DLR

MATROSHKA and other Physical Phantoms used for Dosimetry in Space

Guenther Reitz

Institute Nuclear Physics, Prague, Czech
German Aerospace Center (DLR),
Aerospace Medicine, Köln, Germany

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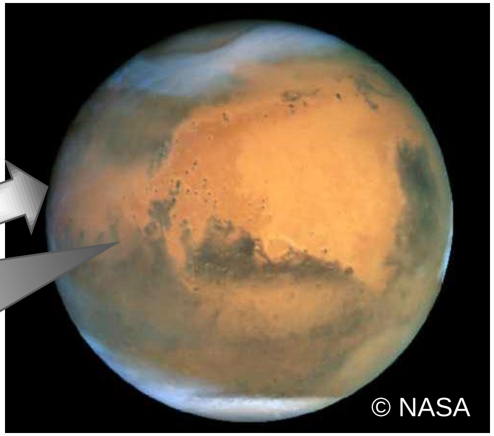
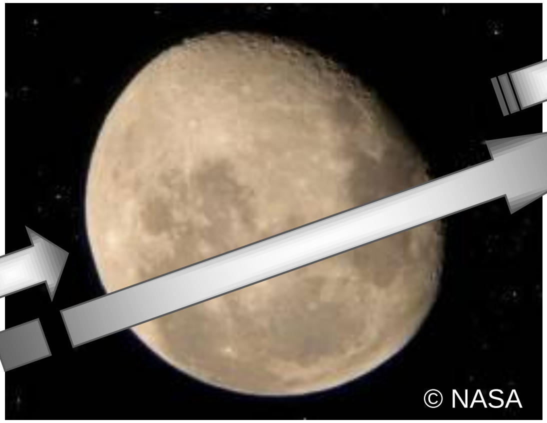
Perspectives



Missions to Mars



Missions to Moon, Deep Space Habitat in Cis- Lunar Space, lunar human outpost on the South Pole

Utilization of the ISS

Low Earth Orbit (LEO)

Beyond LEO

Major Objective of Space Radiation Protection Research

Radiation constitutes one of the major hazards for humans in long-term missions…….

……   therefore we have to assure that the radiation risk of the astronauts remains within acceptable levels

……   a precondition is a reliable forecast and the provision of precise measurements

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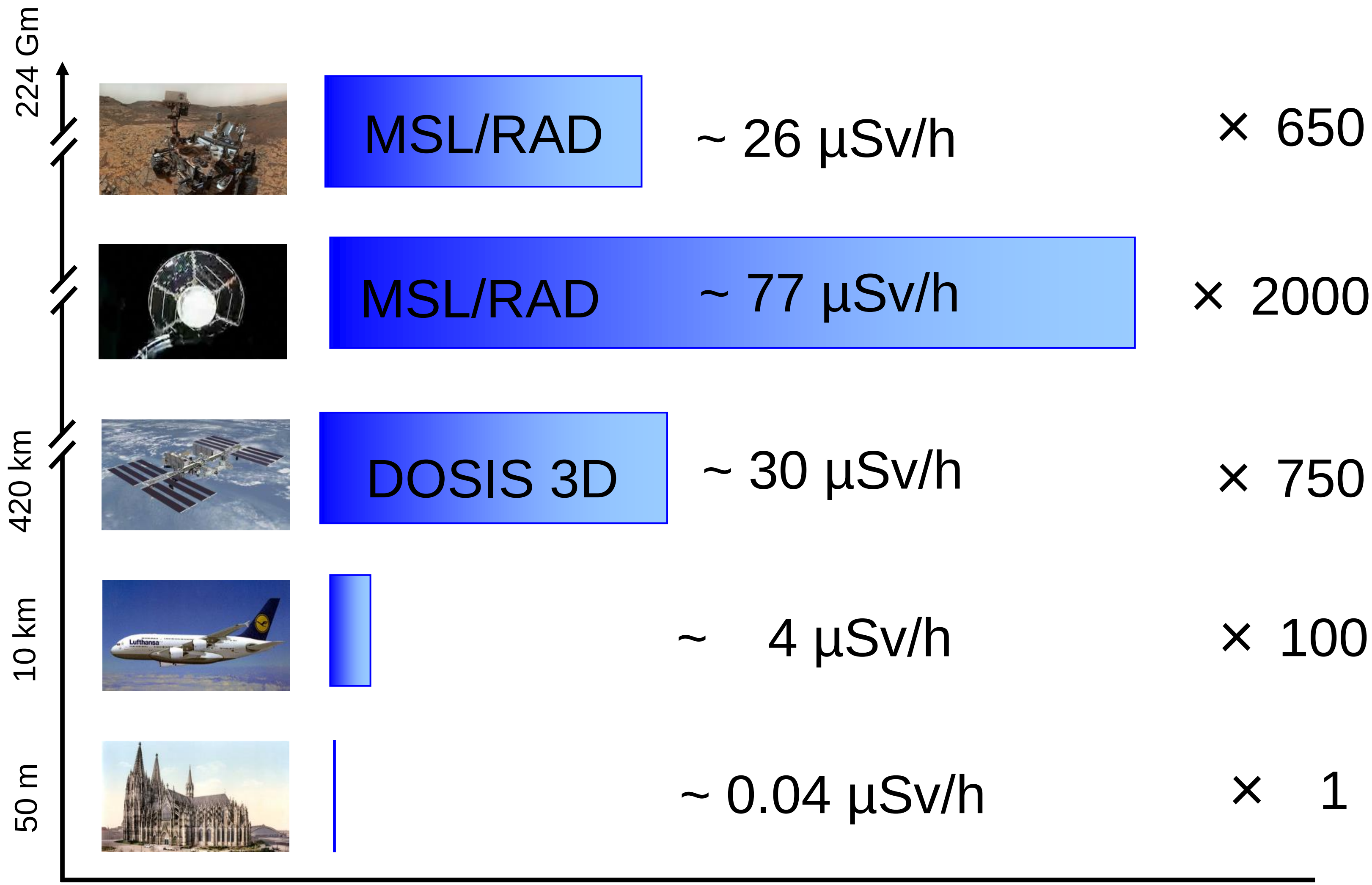
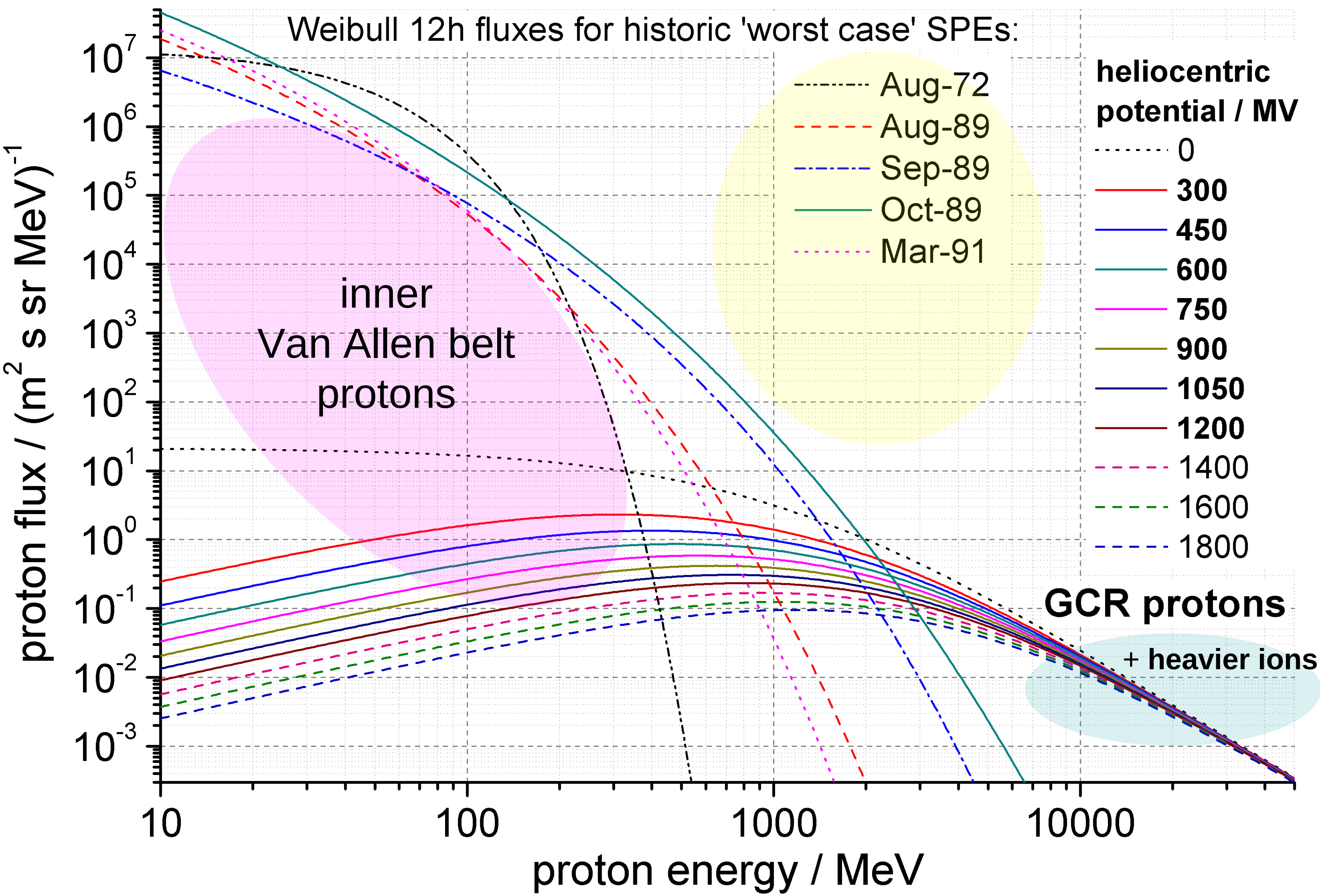
Radiation Exposure by GCR



Fluxes of primary space radiation components



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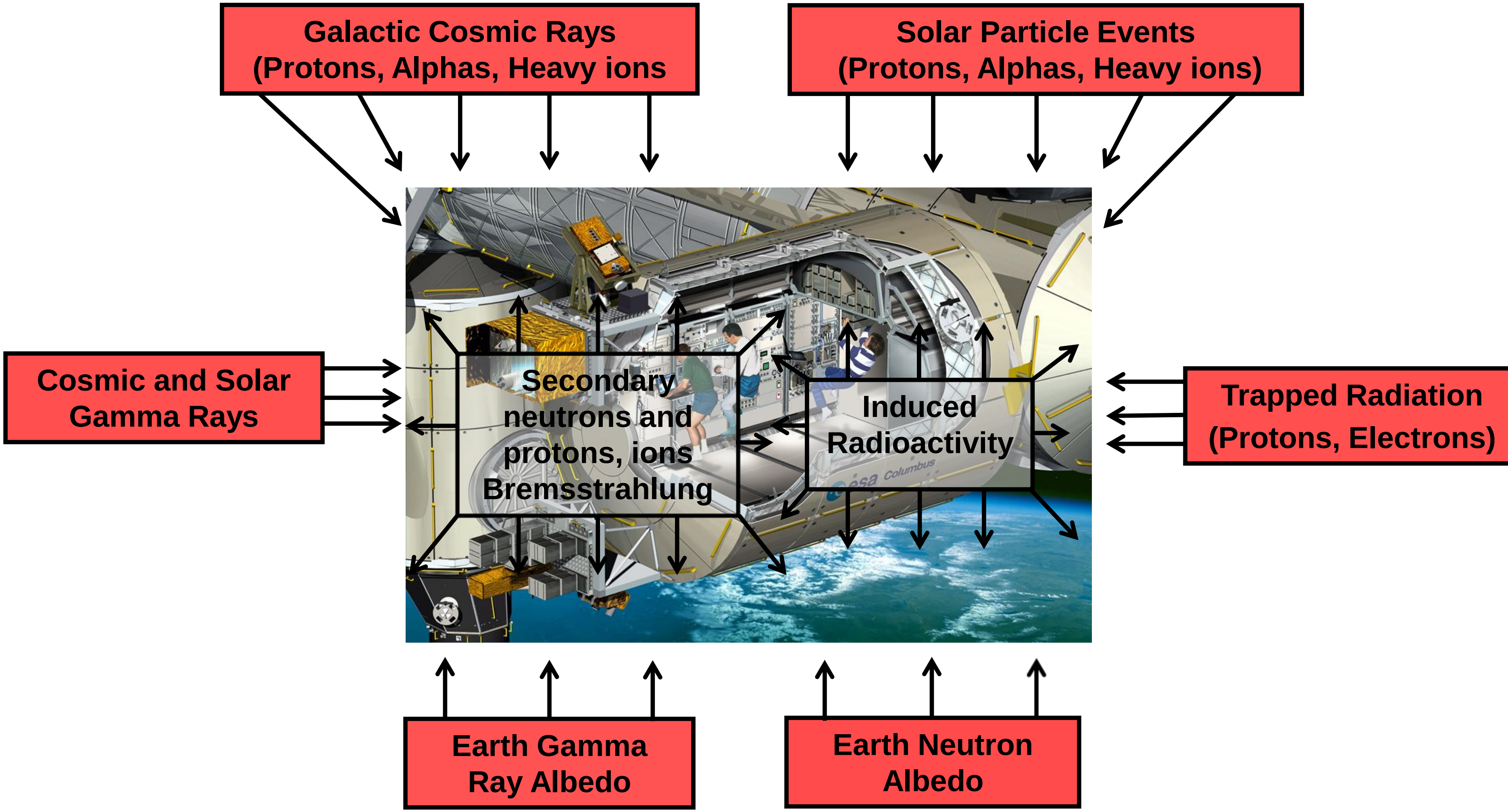
Secondary Radiation



Dosimetric Quantities

Absorbed Dose

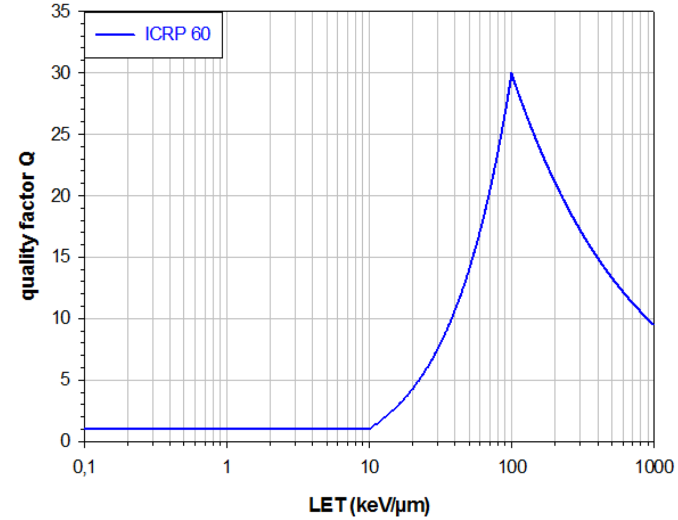
$$D = \frac{d\bar{\varepsilon}}{dm}$$

Unit: J/kg = Gy

Dose Equivalent

$$H = \int_L Q(L) * D(L) dL$$

Q = dimensionless
L = Linear Energy Transfer
Unit: J/kg = Sv



Effective Dose Equivalent

$$E = \sum_T w_T \bar{H}_T$$

w = organ weighting factor

$$\bar{H}_T = M_T^{-1} \int_x \int_L Q(L) D(L) \rho(x) dL dx$$

Tissue or organ	w_T
Bone Marrow, Breast, Colon, Lung, Stomach, Remainder tissue	0.12
Gonads	0.08
Bladder, Liver, Thyroid, Oesophagus	0.04
Skin, Brain, Salivary Glands, Bone surface	0.01

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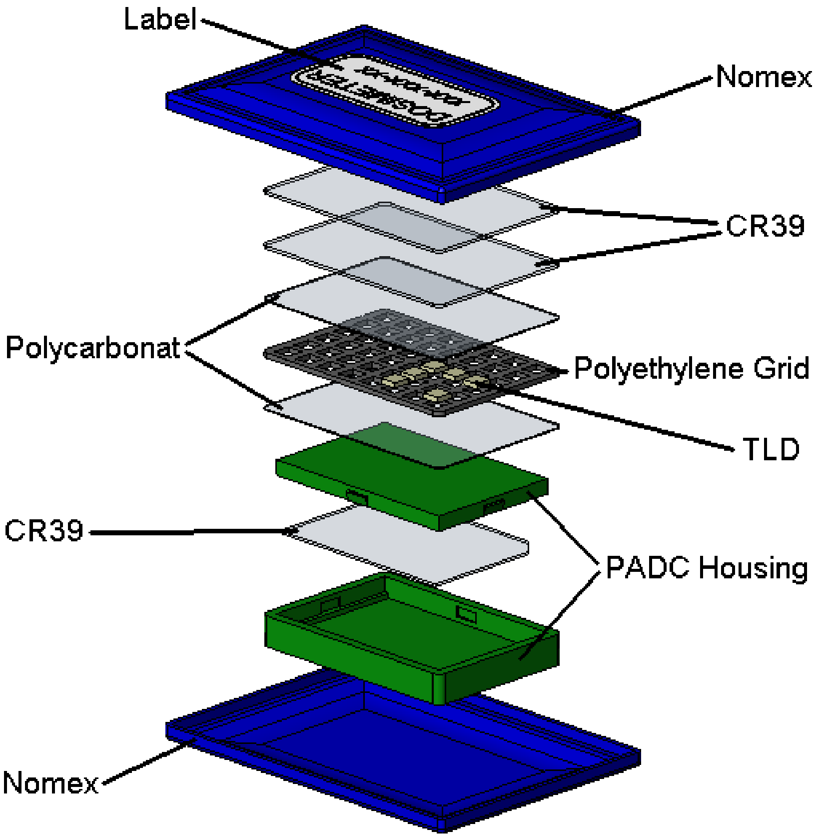
Primary Objectives of Operational Dosimetry

- Accurate monitoring of astronaut radiation exposure
- Implementation of ALARA Principle
- Provision of warning of heightened exposures levels
- Document and provide an archival record of each astronaut‘s radiation exposure
- Inform astronauts on their risk
- Provide evidence that no limits have been exceeded
- Provide supplimentary information related to intepreation of instrument readings and risk assessments

European Crew Personal Dosemeter

Light weight (~ 30g) passive dosemeter system



- ➢ Thermoluminescence Detectors (TLD´s)
- ➢ CR-39 Nuclear Track Etch Detectors
- ➢ PADC Neutron Detector

Phantom Experiments in Space

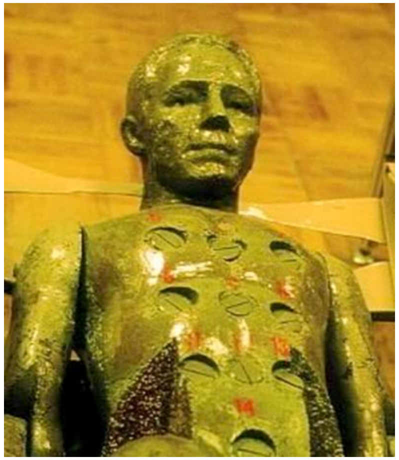
FM-2 Phantom Mannequin	1969 1970	Zond 7 Cosmos 368
Phantom Head	1989 – 1990	Space Shuttle
Spherical Phantom	1997 – 1999	Space Station MIR
Anthropomorphic Phantom	1998	Space Shuttle
Anthropomorphic Phantom	2001	International Space Station
Spherical Phantom MATROSHKA-R	2004 – until now	International Space Station
Anthropomorphic Phantom MATROSHKA	2004 – 2011	International Space Station

First Phantom flown in Space

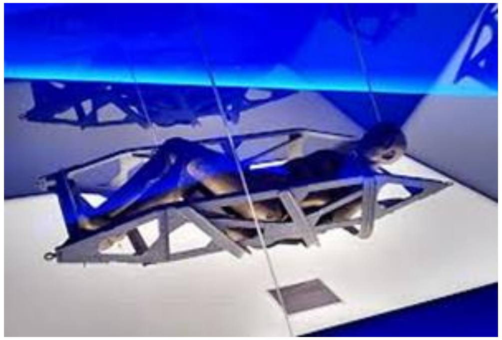
The FM-2 phantom mannequin was developed in the Research Institute of Medical and Biological Problems of the USSR Academy of Sciences in 1968. His first mission was aboard Zond 7 in August 1969. FM-2 flew past the moon aboard Zond-7 at a distance of 1984.6 km. FM-2 was reused on the six-day orbital flight of Cosmos 368 in October 1970. He was then pensioned off to a place of honor at the Polytechnic Museum, Moscow.

The mannequin with Gagarin's face was designed for the study of the effect of space radiation on the human body.

The task was complicated by the fact that for the correct assessment of the radiation dose, it was necessary for the mannequin to respond to radiation in the same way as do the tissues of the human body. This explains the unusual choice of materials: wheat and sawdust.



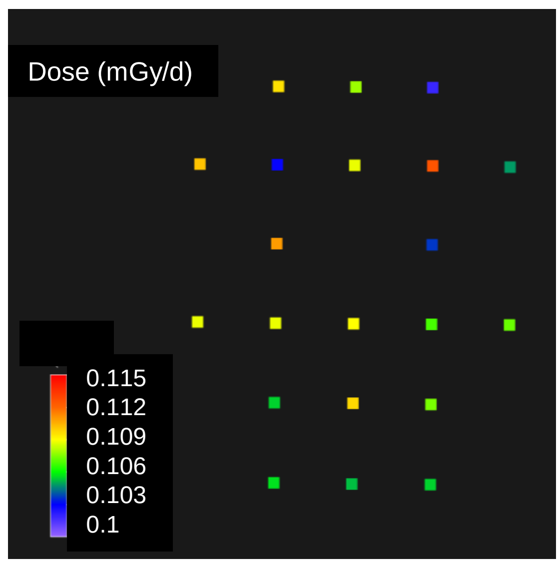
FM-2 Phantom
Credit: © Dietrich Haeseler

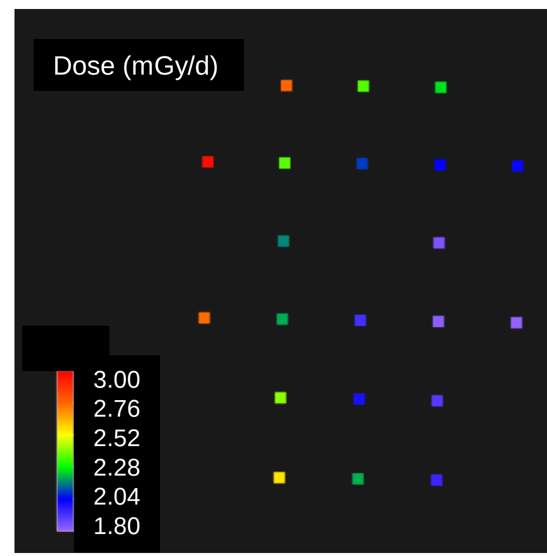


Phantom Head

	STS - 28	STS - 31
Launch date	13-08-1989	24 -04-1990
Duration (hours)	122	121.23
Inclination (°)	57.0	28.5
Altitude (km)	296	620

Konradi A., Atwell W., Badhwar G.D., Cast B.L., Hardy K. A., (1992),. Nucl. Tracks. Radiat. Meas. 20 (1), 49-54



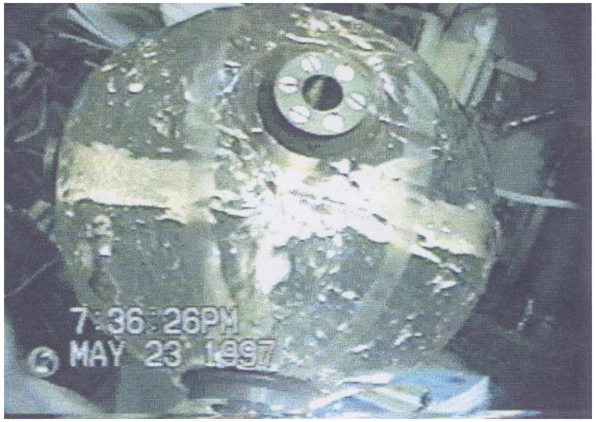


Result: „

- No „hot spots“ in the brain
- No increase in dose inside the human head.

Spherical Phantom

- Phantom 1 MIR (May 1997 – February 1998)
- Phantom 2 MIR (May 1998 – August 1998)
- Phantom 3 MIR (August 1998 – February 1999)

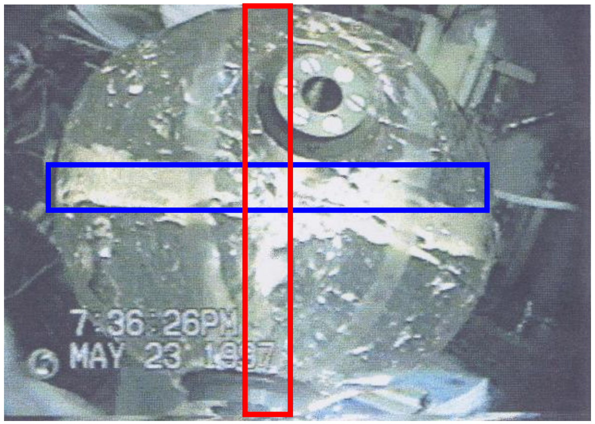


Berger, T. Hajek, M. et al (2002), Application of the HTR-Method for Evaluation of the Depth Distribution of Dose Equivalent in a Water Filled Phantom on Board Space Station MIR, Radiat. Prot. Dosim. 101 (1-4) 503 - 506.

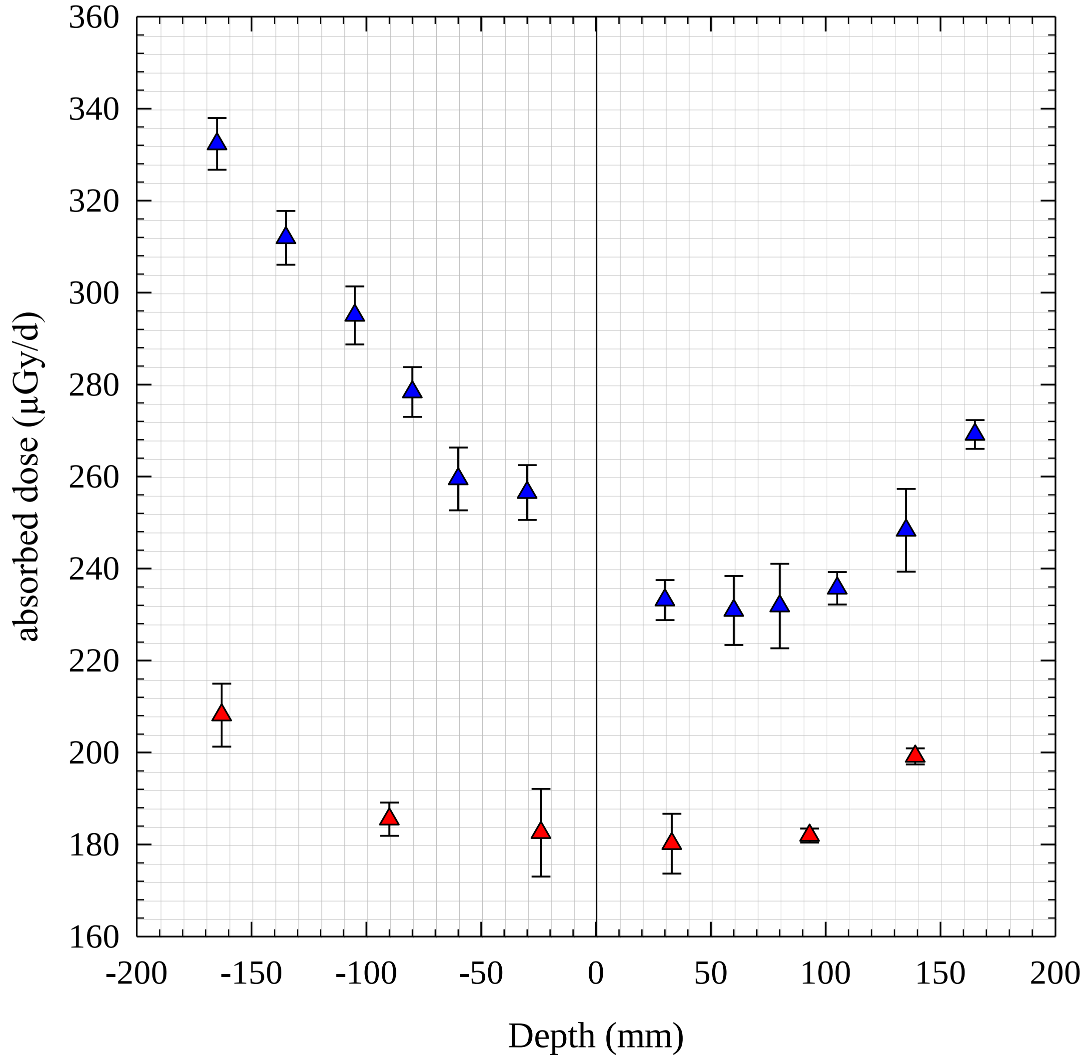
Berger, T., (2003) Dose assessment in mixed radiation fields – Special emphasis on space dosimetry, PhD Thesis, Vienna University of Technology

Space Station MIR – Phantom I / Phantom III

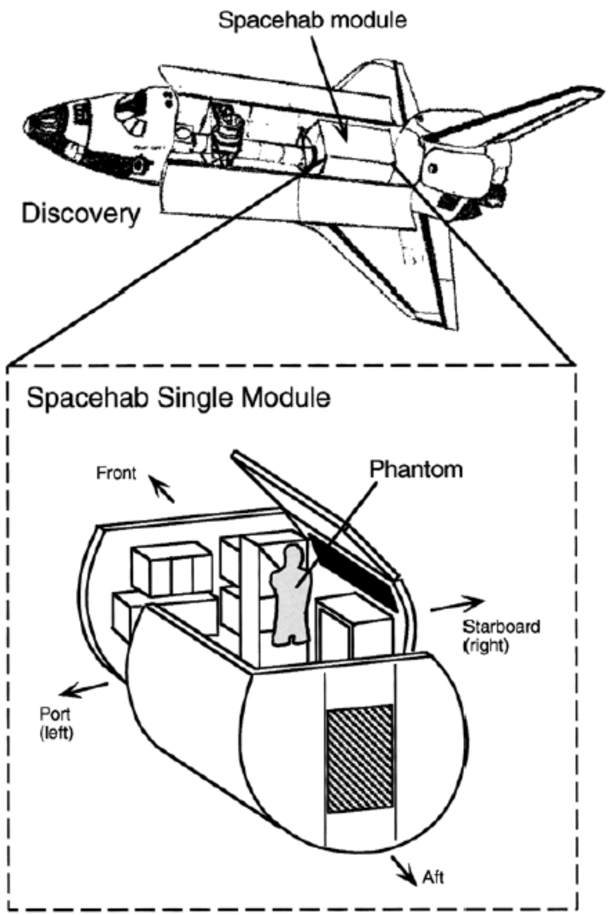
spacecraft hull

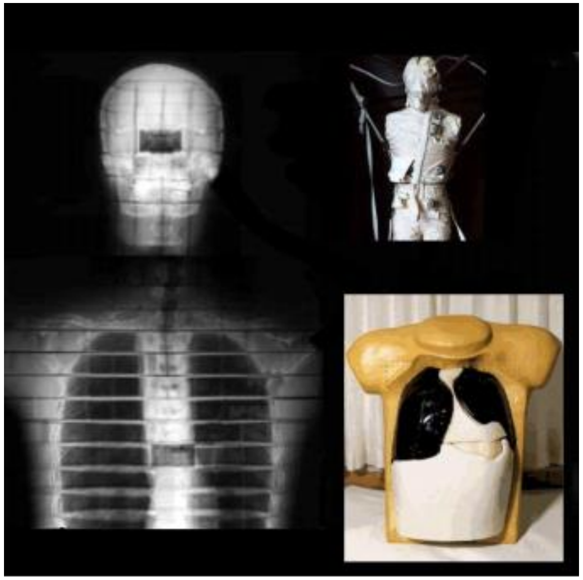


	Phantom I (5/97 – 2/98)	Phantom III (8/98 - 2/99)
Duration (days)	271	170
Location	Commander Cabin	Modul Kwant 2



STS-91 June 1998 : Fred – 1





STS – 91	Shuttle-Mir Mission
Launch	02-06-1998
Duration (hours)	236
Inclination (°)	51.56
Altitude (km)	~ 390

Badhwar G.D., Atwell W., Badavi F.F., Yang T.C., Cleghorn T.F., (2002), Radiat. Res. 157 (1), 76-91

Yashuda H., Badhwar G.D., Komiyama T., Fujikata K., (2000), Radiat. Res. 154 (6), 705 – 713

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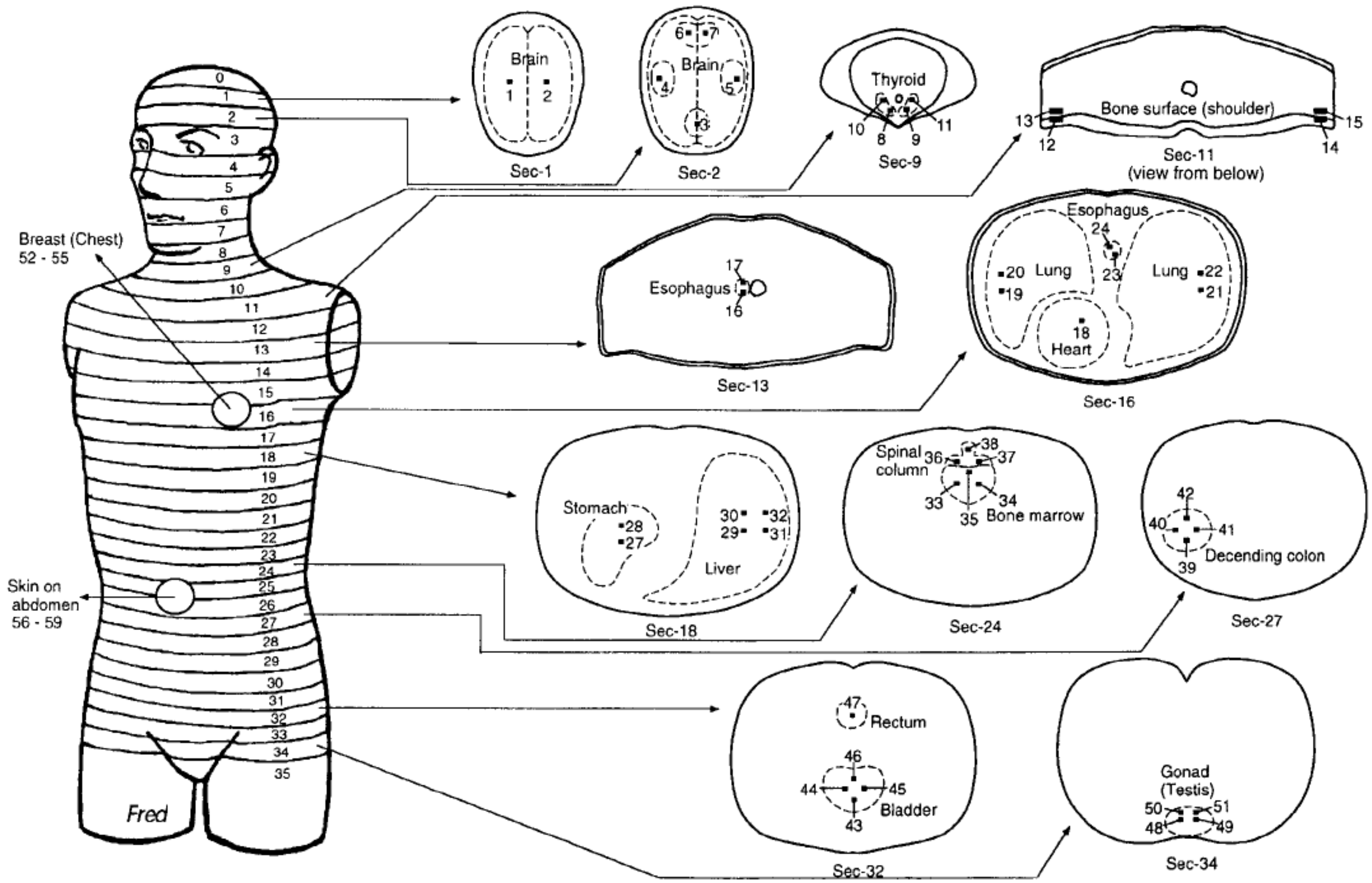
Human Phantom Torso indicating the positions of detector cases



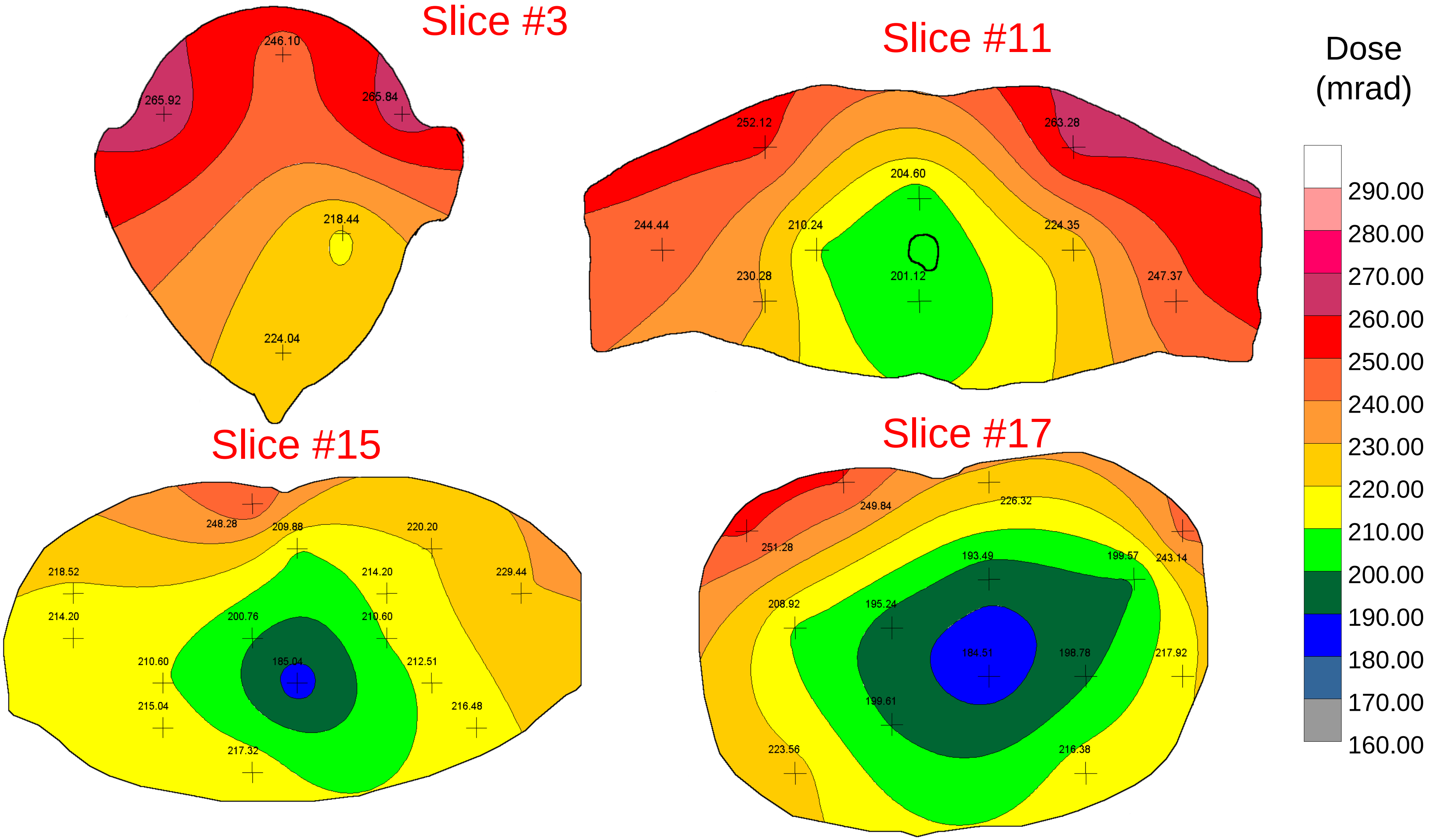
59 Positions
(NIRS/JAXA)

TLD+CR-39
(Organ dose)

358 Positions
(NASA)

TLD
(Depth dose)

RESULTS: STS-91 June 1998 – TLD Depth Dose



Data provided by: E. Semones, NASA, JSC

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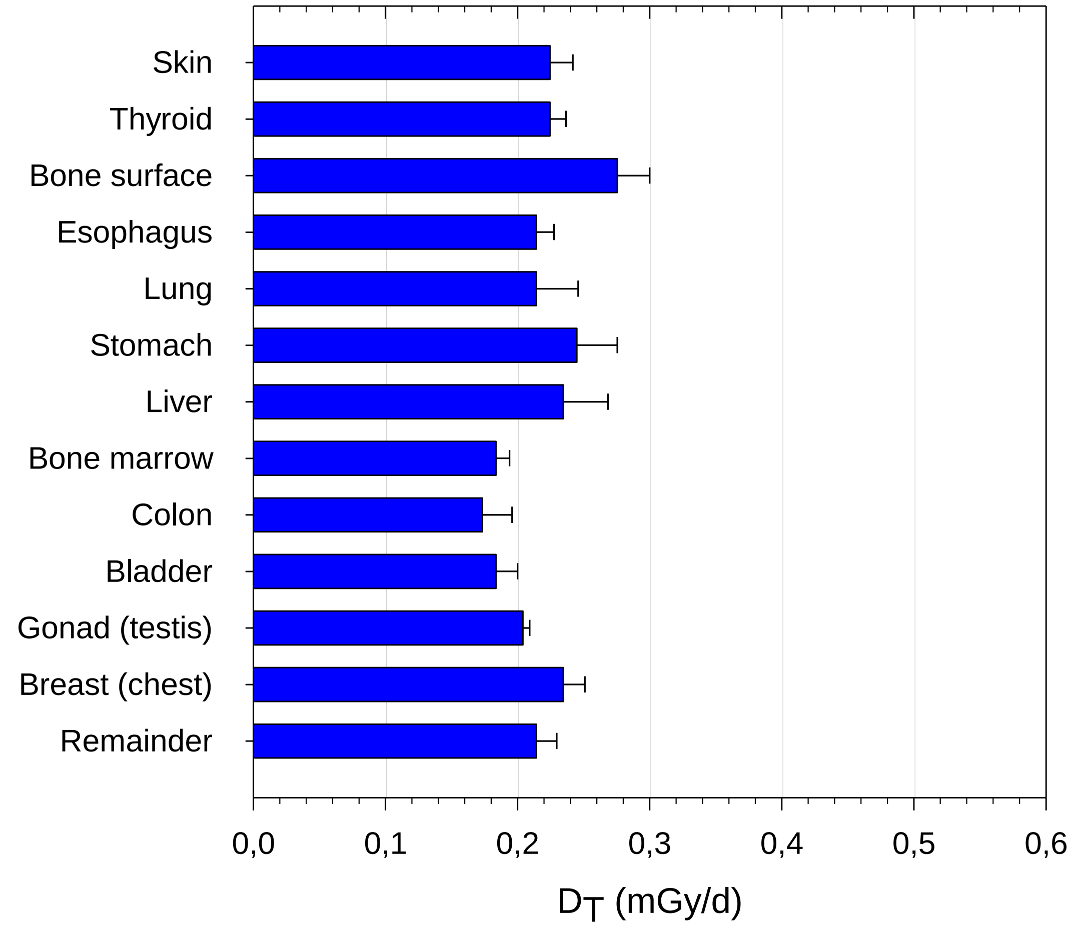
RESULTS: Organ absorbed doseSTS-91 June 1998 – TLD + CR-39



Yashuda H., Badhwar G.D., Komiyama T., Fujikata K., (2000), Effective Dose Equivalent on the Ninth Shuttle MIR Mission (STS-91), Radiat. Res. 154 (6), 705 – 713

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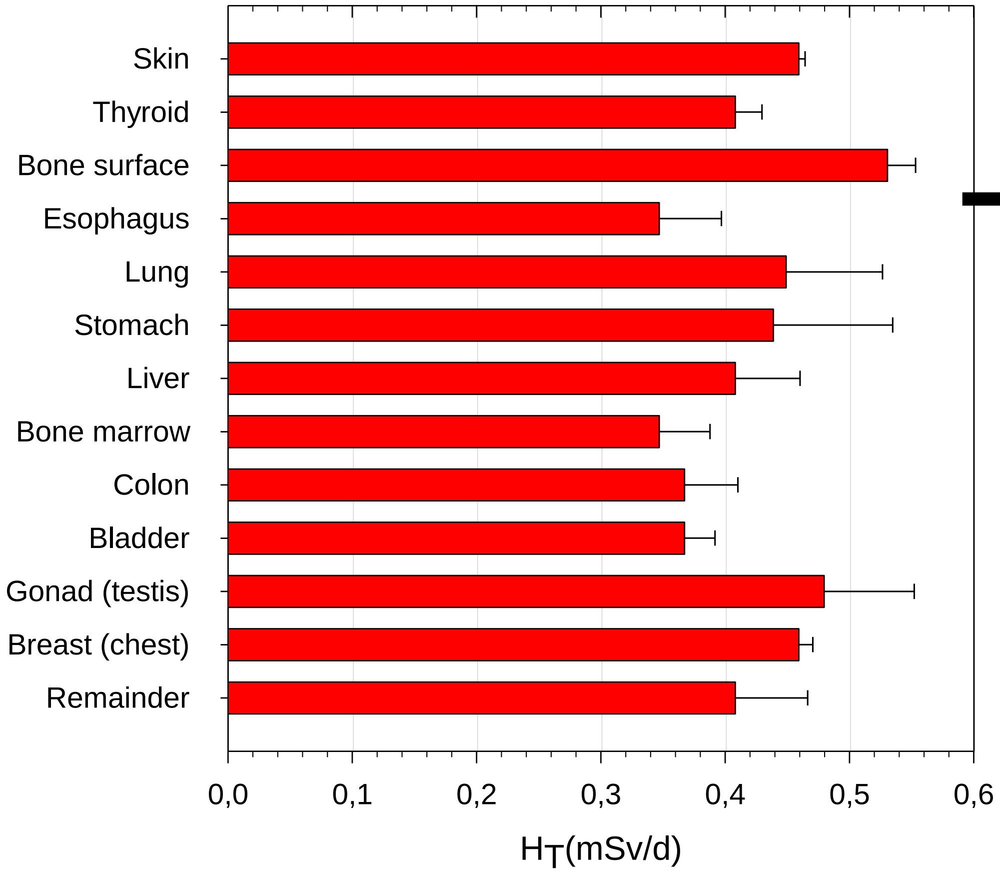
RESULTS: STS-91 June 1998 : Effective Dose E



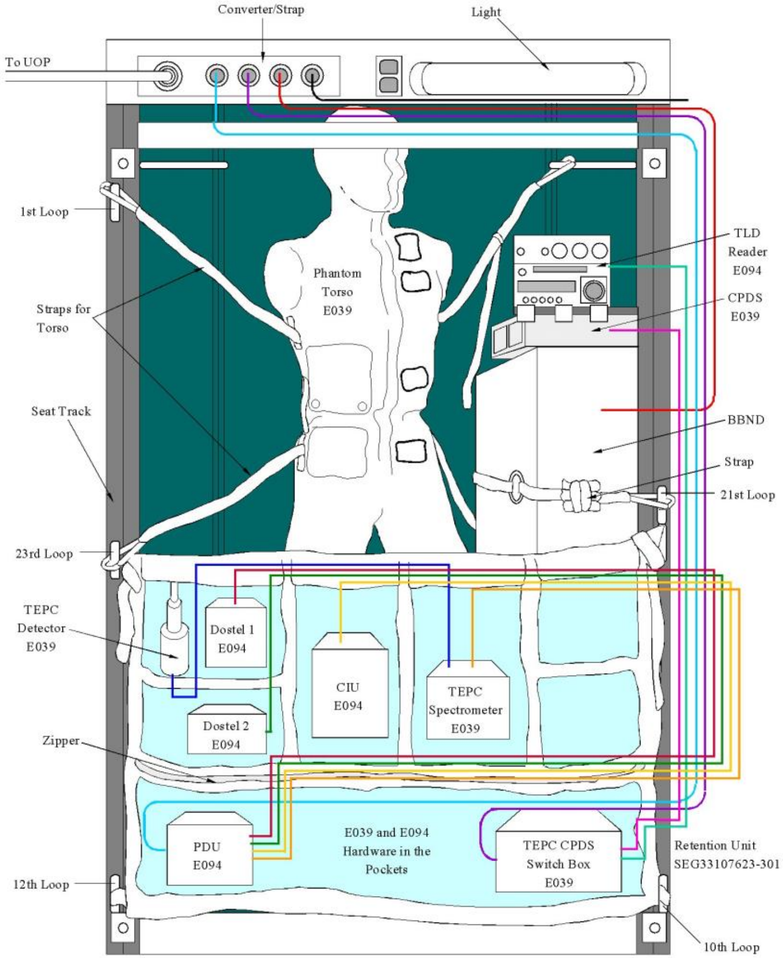
$$E = \sum_T w_T \overline{H}_T$$

E = 0.41 ± 0.2 mSv/d

(H (Skin) = 0.45 ± 0.005 mSv/d)

Ratio: H (Skin) / E = 1.1

ISS 2001 : Fred – 2



NOTE: Colored cables (shown separate for clarity) will be bundled, will run down the seat track, and will flow through the pockets of the retention unit.

Fred on ISS	
Duration (days)	123 (04-2001/08-2001)
Location	US LAB

Cucinotta, F., Myung-Hee Y. Kim, M., Willingham V., George, K., Radiation Research 170, 127–138 (2008)

Yasuda, H., J. Radiat. Res., 50, 89–96 (2009)

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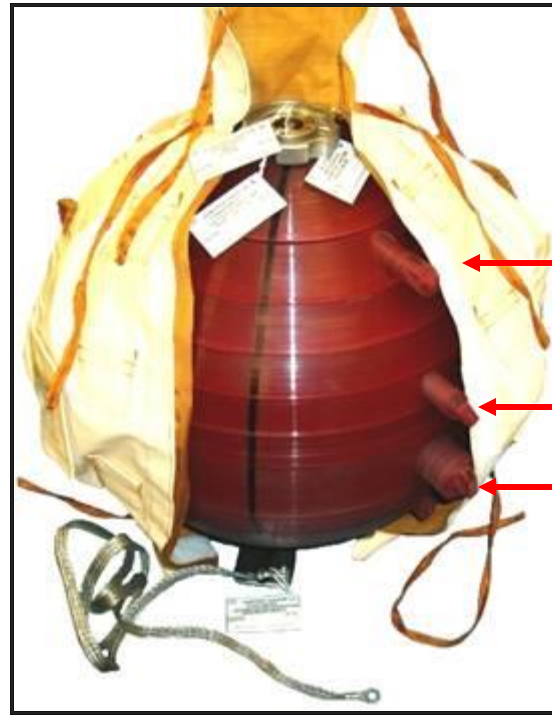
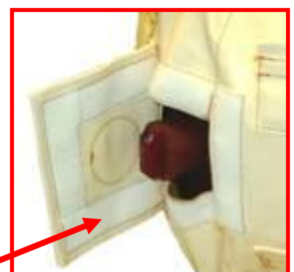
SPHERICAL TISSUE-EQUIVALENT PHANTOM

Size: 370x370x390 mm; mass: 32 kg

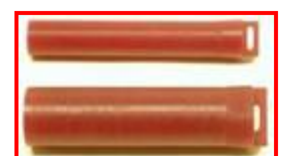


Working jacket with

LiF TLDs and
CR-39 in pockets



Container



Containers

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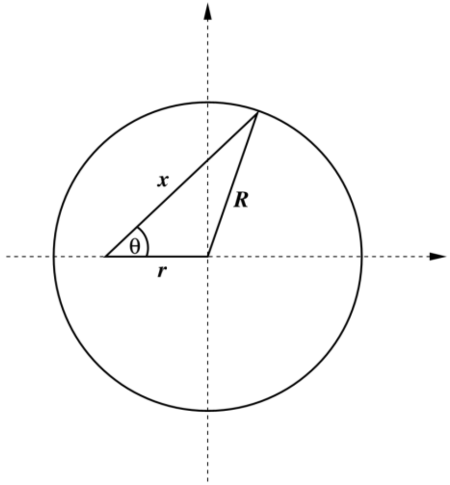
Mean Shielding in a Water Sphere



R = radius of the sphere
r = distance from the center of the sphere
x = path-length through the sphere

$$x(r,\theta) = r\cdot\cos(\theta) + \sqrt{r^2\cdot\cos^2(\theta) + R^2 - r^2}$$

$$\bar{x}(r) = \frac{1}{4\pi}\int_0^{2\pi} d\varphi \int_0^{\pi} d\theta \sin(\theta)\cdot x(r,\theta)$$

$$\Rightarrow \text{mean shielding}: \bar{d}(r) = \rho\cdot\bar{x}(r)$$

$$\text{density } \rho = 1\,\text{g/cm}^3$$

$$\text{center of the sphere}: r = 0 \rightarrow \bar{x} = R$$

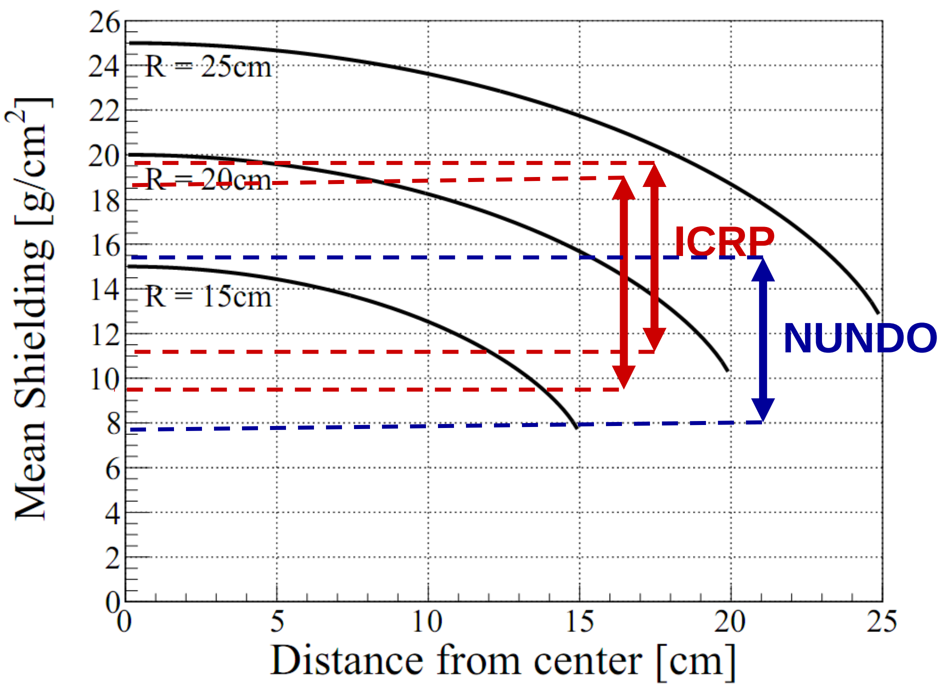
$$\text{edge of the sphere}: r = R \rightarrow \bar{x} = R/2$$

R = 25 cm: 12.5 g/cm^2 – 25 g/cm^2
R = 20 cm: 10 g/cm^2 – 20 g/cm^2
R = 15 cm: 7.5 g/cm^2 – 15 g/cm^2

Mean organ shielding:

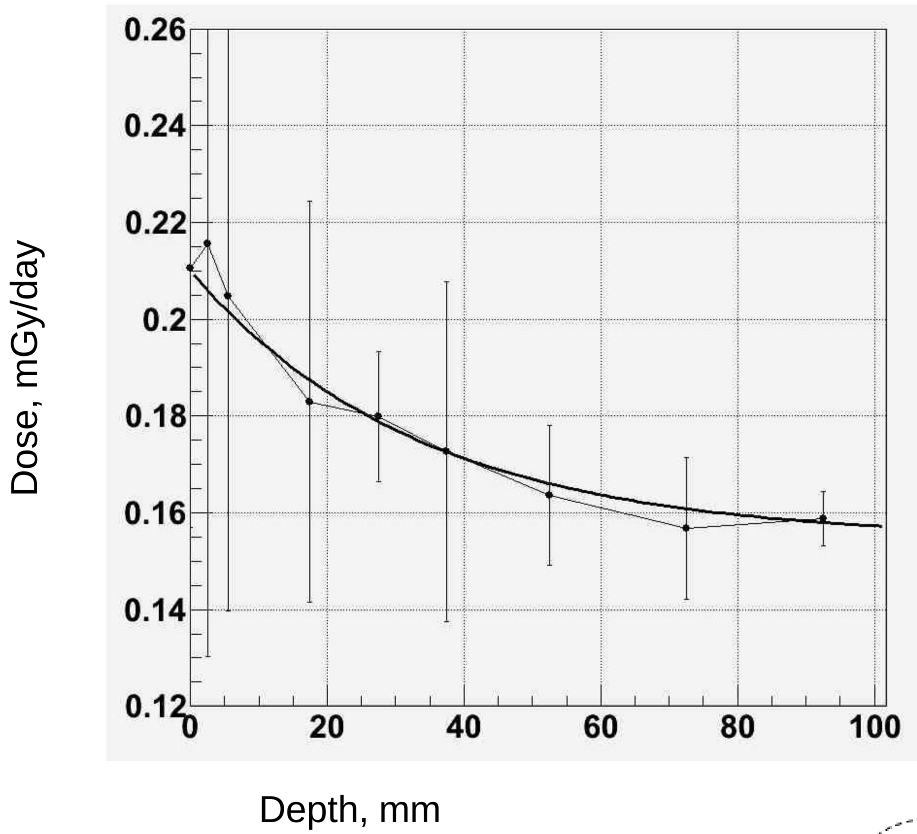
ICRP – Phantom:
Male: 10.5 – 19.1 g/cm^2
Female: 8.8 – 18.4 g/cm^2

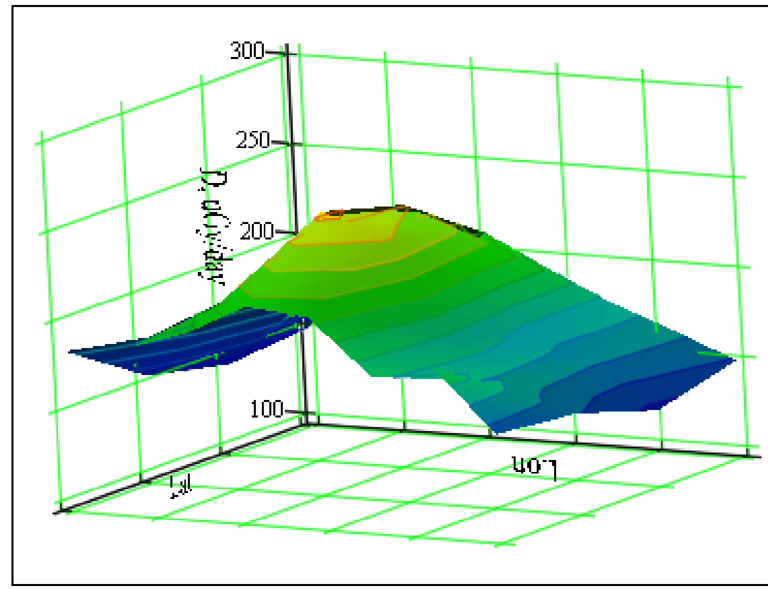
NUNDO – Phantom:
7.7 – 15.5 g/cm^2

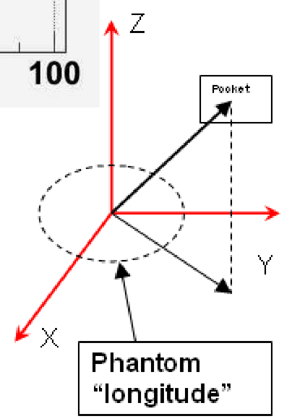


Surface dose and dose as a function of depth in the phantom

Crew quarter (session 2, 425 day)







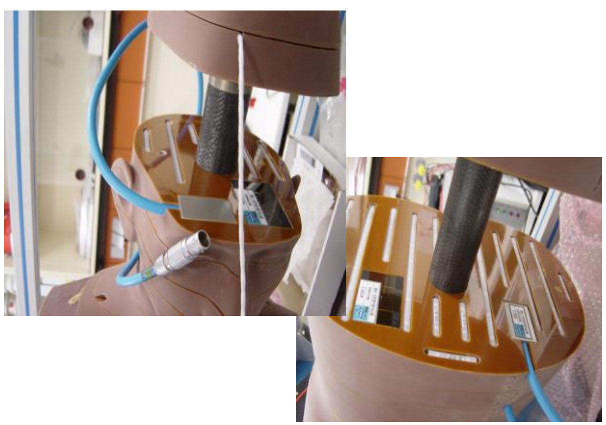
$D_{mean\text{-}surface}$ = 211 μGy/day

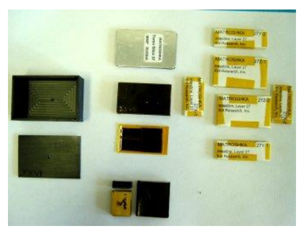
D_{min} = 137

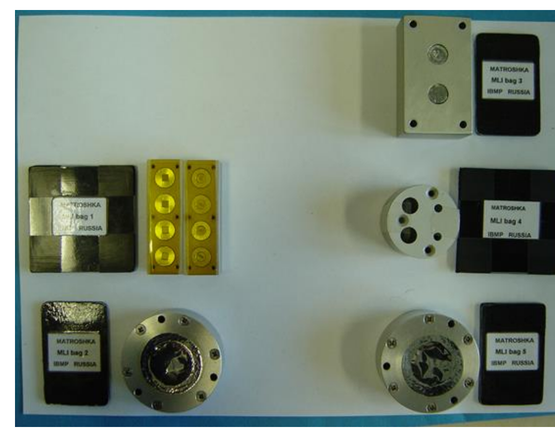
D_{max} = 253

D_{max}/D_{min} = 1.9

MATROSHKA Experiment







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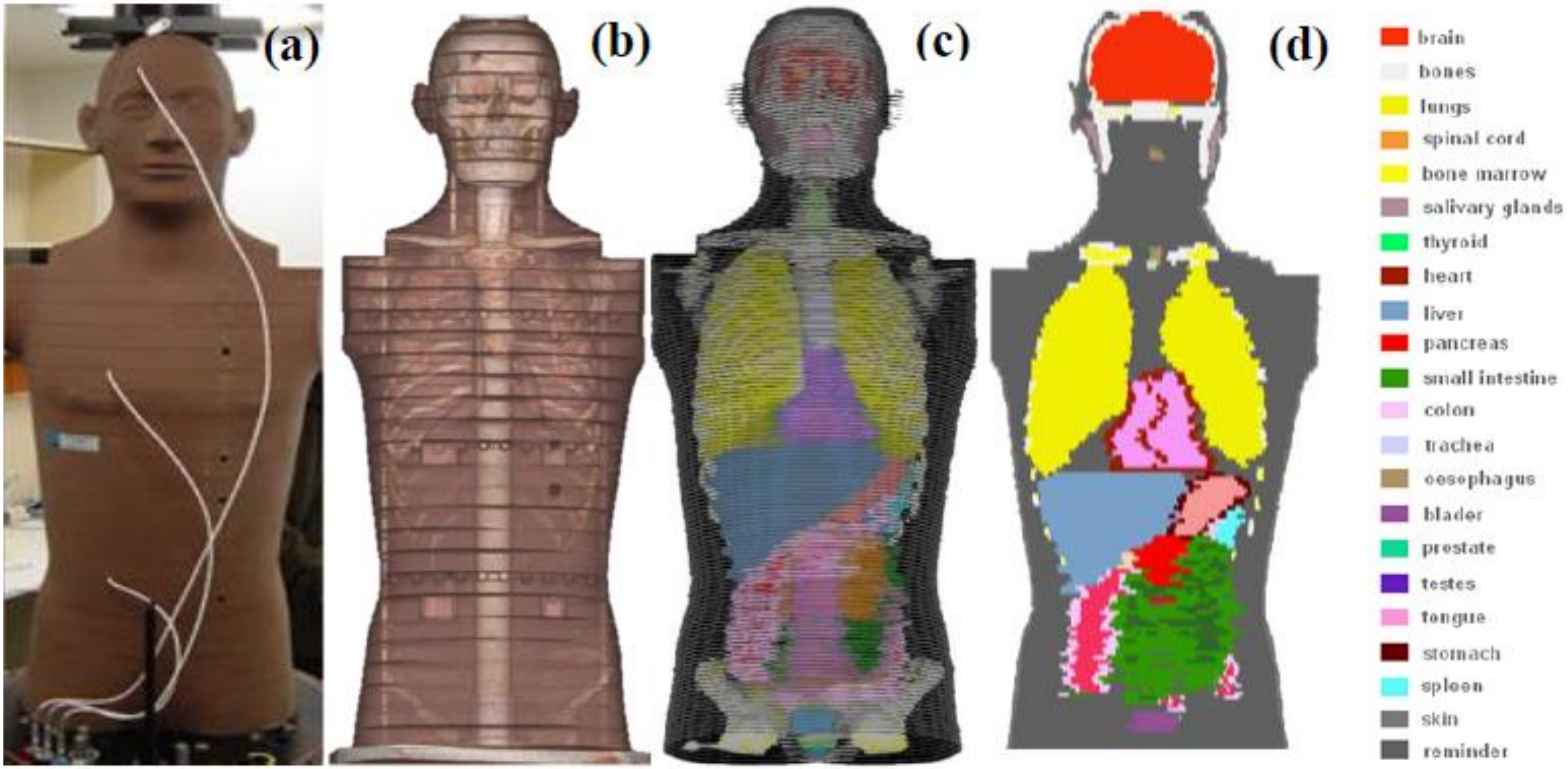
Modeling of the Numerical RANDO phantom (NUNDO)



The front view of RANDO phantom; **(b)** CT scan of RANDO phantom, **(c)** and **(d)** the numerical voxel phantom NUNDO. NOTE to **(c)** and **(d)**: Organs and tissues are represented by different colors. Not all organs are visible.

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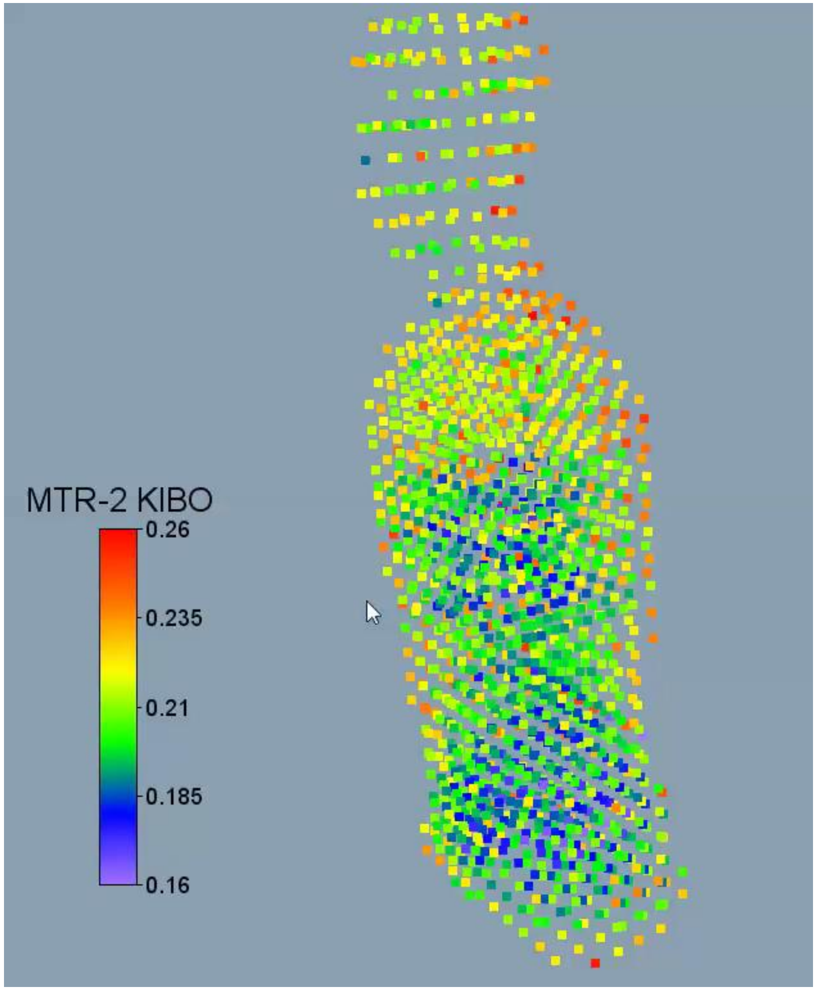
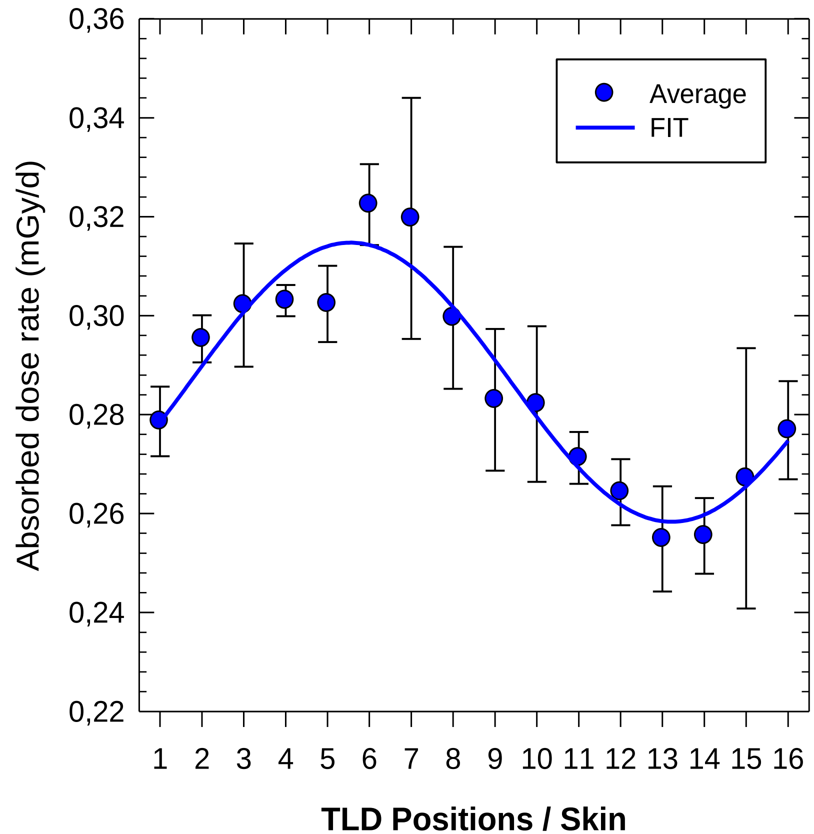
MTR-2 KIBO: Results / 3D Dose Distribution and Skin Dose





DATA: ATI, DLR, IFJ

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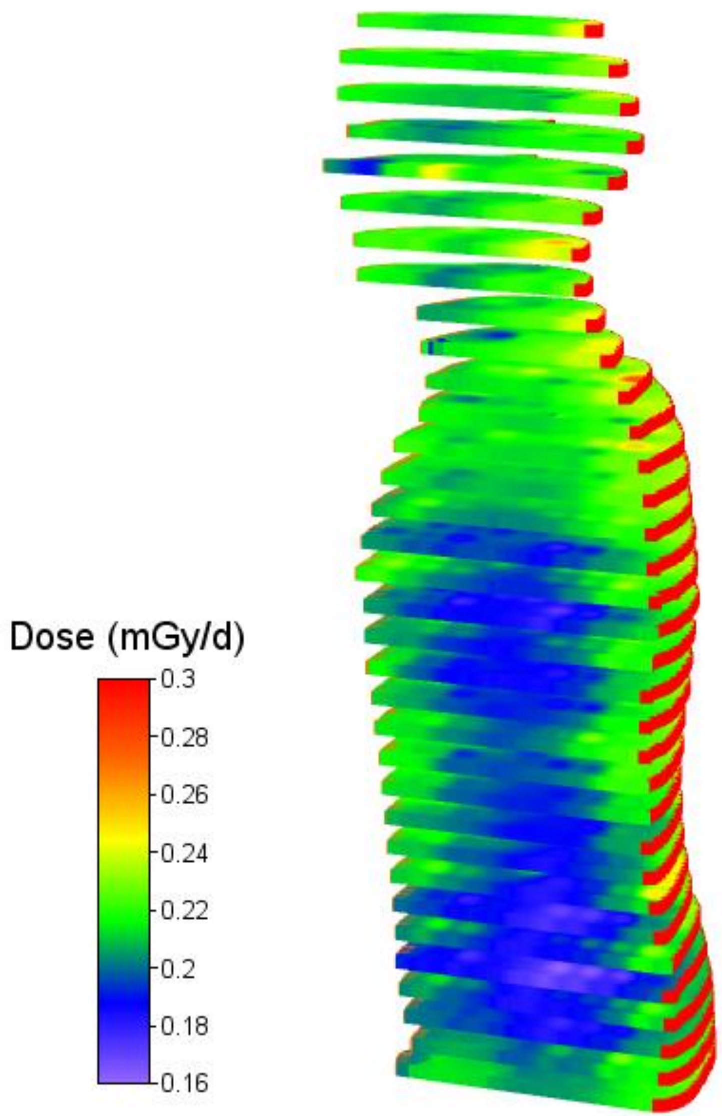
MTR-2 KIBO: Results / 3D Dose Distribution



DATA: ATI, DLR, IFJ

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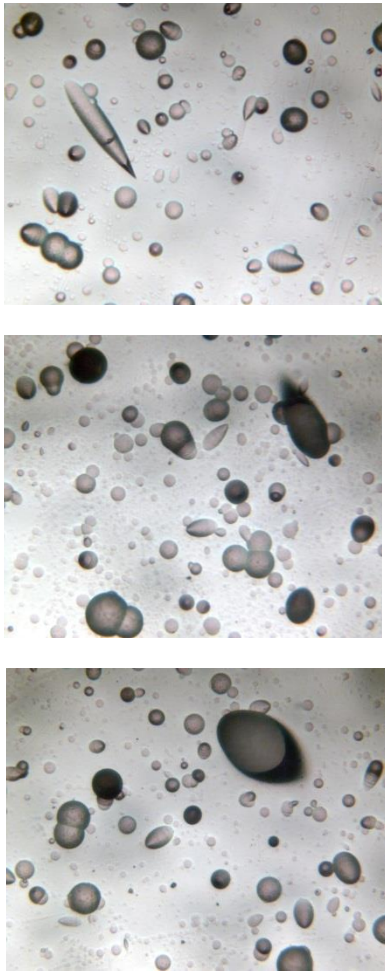
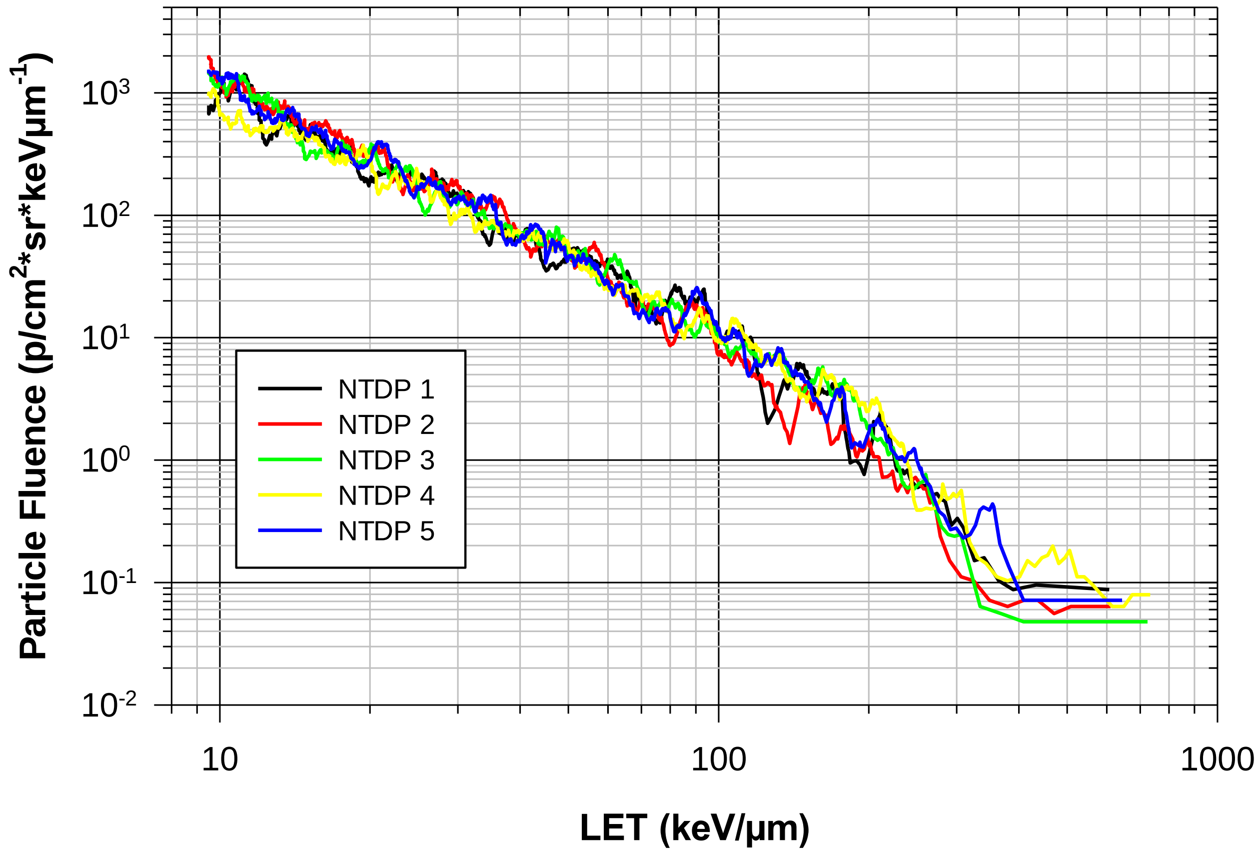
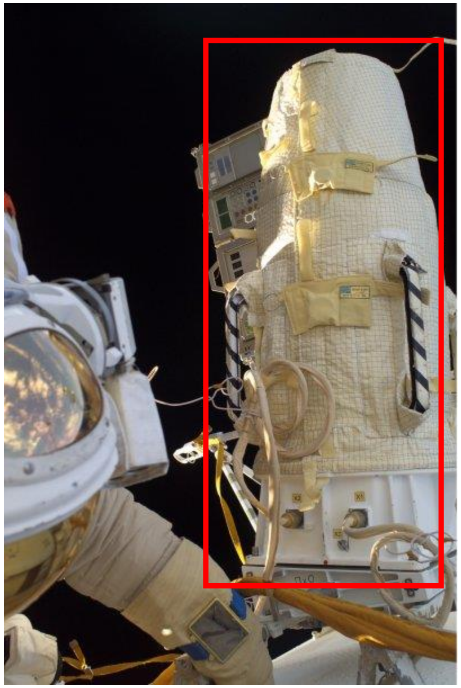
MTR-2 KIBO: Results / CR-39 (DLR)

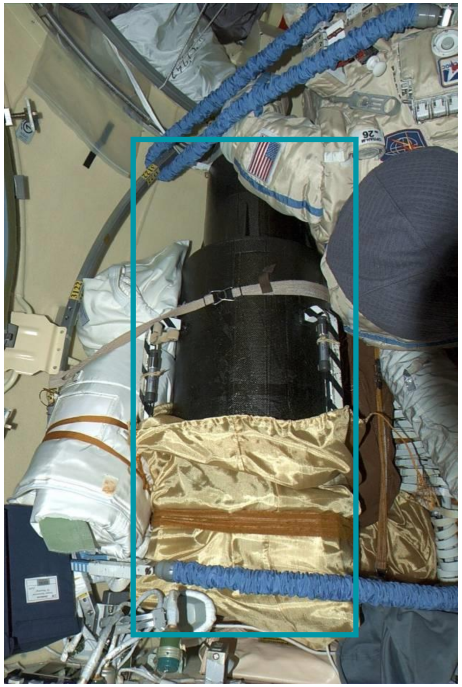




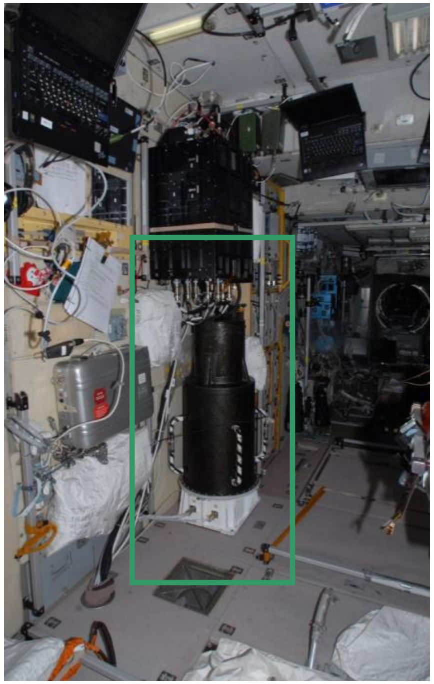
MATROSHKA: Comparison



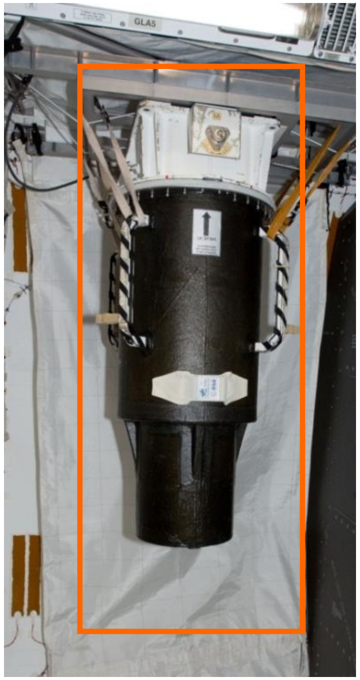
MTR-1
(2004−05)
539 days



MTR-2A
(2006)
337 days



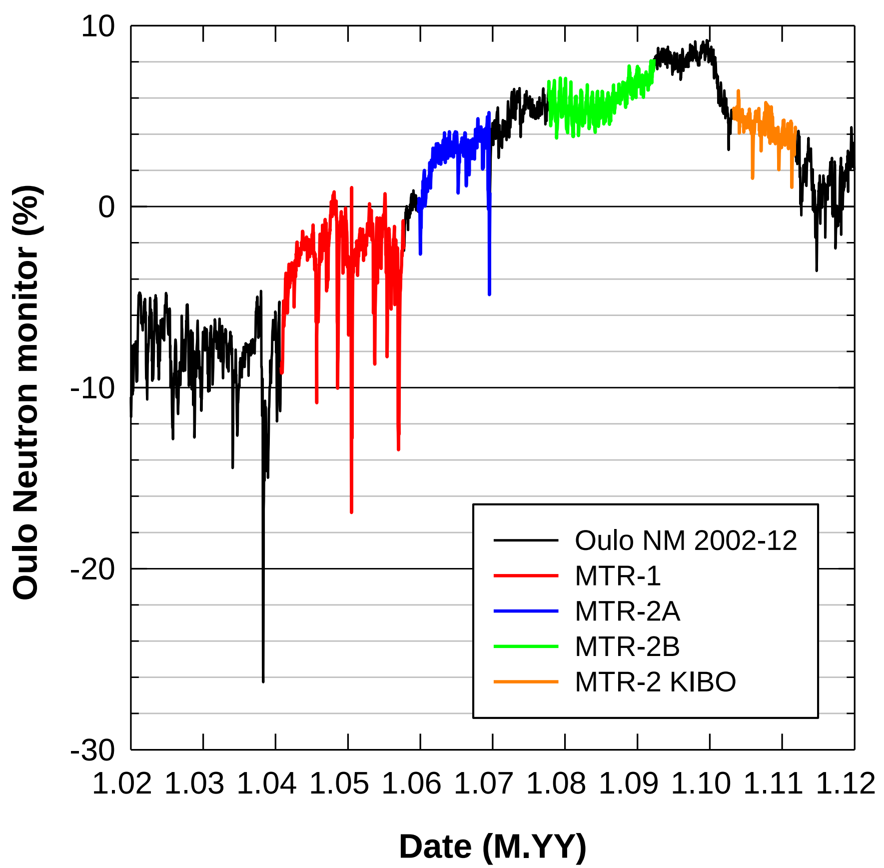
MTR-2B
(2007−09)
518 days



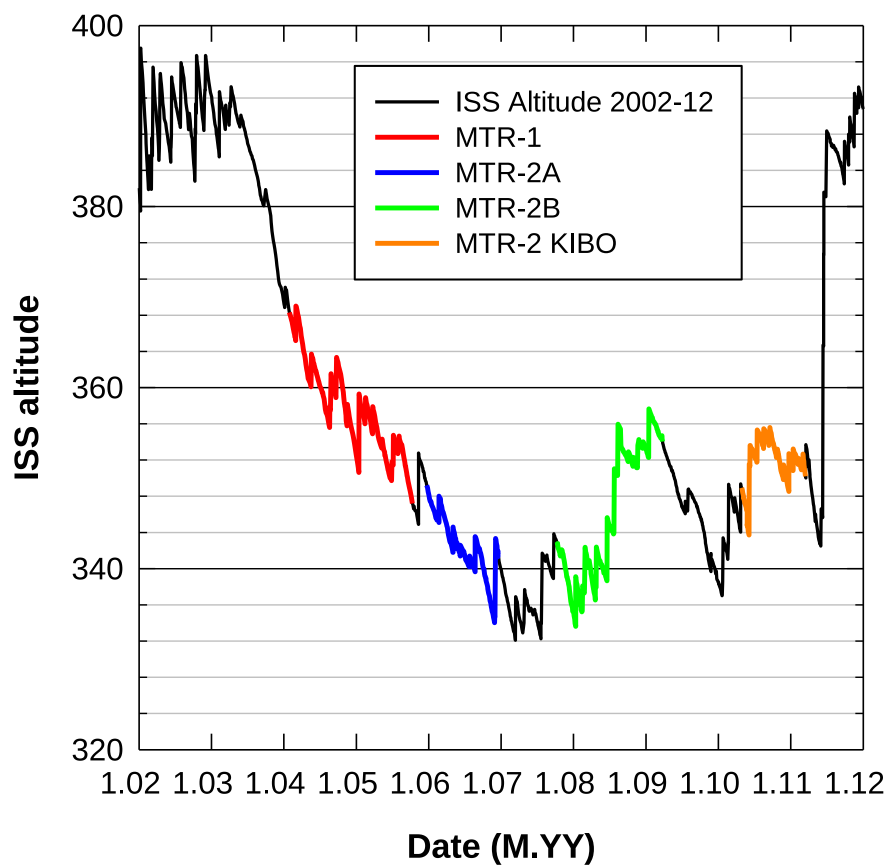
MTR-2 KIBO
(2010−11)
310 days

MATROSHKA Environmental Parameters

Oulu Neutron Monitor



ISS Altitude



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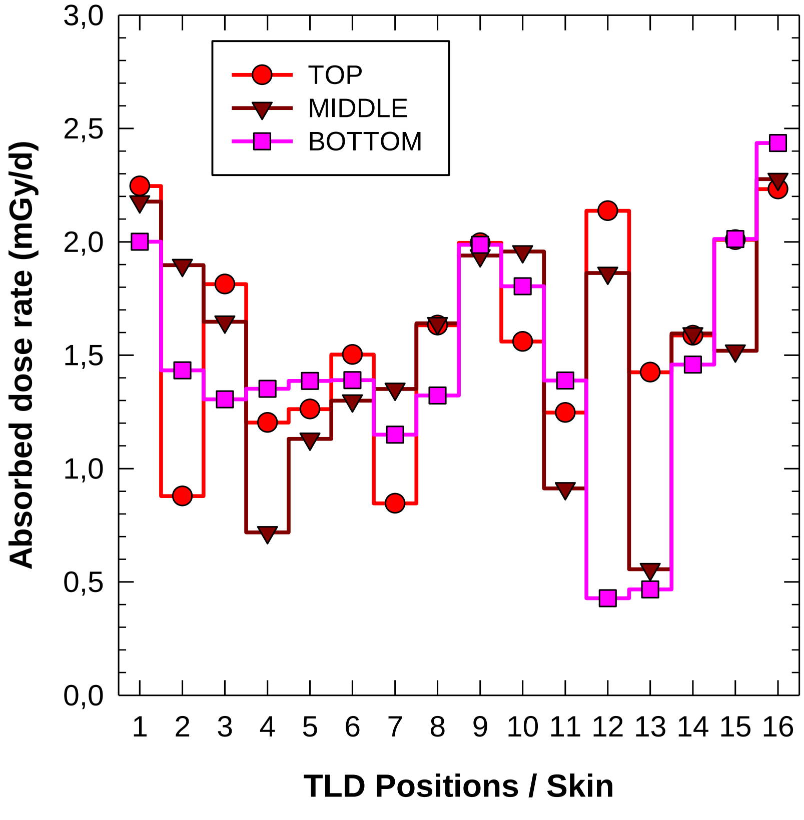
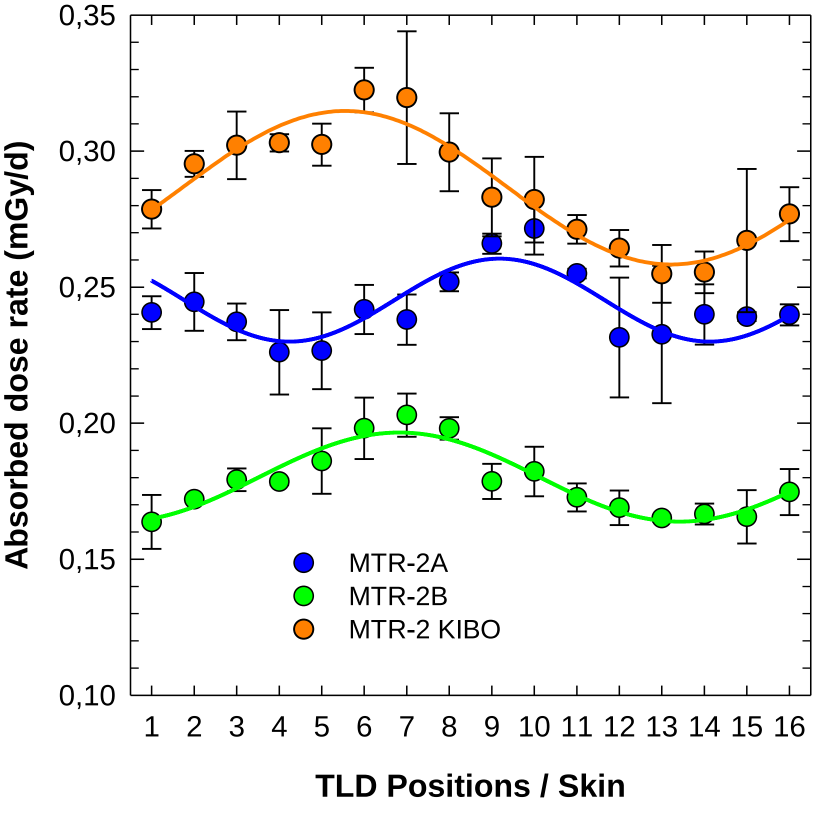
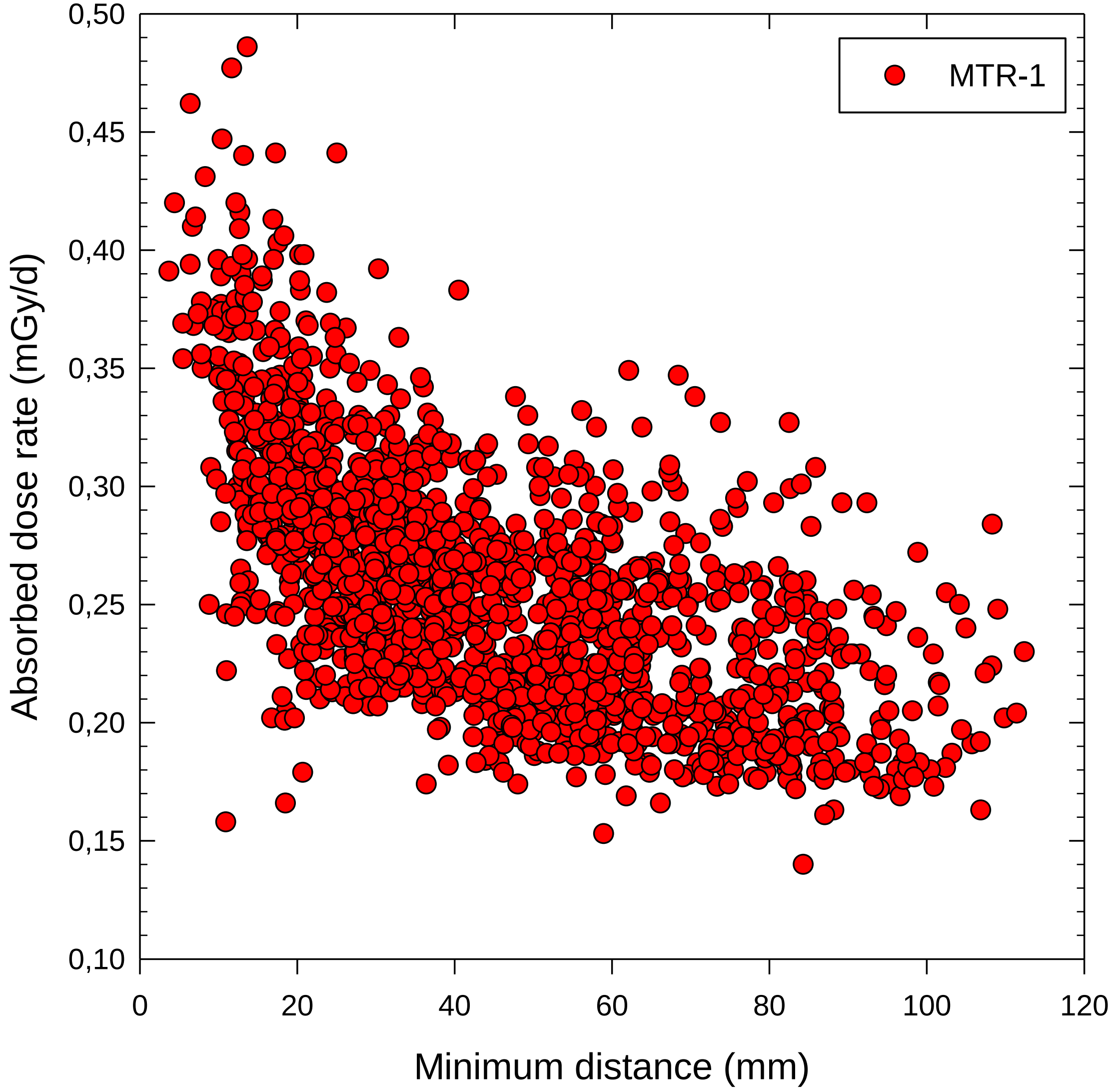
MATROSHKA: Comparison I → Skin

MTR-1
MTR-2A
MTR-2B
MTR-2 KIBO

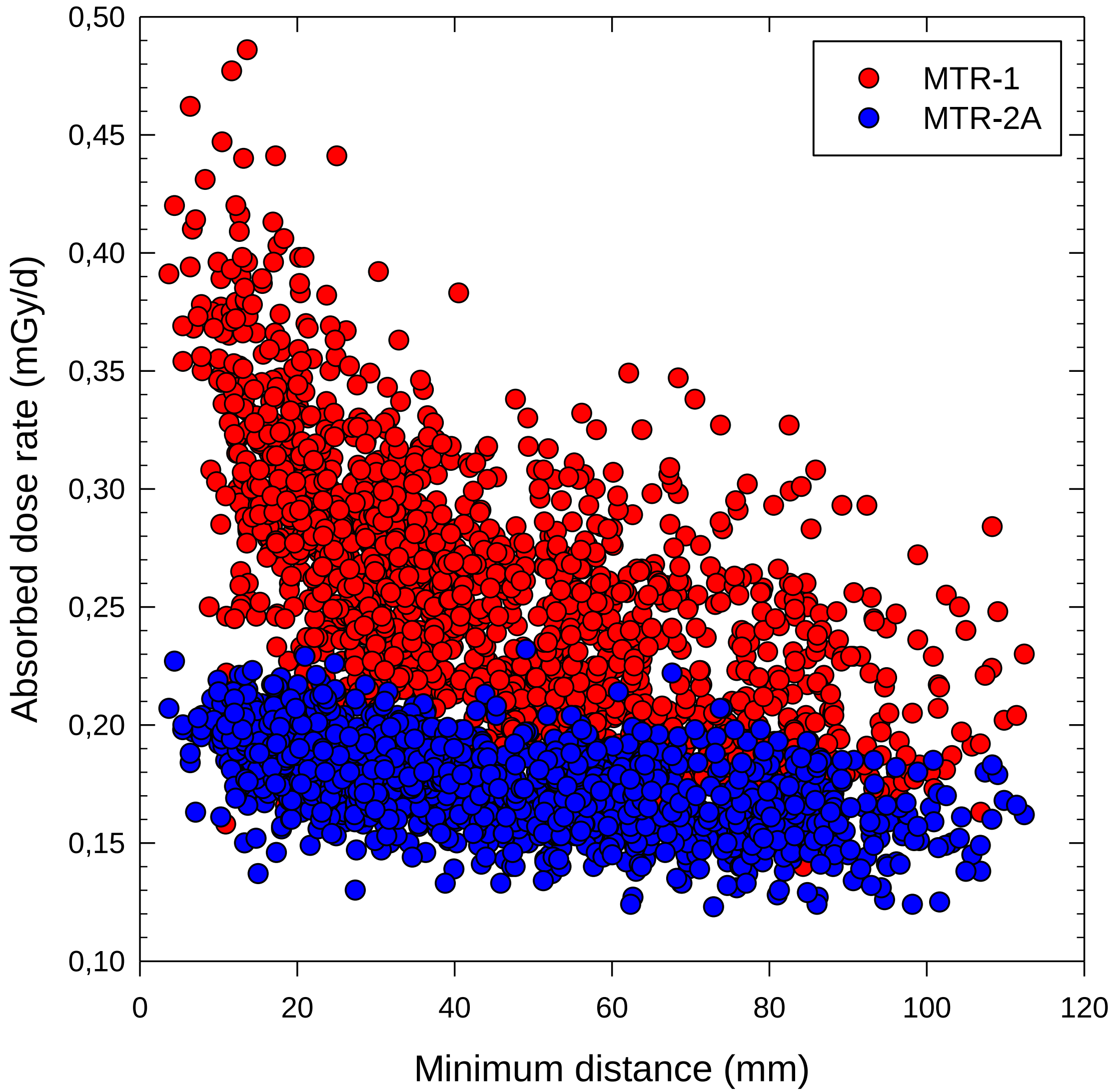




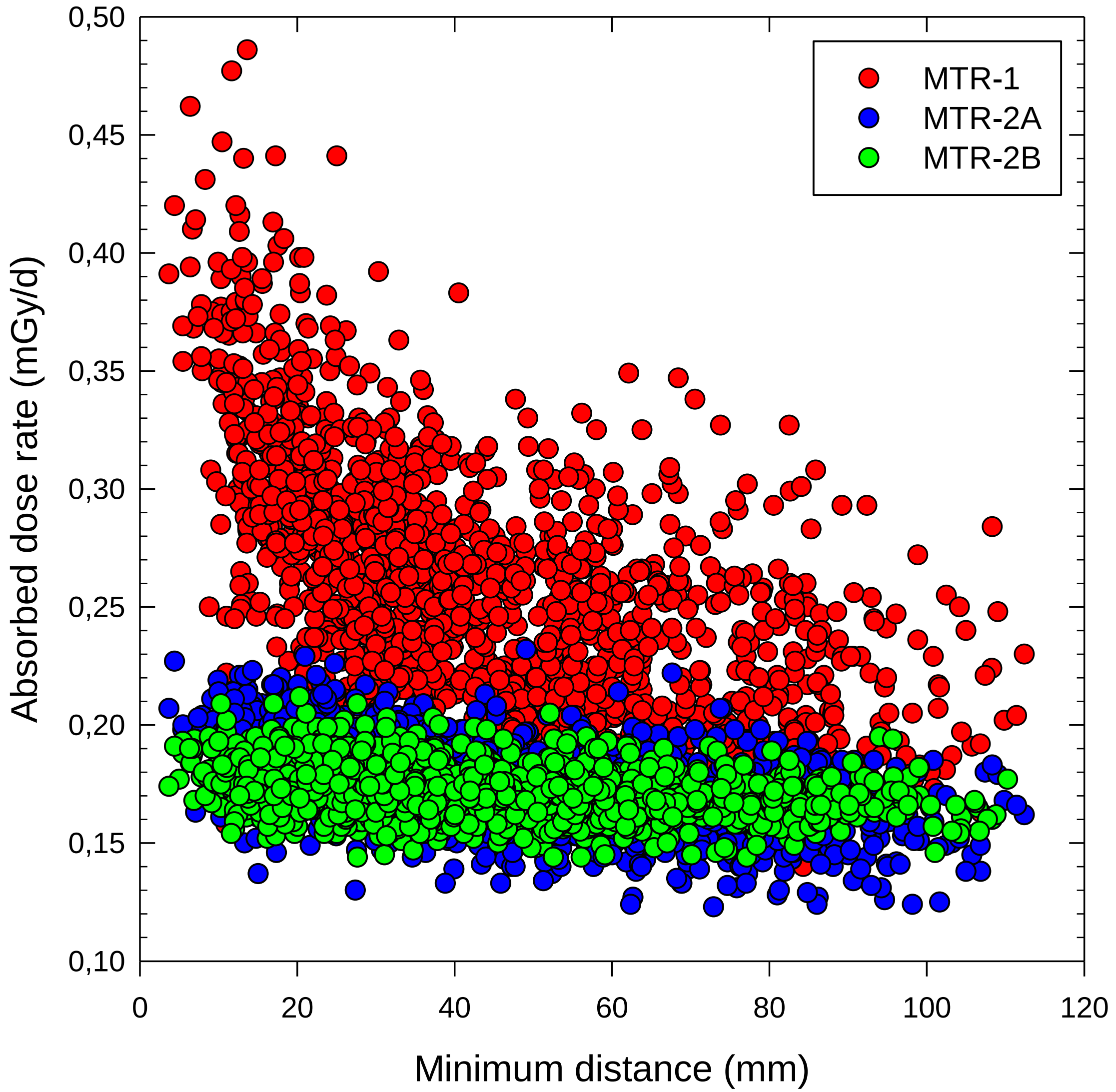
MATROSHKA: Comparison III → Depth Dose Distribution



MATROSHKA: Comparison III → Depth Dose Distribution



MATROSHKA: Comparison III → Depth Dose Distribution



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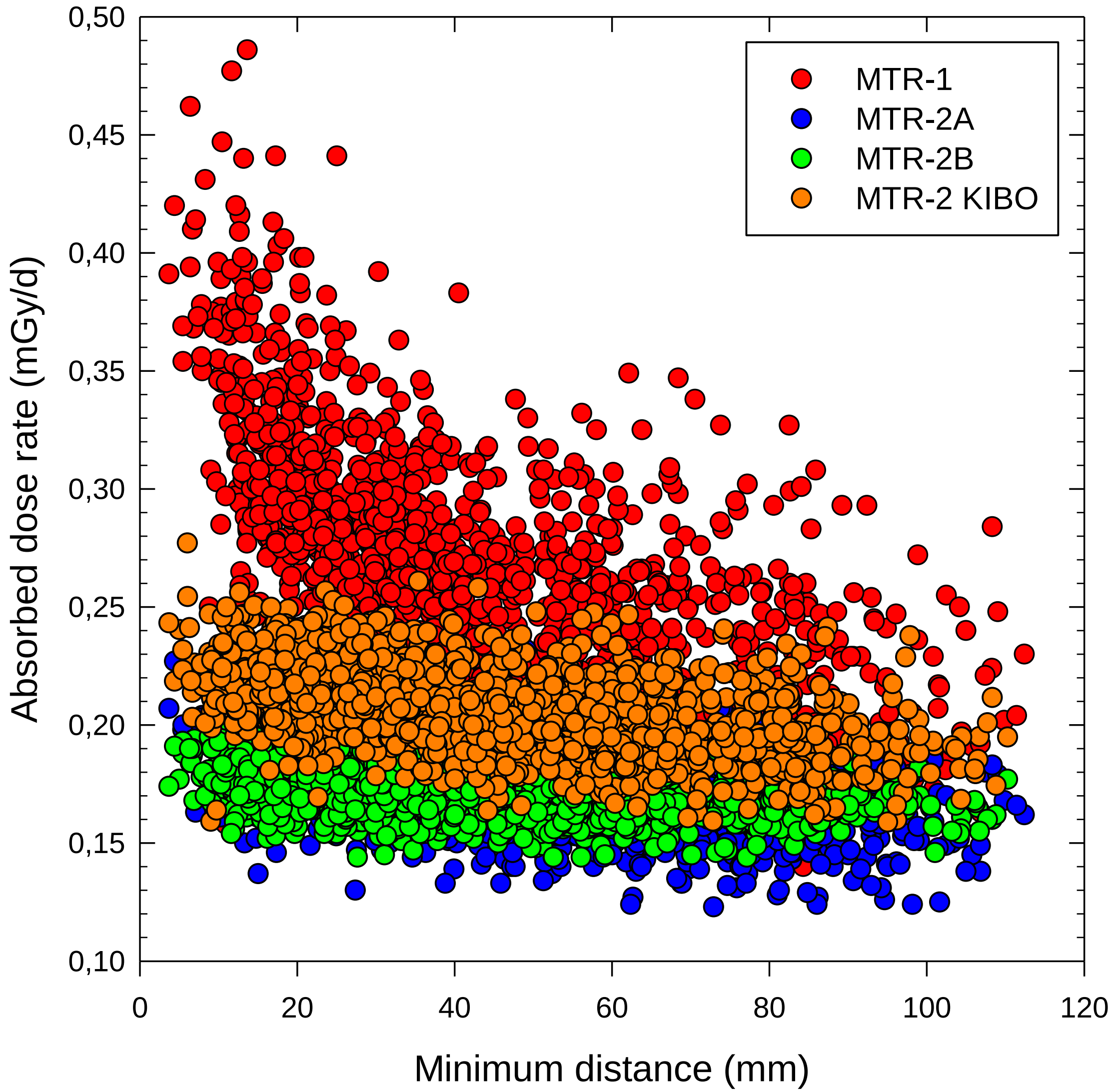
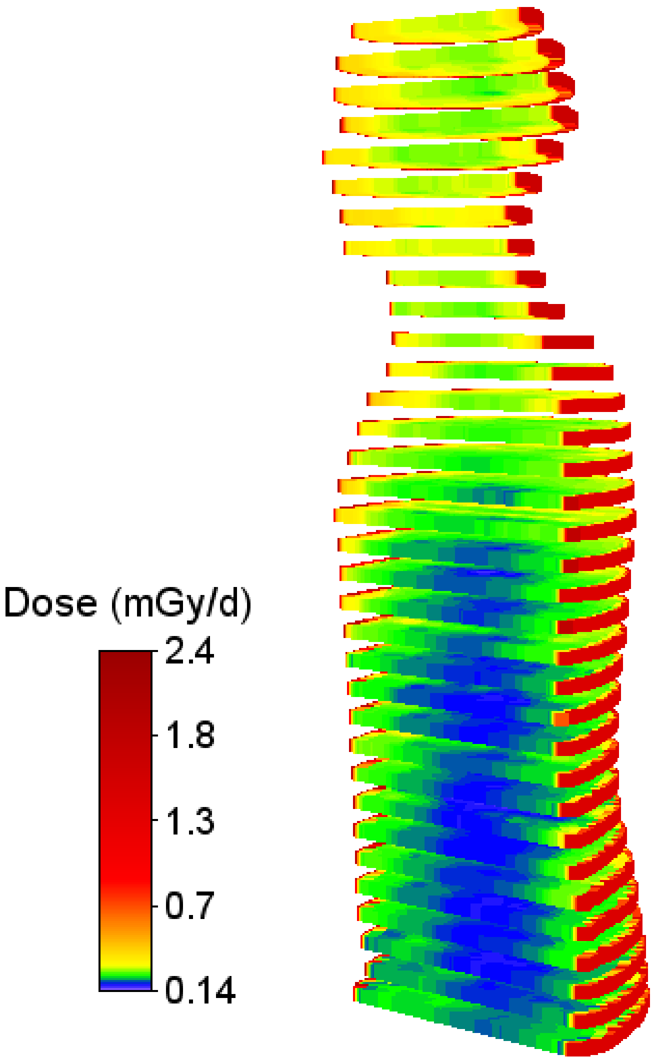
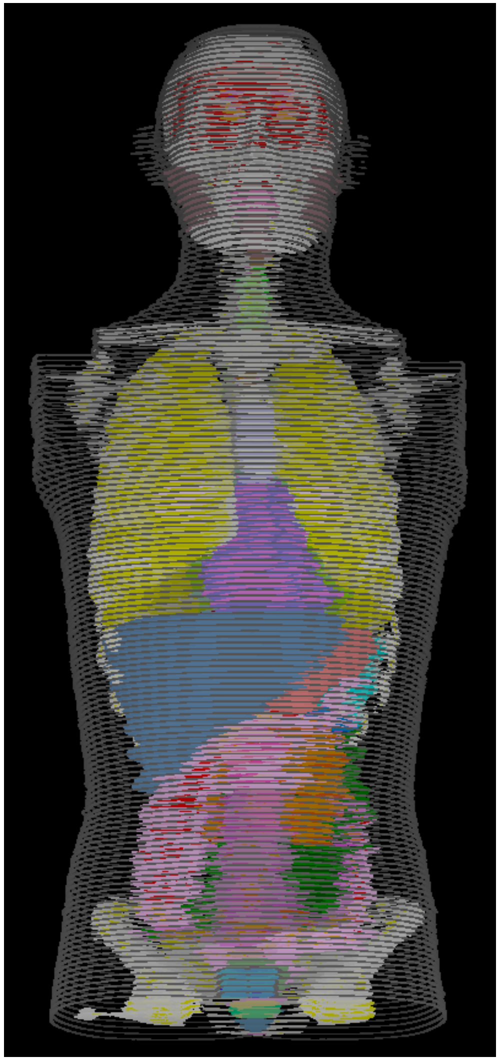
MATROSHKA: Comparison III → Depth Dose Distribution

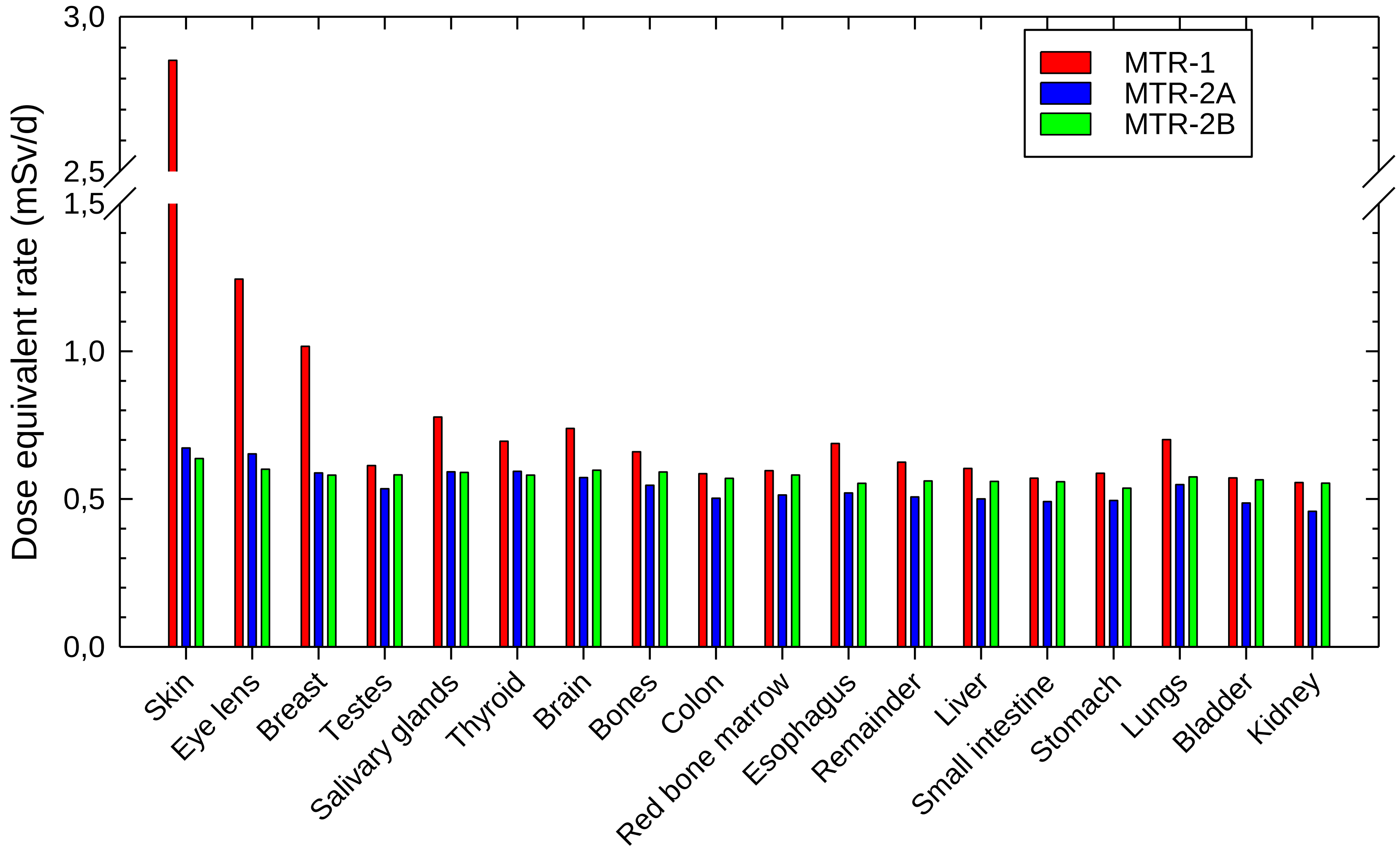


MATROSHKA: Organ dose equivalent





MATROSHKA: Organ Dose Equivalents



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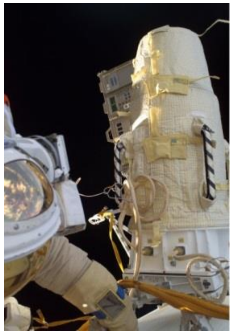
MATROSHKA results: Outside versus Inside Exposure

MTR – 1 	mSv/d
E	0.72 ± 0.04
Personal Dosemeter (PD) H	**3.02 ± 0.45**
H / E	**4.2**

MTR – 2A 	mSv/d
E	0.55 ± 0.03
Personal Dosemeter (PD) H	**0.64 ± 0.03**
	1.15

Overestimation of Effective dose by Personal Dose measurements
for IVA by a factor of 1.15
in an EVA by a factor of 4.2

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Neutron Doses Measured in MATROSHKA

Applying mean dose-per-count data to measured neutron count data provides final dose results:

Phase	E_{ISO} (mSv) [a]	Dose Rate (μSv/d) [a]	H_p(10, ISO) (mSv) [b]	Dose Rate (μSv/d) [b]
MTR-1	48 (23)[c]	78 (37)[c]	58 (28)[c]	94 (45)[c]
MTR-2A	53 (17)[c]	145 (46)[c]	65 (21)[c]	177 (57)[c]
MTR-2B	44 (14)[c]	106 (34)[c]	53 (17)[c]	127 (41)[c]

a) Using E_{ISO} calibration of 120 (14) mSv^{-1}
b) Using H_{p}(10, ISO) calibration of 99 (12) mSv^{-1}
c) Combined standard uncertainty

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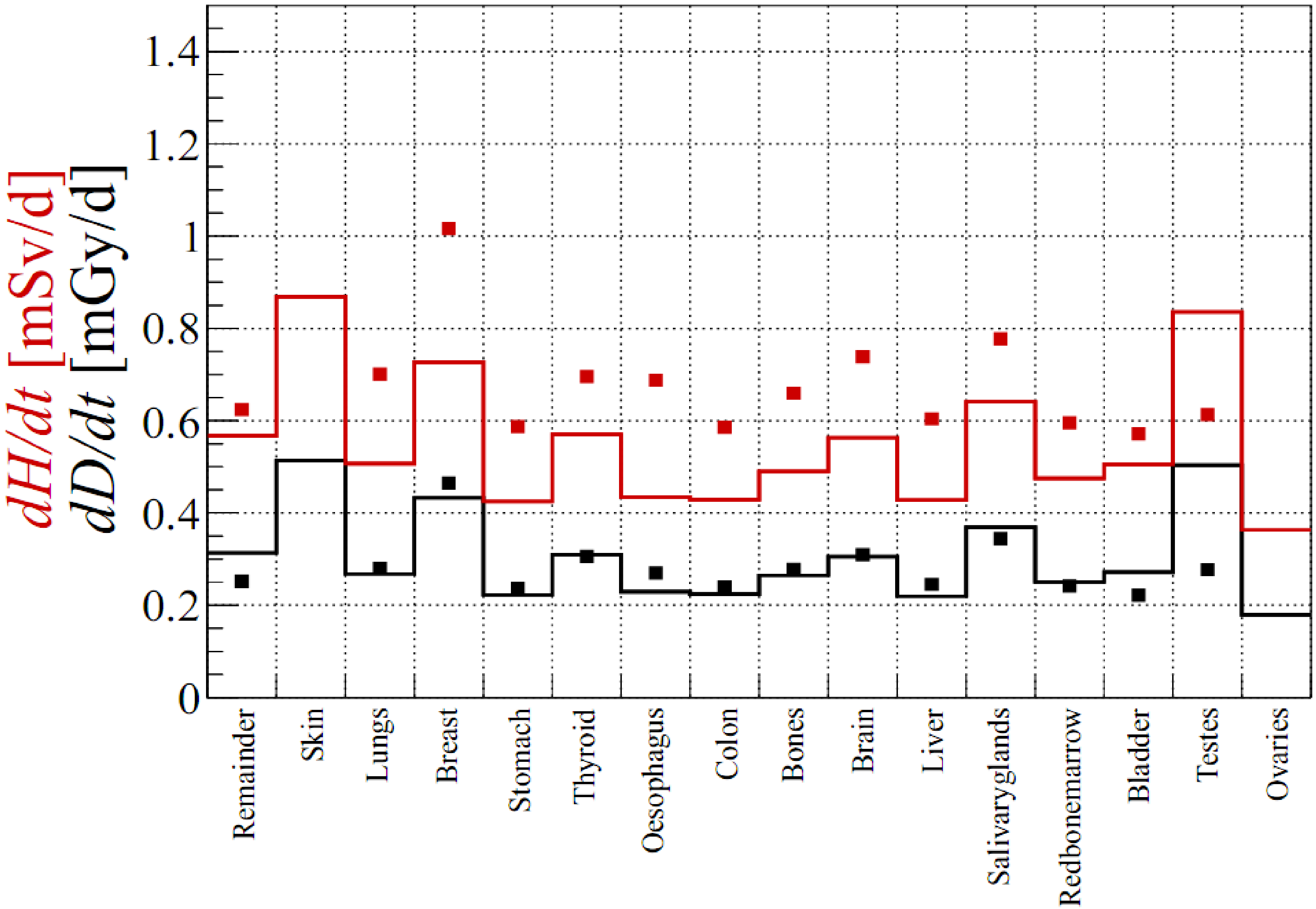
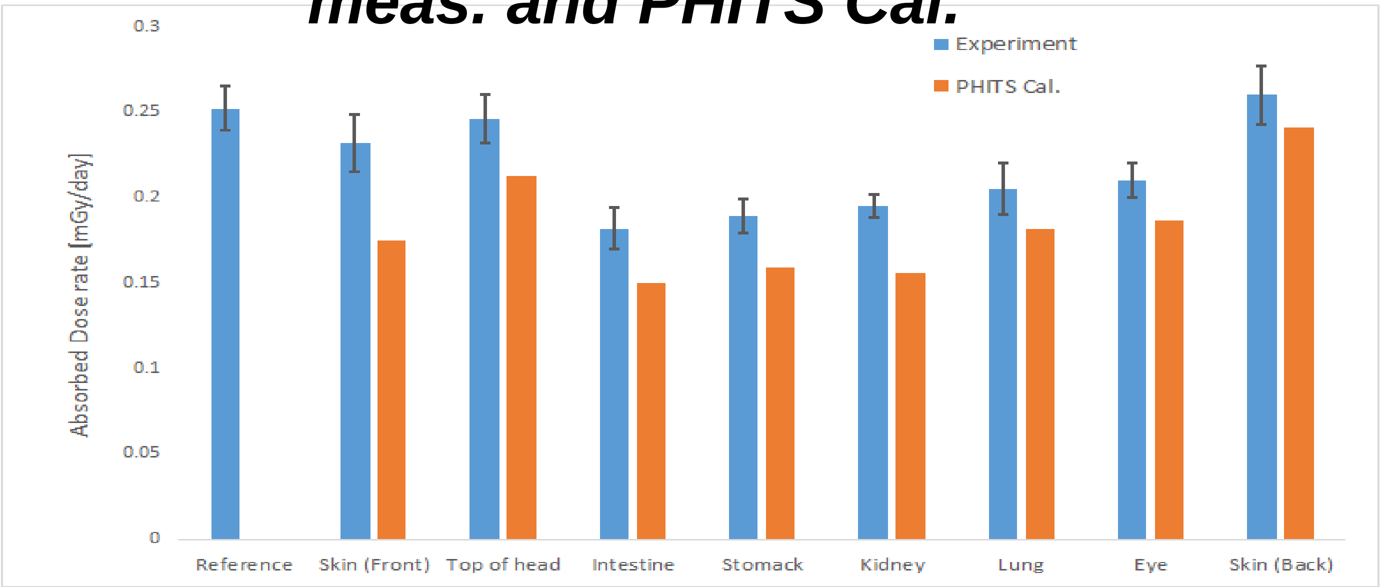
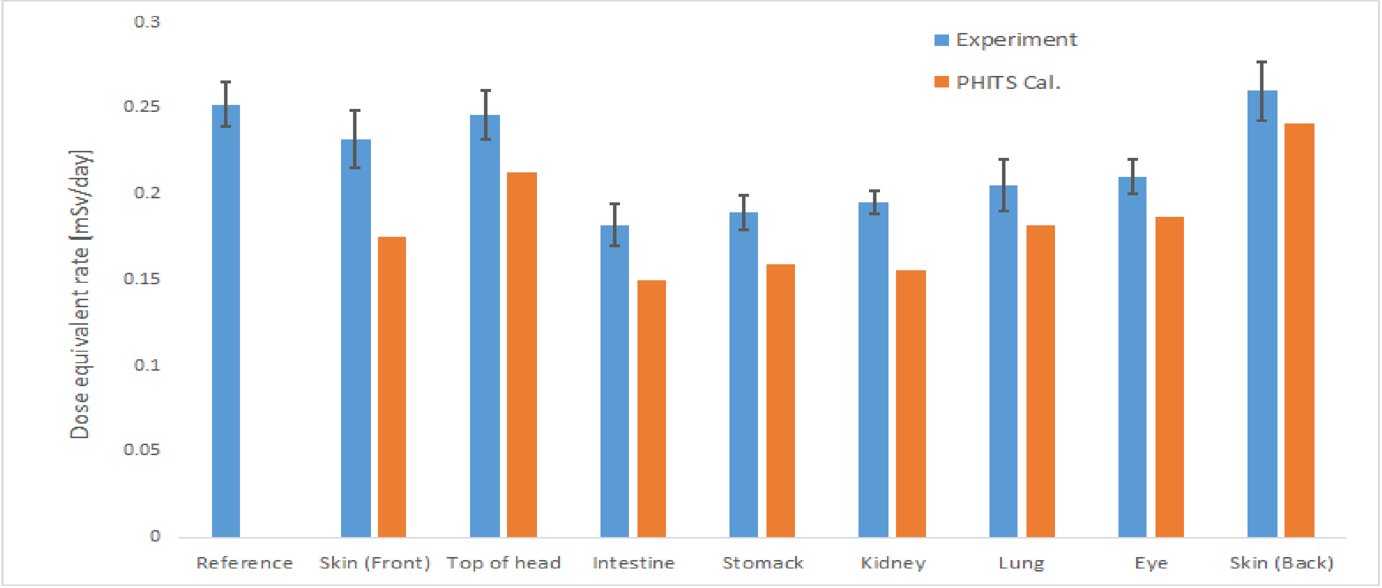
MTR-1 Absorbed Dose and Dose equivalent rate – Calculation (1g/cm2 shielding) and Measurements



MATROSHKA_KIBO Benchmark evaluation between actual meas. and PHITS Cal.





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Summary

The different phantom experiments show that inside spacecrafts the ratio between skin dose and the effective dose equivalen is between 10 and 15%.

.

MATROSHKA was the first phantom experiment providing measurements outside and inside the ISS (http://www.fp7-hamlet.eu). The ratio skin dose and effective dose equivalent is about a factor of 4 for an outside exposure.

An increase in dose equivalent in the inner organs has not been observed, except measurements in the FRED phantom inside Shuttle showed a slight increase of absorbed dose close to the bone marrow.

Depending on shielding distributions chosen, model calculations agree very well for absorbed dose, and underestimate slightly for dose equivalent.

Comprehensive database was provided as input for radiation transport calculations / benchmarking of radiation transport codes.

MATROSHKA will be refurbished for the ISS with new active detectors inserted (Silicondetector telescope, 3D silicondetectors, Timepix). Two new MATROSHKA female phantoms will be flown in the NASA Orion Program (MARE).

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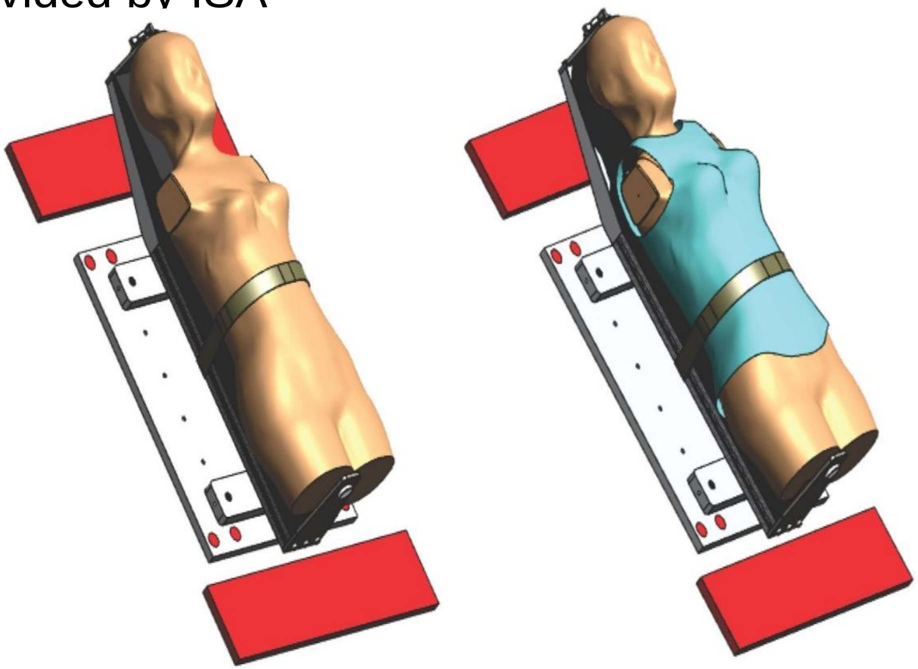
ORION EM-1 [MATROSHKA AstroRad Radiation Experiment [MARE]]

The two MARE phantoms / one phantom fitted with the AstroRad PPE manufactured by StemRad & provided by ISA



The MARE team includes Lockheed Martin personnel collocated with the Orion program for efficient payload integration

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MATROSHKA Investigators

G. Reitz	German Aerospace Center, DLR, Cologne, Germany
R. Beaujean	Christian-Albrechts-Universität Kiel, Kiel, Germany
M. Luszik-Bhadra	Physikalisch-Technische Bundesanstalt, PTB, Braunschweig, Germany
P. Beck	Seibersdorf, Austria
V. Shurshakov, Y. Akatov	Institute for Biomedical Problems, IMBP, Moscow, Russia
P. Olko, P. Bilski	Institute for Nuclear Physics, INP, Krakow, Poland
J. Palfalvi	Atomic Energy Research Institute, AERI, Budapest, Hungary
S. Deme, I. Apathy	KFKI, Budapest, Hungary
D. O´Sullivan	DIAS, Dublin, Ireland
M. Durante	University of Naples, Italy
M. Casolino	INFN, Rome, Italy
C. Lobascio	Alena Spazio, Italy
L. Shiver	Chalmers University, Goethenburg, Sweden
D. Bartlett. L. Hager	National Radiological Protection Board, NRPB, Chilton, UK
N. Vana	Atominstitute of the Austrian Universities, ATI, Vienna, Austria
Y. Uchihori	NIRS, Chiba, Japan
S. Yoshitomi, A. Nagamatsu	JAXA, Japan
F. Cucinotta, E. Semones	NASA JSC, Houston, TX, USA
E. Benton	Eril Research Inc. Richmond, CA , USA
S. McKeever	Oklahoma State University, Stillwater, USA
J. Miller and C. Zeitlin	Lawrence Berkeley Laboratory, Berkeley, CA, USA

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