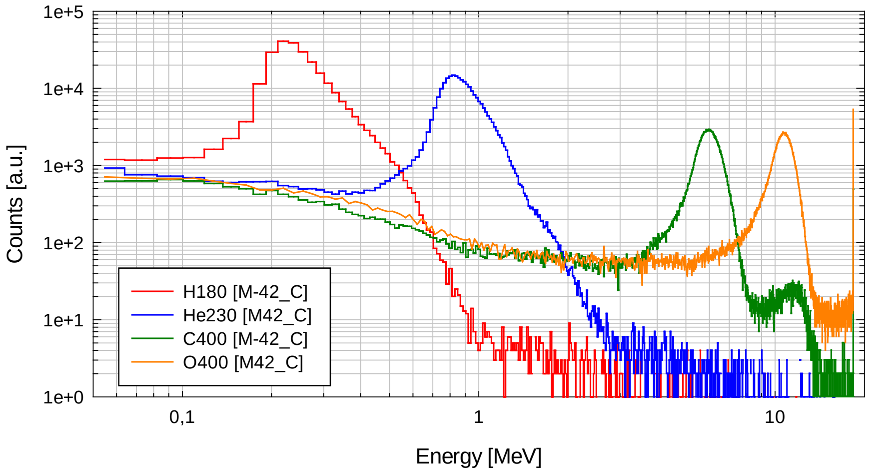
DLR M42 HIMAC Exposure

HIMAC Research Project 17H374



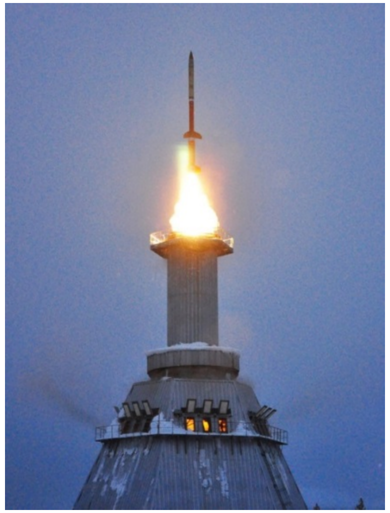


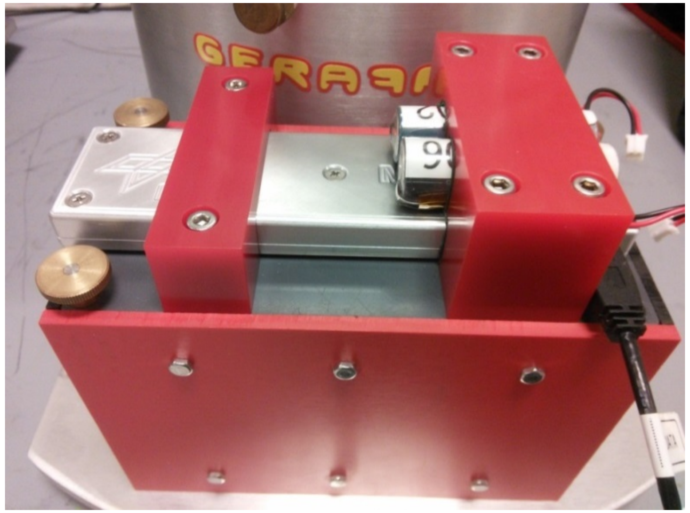


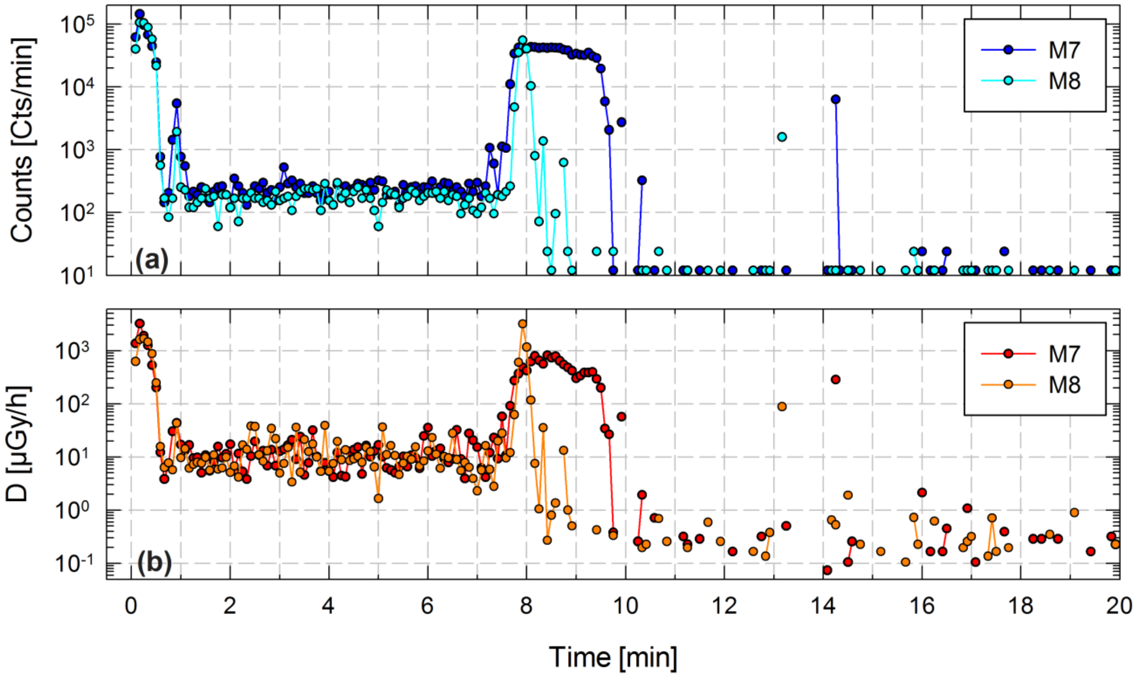


DLR M42 MAPHEUS 7 and 8 testing

- **Load detector test performed aboard MAPHEUS DLR research rockets**
  - Max Altitude = 260 km
  - Flight Time = 14 min 10 s (6 min microgravity)
  - Launched from ESRANGE, Kiruna, Sweden (Feb 2018 + July 2019)
  - Dose rate: **239.8 µGy/day in Si**







DLR

DLR M42 MAPHEUS 7 and 8 testing

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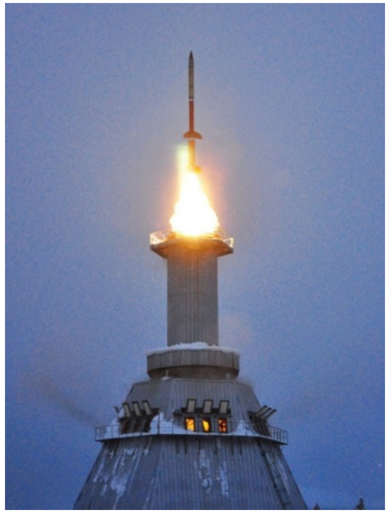
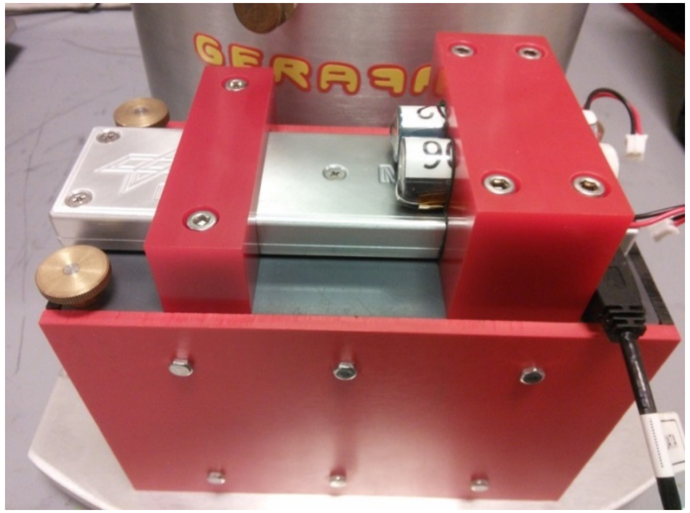
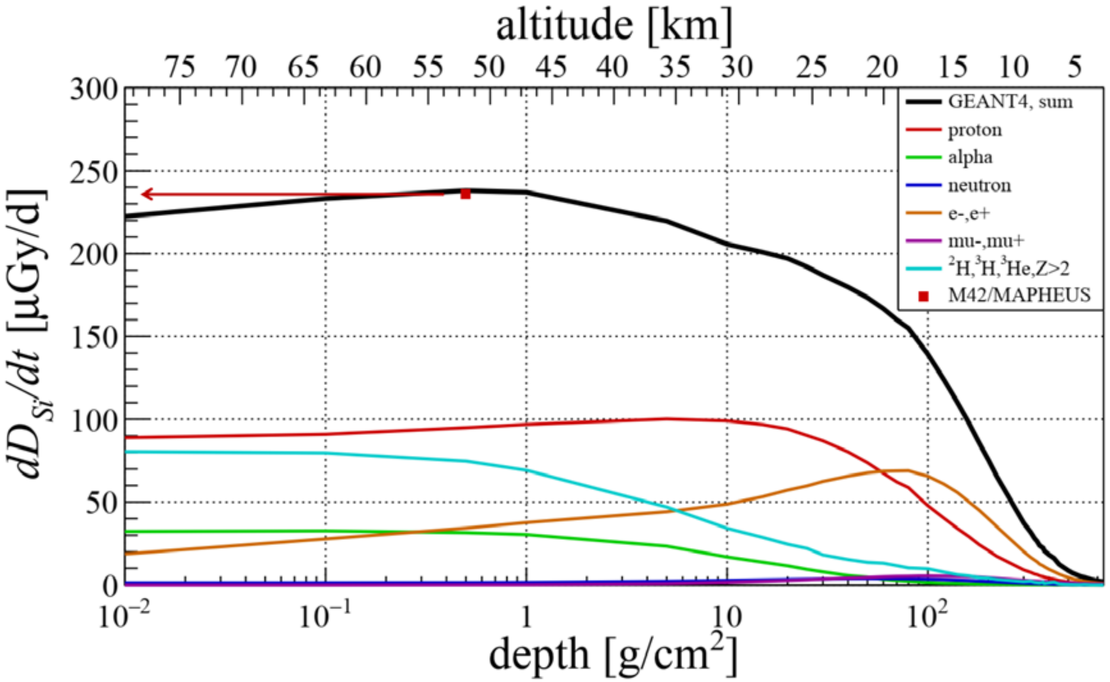






NASA CAD

- Crew Active Detector
- ISS Tech Demo was successfully completed in July 2018, transition to ISS operational use 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 CADs to be flown on Artemis 1 outside of MARE

DOSIS 3D PDP

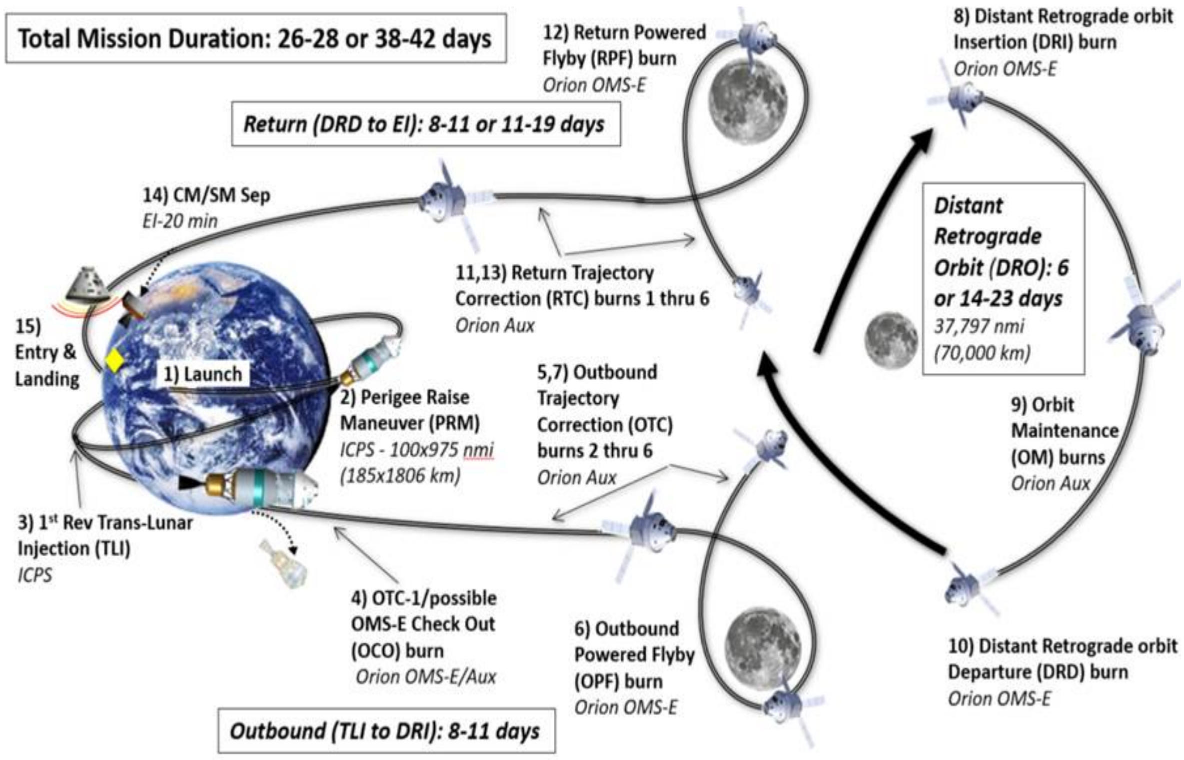
- **Dose Distribution Inside the International Space Station - 3D**
  - DLR lead effort to dose map all the ISS segments (2012 – 2018)
  - Passive Dosimeter Package (PDP) includes TLDs + OSLDs + CR-39 PNTDs
  - Large international participation includes:
    - Technical University Vienna, ATI, Austria
    - 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

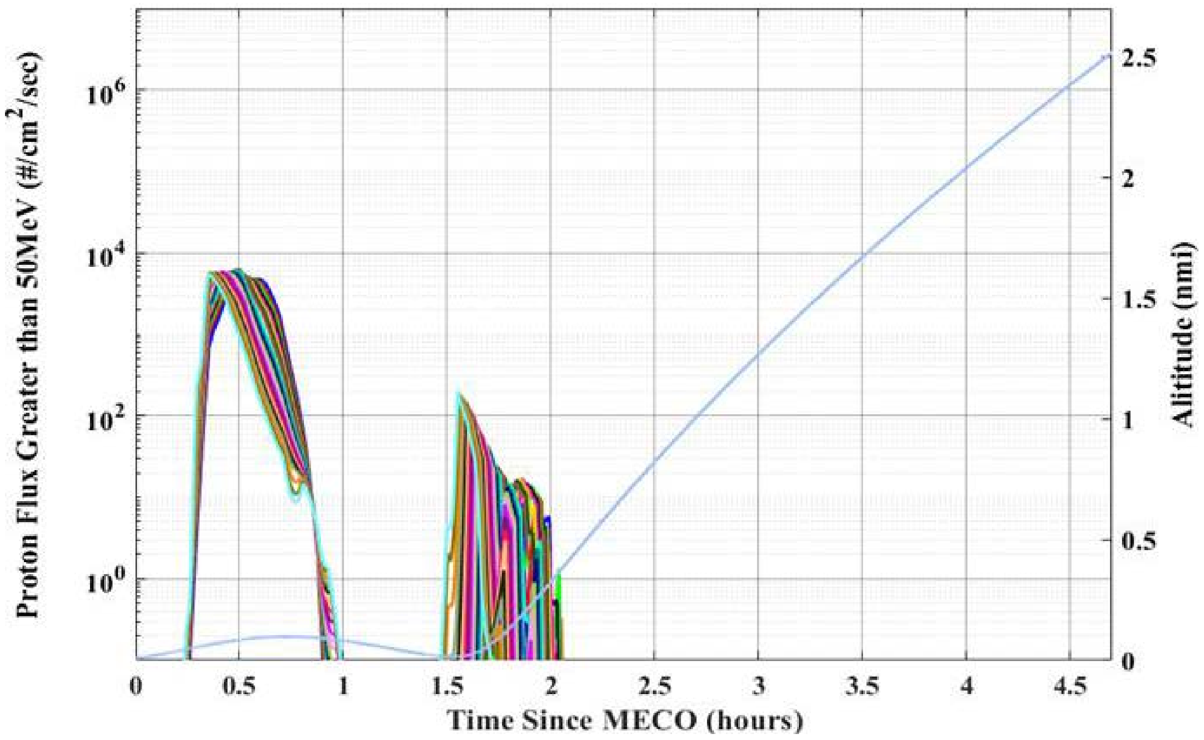
ESA Active Dosimeter (EAD)

- **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 Artemis 1 outside of MARE
- **Mass 150 g, volume 6x10x3 cm^3**
- **Thin/Thick Silicon Detector**
- **Instadose®**
- **RadFET**

Artemis 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)





Payload Integration Status

- **Successfully completed combined PDR/CDR (Mar 2019)**
  - Structural analysis, Vibration testing
- **Successfully completed Phase 0/I/II Safety Reviews (Mar 2019)**
- **Installation validation in the Orion Structural Test Article**
  - Mass representative mock-ups (Scheduled for first week of October 2019)
- **Science activities**
  - Additional detectors from HERADO / Hellenic space Agency / Thessaloniki University (Greece)
  - Environment and Dose Projection Refinements
- **Late stow vehicle installation**
- **Artemis 1 Flight (2020)**
- **Post-flight data processing, consolidation and publication**
  - AstroRad vest improvements

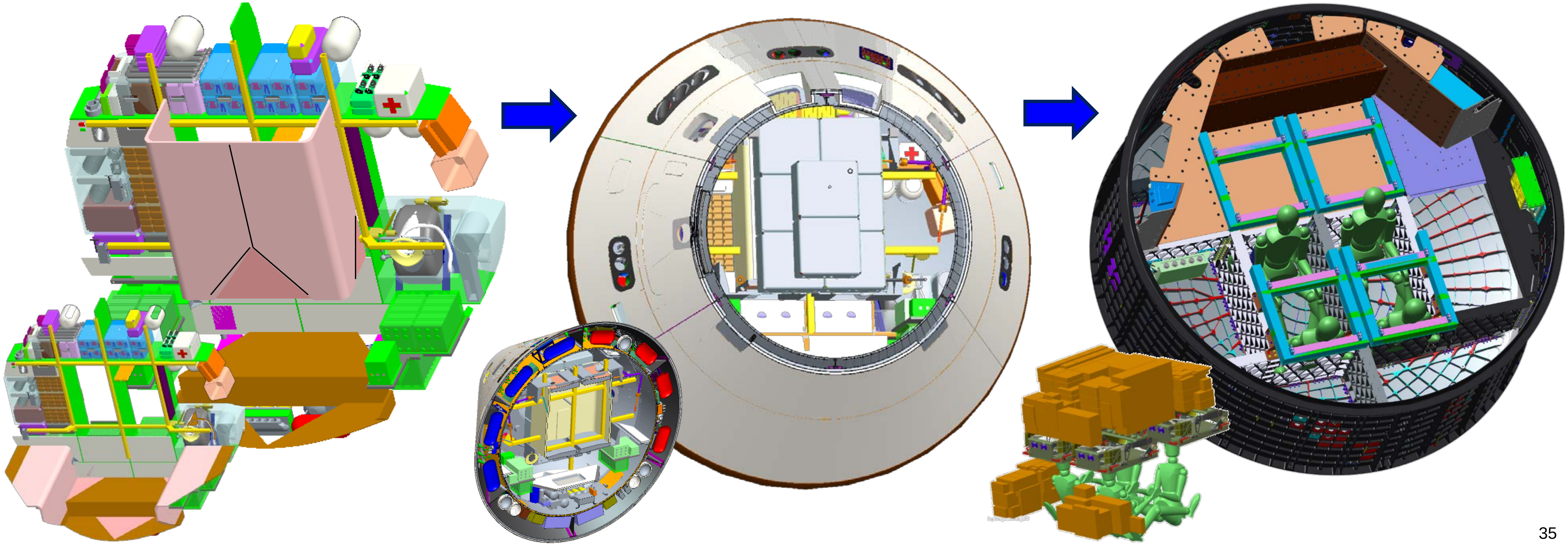
Conclusion

- **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

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

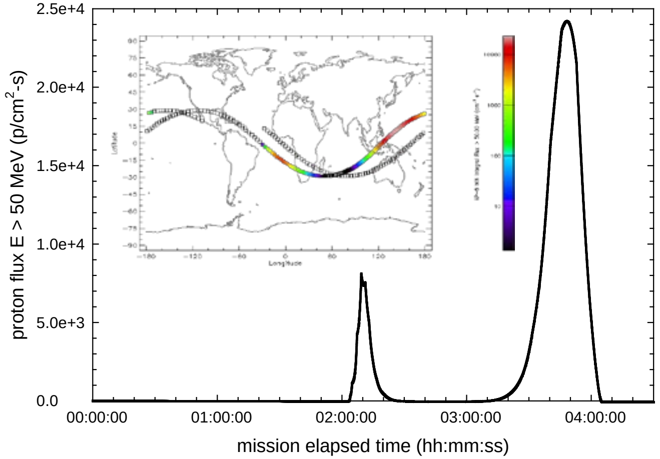
Image Credit: NASA

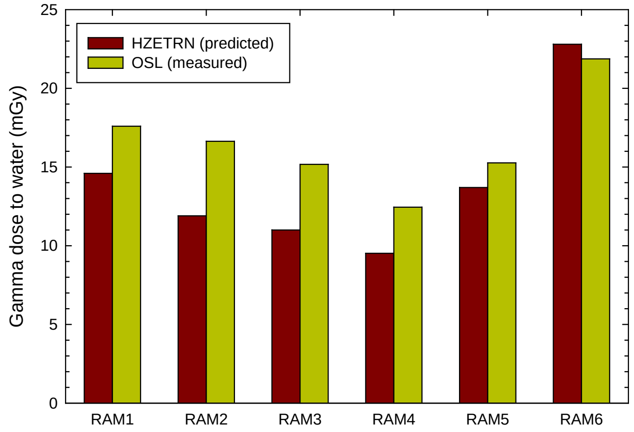
Cabin Reconfigured for SPE

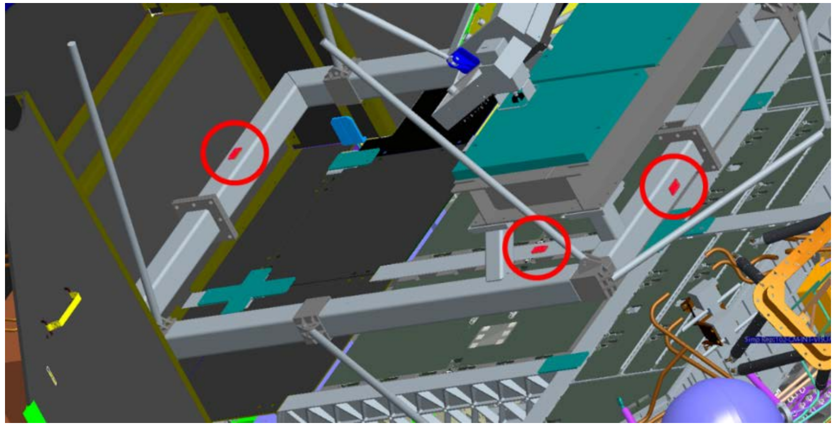
Image Credit: NASA

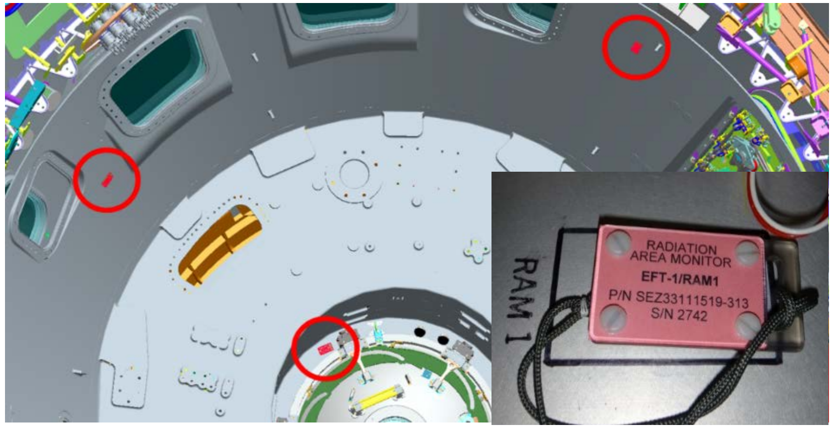
Radiation Analysis Verification by Measurement

- **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