Mars Mission Scenarios Suggesting Requirements for GCR Shielding, Surface Excavation & Construction

Lunar Surface Innovation Consortium Excavation/Construction Focus Group

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Presented by Robert Moses

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“Evaluating the effectiveness of common aerospace materials at lowering the whole body effective dose equivalent in deep space”, Acta Astronautica 165 (2019) 68–95

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PURPOSE OF THIS PRESENTATION

- **To indicate the need for shielding to protect crew from Galactic Cosmic Ray (GCR) radiation**
  - Driven by
    - proxy dose limit value on lifetime exposure (millisievert (mSv))
      - 1 mSv is the dose produced by exposure to 1 milligray (mG) of radiation
    - Mission durations in GCR radiation environments
      - Different levels in Space compared to on Surface
- **To suggest that (Autonomous) Excavation & Construction on the Moon (and Mars) enables a posture of "reasonably achievable" for GCR shielding within the Artemis Program and beyond**
  - Driven by
    - The shielding performance of regolith
    - The equipment to reposition "large quantities" of regolith, perhaps autonomously

OUTLINE

- **RADIATION ISSUES & MITIGATION CONSIDERATIONS FOR HUMANS-MARS**
  - DOSE PROXY LIMIT VS MISSION DURATIONS
- **GALACTIC COSMIC RAY (GCR) SHIELDING TRADE STUDY**
  - 5 MISSION PHASES EXPLORED BEGINNING WITH ROUNDTRIP MARS
  - OVERCOAT MATERIAL SELECTIONS
  - VARY ROUNDTRIP MARS DURATIONS VIA FAST TRANSITS AND SURFACE STAY TIME
  - LOOKING FOR SOLUTIONS THAT ALSO OFFER SOME “SAFE DAYS” FOR PREREQUISITE CREW CISLUNAR TRAINING
- **GCR SHIELDING IMPLICATIONS FOR 5 MARS ROUNDTRIP TRAJECTORY CASES**
  - FOCUSING ON FAST TRANSIT OPTIONS
  - INCLUDE TYPICAL MINIMUM ENERGY AND TYPICAL SHORT STAY CASES FOR COMPARISON
  - UNSHIELDED ONLY DURING TO/FROM MARS (IMPLICATIONS FOR FAST TRANSITS)
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- **CONCLUSION**

RADIATION ISSUES & MITIGATION CONSIDERATIONS FOR HUMANS-MARS

- **Presentation is drawn from Conference paper AIAA 2018-5360 and the Radiation Blue Sky Workshop October 2019**
- **GCR remains the major impediment to crew health for humans to Mars**
  - Roundtrip times considered as Design Reference Mission***** cases greatly exceed 200 days
    - ***** New Planning Guidance released by NASA (later herein)
  - Acceptable radiation effective dose limit is set to a lifetime proxy value of 150 mSv******
    - ****** New proxy dose limit value may be announced soon
- **Trade space for remaining below the total (cumulative) lifetime proxy radiation effective dose level of 150 mSv for roundtrip humans-Mars missions is defined by the**
  - Physics of fast transit to reduce time spent in deep space radiation conditions
  - Performance of shielding materials to reduce the radiation that reaches the crew
    - Regolith on the Lunar and Mars surfaces
    - Habitat shielding while in Cis-Lunar and Mars Node Staging & Aggregation Orbits
  - Propulsion system capability to push massive reusable in-space overcoats to/from Mars
- **How does Earth's Moon and CisLunar Space offer a Mars Analog and Proving Ground of potential solutions <u>if the prerequisite crew training portion there</u> cannot be accommodated within the lifetime (proxy) dose limit when added to the expected roundtrip Mars mission dosage?**

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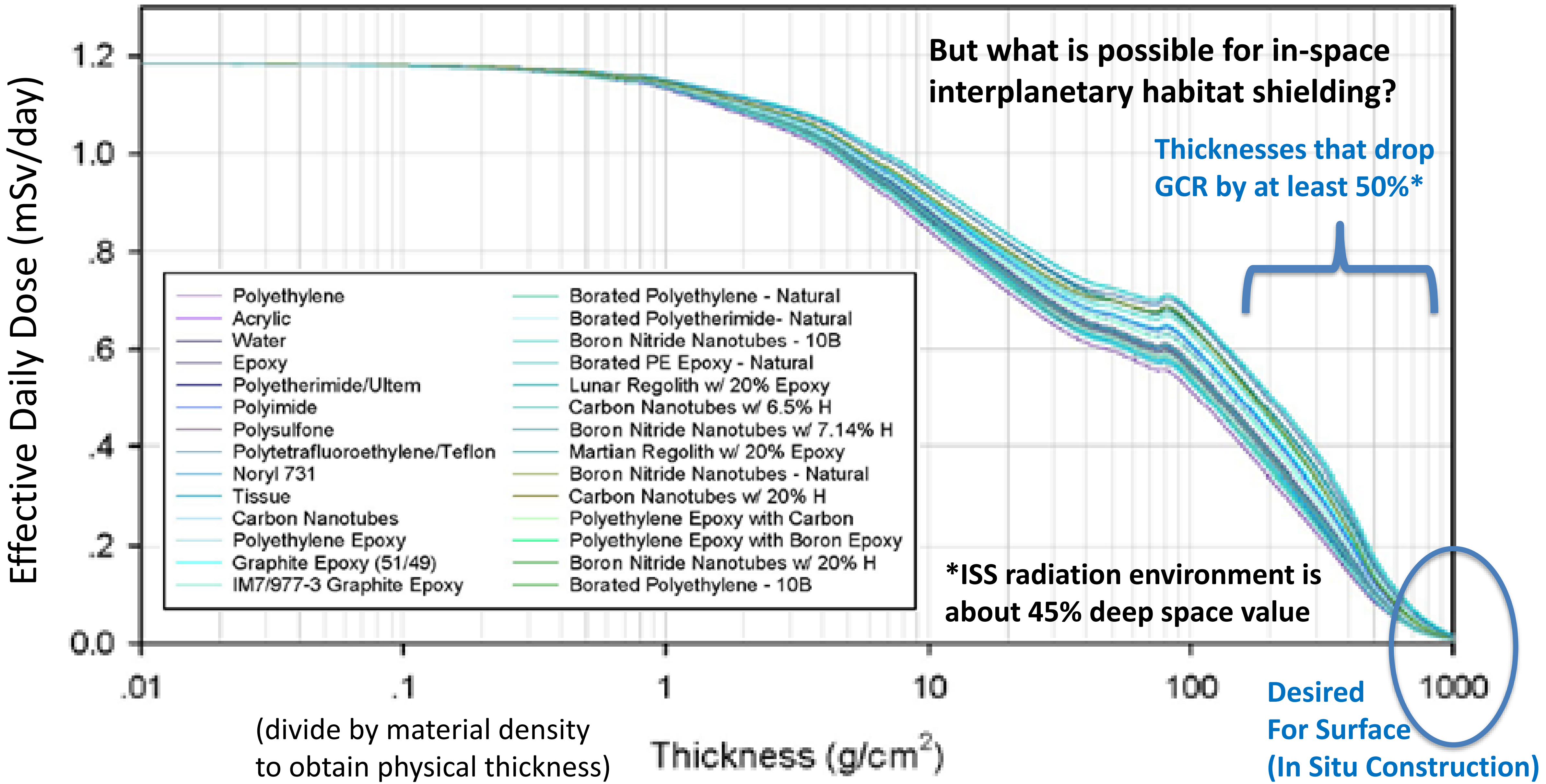
GALACTIC COSMIC RAY (GCR) SHIELDING TRADE STUDY

- **For the cumulative GCR response evaluation, a preliminary GCR Shielding Design Reference Mission was created that includes 5 phases:**
  - **Cis-lunar habitat stay**
  - **Lunar surface stay**
  - **Lunar to Mars interplanetary transit**
  - **Mars surface stay**
  - **Mars to Earth return transit**
- **Some initial values for durations and overcoat material for each phase were selected for constructing an Evaluation Tool that allows total exposure to be summed up for all 5 phases**
  - Polyethylene (PE) was selected as the overcoat material for the in-space phases
  - Surface Regolith was selected as the overcoat materials for the surface stays
- **In-Space Shielding Overcoat would remain In-Space and be reused**
  - Cis-lunar habitat overcoat remains in cis-lunar orbit
  - If “affordable to propel” for interplanetary transit, GCR overcoat for shielded case would remain with interplanetary transport for subsequent transits to/from Mars

OVERCOAT OPTIONS - POLYMER AND COMPOSITE RESPONSE TO GCR



(divide by material density to obtain physical thickness)

EVALUATION TOOL - DOSE LEVELS AND OVERCOAT MASS ESTIMATES

OVERCOAT THICKNESS (g/cm^2)	DAILY EFFECTIVE DOSE (mSv/day) – 5 PHASES					EFFECTIVE DOSE (mSv/Phase) – 5 PHASES					Total mSv	MASS OF OVERCOAT (tonnes) – 5 PHASES					Total
0	0.802094	0.513638	0.802094	0.406889	0.853861	144.3770	92.4585	48.1257	12.2067	51.2316	348.3994	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
20	0.749199	0.460369	0.749199	0.396037	0.781685	134.8558	82.8665	44.9519	11.8811	46.9011	321.4564	51.8237	137.1159	51.8237	155.6379	51.8237	448.2249
50	0.694844	0.440639	0.694844	0.379523	0.727577	125.0719	79.3149	41.6906	11.3857	43.6546	301.1178	140.5863	389.5776	140.5863	445.5392	140.5863	1256.876
100	0.587664	0.418256	0.587664	0.343733	0.619364	105.7795	75.2860	35.2598	10.3120	37.1619	263.7992	320.4425	951.5859	320.4425	1100.2178	320.4425	3013.131
150	0.479446	0.383030	0.479446	0.302255	0.507095	86.3004	68.9455	28.7668	9.0676	30.4257	223.5060	544.2809	1716.9080	544.2809	2003.3942	544.2809	5353.145
200	0.382964	0.340173	0.382964	0.260272	0.405919	68.9335	61.2312	22.9778	7.8082	24.3551	185.3059	816.8141	2716.4271	816.8141	3194.4267	816.8141	8361.296
250	0.301771	0.295530	0.301771	0.220653	0.320332	54.3187	53.1954	18.1062	6.6196	19.2199	151.4600	1142.7543	3981.0262	1142.7543	4712.6737	1142.7543	12121.96
300	0.235109	0.252524	0.235109	0.184746	0.249881	42.3196	45.4544	14.1065	5.5424	14.9928	122.4157	1526.8140	5541.5885	1526.8140	6597.4935	1526.8140	16719.52
350	0.181468	0.212982	0.181468	0.153091	0.193057	32.6642	38.3368	10.8881	4.5927	11.5834	98.0652	1973.7056	7428.9970	1973.7056	8888.2444	1973.7056	22238.36
400	0.138920	0.177699	0.138920	0.125730	0.147913	25.0055	31.9858	8.3352	3.7719	8.8748	77.9731	2488.1414	9674.1350	2488.1414	11624.2849	2488.1414	28762.84
450	0.105594	0.146897	0.105594	0.102448	0.112509	19.0068	26.4414	6.3356	3.0734	6.7506	61.6079	3074.8338	12307.8854	3074.8338	14844.9732	3074.8338	36377.36
500	0.079767	0.120463	0.079767	0.082893	0.085042	14.3581	21.6833	4.7860	2.4868	5.1025	48.4168	3738.4953	15361.1314	3738.4953	18589.6677	3738.4953	45166.28
Days	180	180	60	30	60						Density	1	1.6	1	1.7	1	
											RCC inside radius (cm)		300				
Limit	150.000000	mSv									RCC inside height (cm)		1000				
											RCC Inside Volume (cm^3)		282743338.8				

User Selected Values – For Calculating Cumulative Effective Dose & Overcoat Mass for Each Phase

VALUES IN CELLS FOR DAILY EFFECTIVE DOSE WERE CALCULATED USING RADIATION MODELING SOFTWARE FOR SPECIFIC MATERIAL TYPES (PE & REGOLITH) & OVERCOAT THICKNESSES

OVERCOAT THICKNESSES VS DAILY EFFECTIVE DOSE

Overcoat Thickness (g/cm^2)	Effective Dose (mSv/day)					Effective Dose per leg (mSv)					Total mSv
	E2cisL (poly)	Lsur (regolith)	L2Msur (poly)	Msur (regolith)	Msur2E (poly)	E2cisL (poly)	Lsur (regolith)	L2Msur (poly)	Msur (regolith)	Msur2E (poly)	
0	0.802094	0.513658	0.802094	0.406889	0.853861	144.3770	92.4585	48.1257	12.2067	51.2316	348.3994
20	0.749199	0.460369	0.749199	0.396037	0.781685	134.8558	82.8665	44.9519	11.8811	46.9011	321.4564
50	0.694844	0.440639	0.694844	0.379523	0.727577	125.0719	79.3149	41.6906	11.3857	43.6546	301.1178
100	0.587664	0.418256	0.587664	0.343733	0.619364	105.7795	75.2860	35.2598	10.3120	37.1619	263.7992
150	0.479446	0.383030	0.479446	0.302255	0.507095	86.3004	68.9455	28.7668	9.0676	30.4257	223.5060
200	0.382964	0.340173	0.382964	0.260272	0.405919	68.9335	61.2312	22.9778	7.8082	24.3551	185.3059
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500	0.079767	0.120463	0.079767	0.082893	0.085042	14.3581	21.6833	4.7860	2.4868	5.1025	48.4168
Days	180	180	60	30	60						
Limit	150.000000	mSv									

Daily Dose without Shielding around In-Space Habitat

Daily Dose with 300 g/cm2 PE Shielding around In-Space Habitat

DAILY EFFECTIVE DOSE & MASS FOR OVERCOAT THICKNESSES

Overcoat Thickness (g/cm^2)	Effective Dose (mSv/day)					Mass (tonnes)					
	E2cisL (poly)	Lsur (regolith)	L2Msur (poly)	Msur (regolith)	Msur2E (poly)	E2cisL (poly)	Lsur (regolith)	L2Msur (poly)	Msur (regolith)	Msur2E (poly)	Total
0	0.802094	0.513658	0.802094	0.406889	0.853861	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
20	0.749199	0.460369	0.749199	0.396037	[illegible]	51.8237	137.1159	51.8237	155.6379	51.8237	448.2249
50	0.694844	0.440639	0.694844	0.379523	0.727577	140.5863	389.5776	140.5863	445.5392	140.5863	1256.876
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450	0.105594	0.146897	0.105594	0.102448	0.112509	3074.8338	12307.8854	3074.8338	14844.9732	3074.8338	36377.36
500	0.079767	0.120463	0.079767	0.082893	0.085042	3738.4953	15361.1314	3738.4953	18589.6677	3738.4953	45166.28

Days	180	180	60	30	60
Limit	150.000000	mSv			

Daily Dose <u>without</u> Shielding around In-Space Habitat

Daily Dose <u>with</u> 300 g/cm2 PE Shielding around In-Space Habitat

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DETAILS FOR 5 MARS ROUNDTRIP TRAJECTORY MISSION CLASSES

Mission Class	Days of Flight to Mars	Days on Mars Surface	Days of Flight to Earth	Total Roundtrip Days	Propulsion Types	References
Minimum Energy Conjunction	240	420	240	900	Chemical; Nuclear; Solar Electric; Plasma	Mattfield, 2014
Fast-Transit Conjunction *	120	660	120	900	Chemical with aeroassist; Nuclear	Griffin, 2004; Wooster, 2006; Komar, 2017
Opposition; may involve a Venus Flyby	240	30	180	450	Chemical; nuclear; solar electric	Mattfield, 2014
High Specific Impulse, Moderate Thrust *	90	60	150	300	Plasma with Moderate Thrust (VASIMR 10-20 MW); Chemical with Aeroassist in some cases	Ilin, 2011
High Specific Impulse, High Thrust *	60	60	60	180	Plasma with High Thrust (VASIMR 200 MW)	Ilin, 2011

*** Fast Transit Cases**

CALCULATING DOSE LEVEL FOR THE ROUNDTRIP MARS CASES

- **Constraint / Assumption**
  - Effective Dose During Surface Stays are Zero-ed out by using 1000 g/cm^2 of regolith overburden to shield surface habitat
  - In Situ Construction technologies can emplace thickness of regolith to shield surface habitats
- **Calculate cumulative effective dose for the case of unshielded in-space habitat during interplanetary transits to/from Mars**
- **Take resulting Dose Sum and compare to Proxy Lifetime Dose Limit**
  - Dose sum is simply summing up
    - Outbound transit time multiplied by daily dose level
    - Inbound transit time multiplied by daily dose level
  - Proxy Lifetime Dose Limit used for this study is 150 mSv
- **If Dose Sum is below Proxy Lifetime Dose Limit, then proceed to calculate duration for Prerequisite Training (Lunar Surface and CisLunar Space)**

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TOTAL ROUNDTRIP EFFECTIVE DOSE ESTIMATES FOR UNSHIELDED IN-SPACE INTERPLANETARY HABITAT TO/FROM MARS

CASE OF UNSHIELDED IN-SPACE HABITATS & REGOLITH-SHIELDED SURFACE HABITATS

Mission Class	Using Surface Overcoats of 1000 g/cm2; Unshielded In-Space Habitats	Cis-Lunar Orbit Training Days (Unshielded Orbiting Habitat)
M-E Conjunction	400 mSv	n/a
Faster Conjunction	200 mSv	n/a
Opposition	350 mSv	n/a
High Isp, Moderate Thrust	200 mSv	n/a
High Isp, High Thrust	100 mSv	60 days

Depleted 150 mSv Proxy Limit during Interplanetary Transit

High Specific Impulse, High Thrust Mission Class offers Roundtrip within 150 mSv Lifetime Proxy Limit for Effective Dose as well as provides for 60 unshielded training days in Cis-Lunar Orbiting Habitat (i.e., Gateway)

SHIELDING NEEDED FOR INTERPLANETARY IN-SPACE HABITAT TO MEET PROXY LIMIT FOR LIFETIME EFFECTIVE DOSE

Mission Class	Using Surface Overcoats at 1000 g/cm2	Thickness & Mass of PE Overcoat To Achieve 150 mSv Lifetime Proxy on Effective Dose
M-E Conjunction	400 mSv	250 g/cm^2 (1150 tonnes)
Faster Conjunction	200 mSv	100 g/cm^2 (325 tonnes)
Opposition	350 mSv	220 g/cm^2 (950 tonnes)
High Isp, Moderate Thrust	200 mSv	100 g/cm^2 (325 tonnes)
High Isp, High Thrust	100 mSv	n/a

Depleted 150 mSv Proxy Limit during Interplanetary Transit

NOT CLEAR WHETHER THESE OVERCOAT MASSES CAN BE PUSHED BY PROPULSION SYSTEMS WITHIN ALLOTTED TRANSIT TIMES

Mass of overcoat thicknesses needed to meet 150 mSv lifetime proxy on effective dose are well above current payload capacity of 40-60 tonnes planned for Mars

Updated Analysis on Shielding Performance, D.K. Bond et. al (2019)

Table 3
Metal shielding materials [4,24,25,26].

Material Name	$\frac{\#\ of\ Nucleons}{Volume}$ (cm^{-3})	Density ($\frac{g}{cm^3}$)	Line Color	Data Symbol	Material Reference
Aluminum	1.627091×10^{24}	2.7		▲	[4]
310 Stainless Steel	4.756898×10^{24}	7.89		▲	[24]
Aluminum Alloy 2195	1.627150×10^{24}	2.7		▲	[4]
Lead	6.829902×10^{24}	11.34		▲	[25]
Silicon	1.403715×10^{24}	2.333		▲	[4]
Silicon Dioxide (Silica)	1.327414×10^{24}	2.203		▲	[26]
Tantalum	1.005384×10^{25}	16.69		▲	[4]
Tungsten	1.159571×10^{25}	19.25		▲	[25]
Titanium	2.716499×10^{24}	4.506		▲	[25]
Copper	5.401864×10^{24}	8.96		▲	[25]
Lunar Regolith	9.641900×10^{23}	1.7		▲	[4]
Martian Regolith	1.024446×10^{24}	1.6		▲	[4]

(divide by material density to obtain physical thickness)

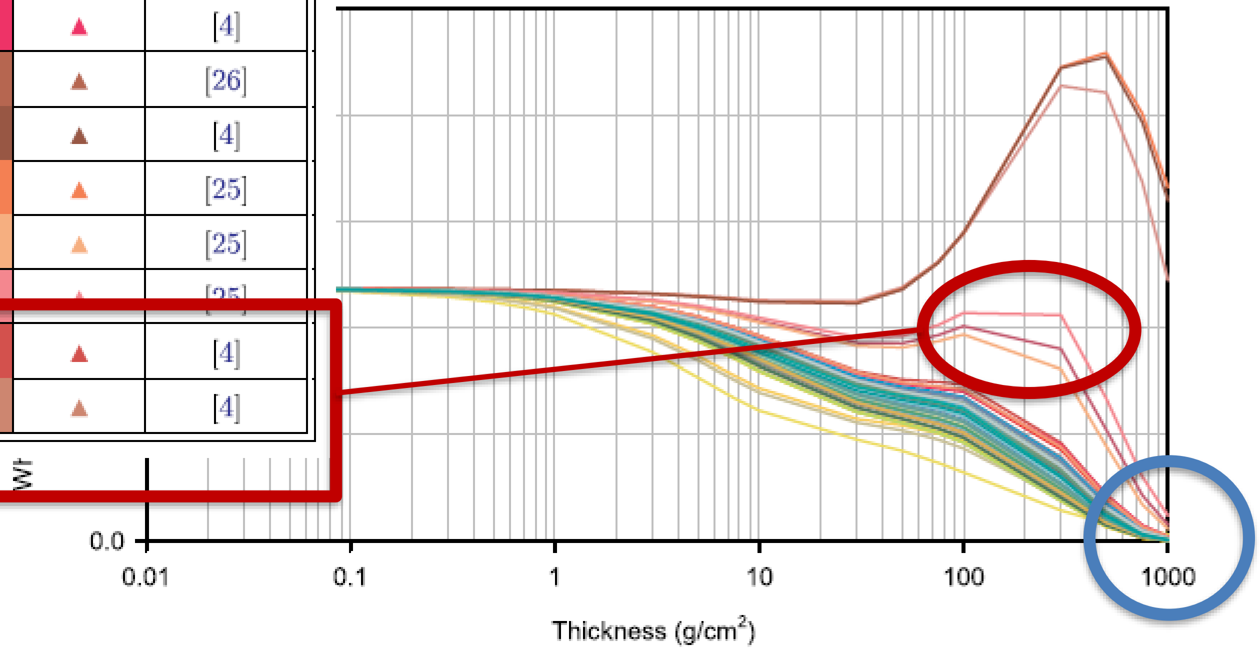

Fig. 4. GCR Environment Effective Whole Body Dose Equivalent for All Materials using the FAX05 Phantom - Ray by Ray Method Using the 1002 Ray Distribution and various Material Thicknesses.

* Planning Guidance on Mission Durations (Recent Documents)

Human Exploration and Operations (HEO) Systems Engineering and Integration (SE&I) Decision Memorandum **Planning Guidance for Artemis Mission Durations as Testbeds to Reduce Risks for Human Missions to Mars** HEO-DM-1004

Appendix A: Planning Guidance for Extended Artemis Testbed Mission

RESEARCH AND DEVELOPMENT TESTBED RM (PPBE2		
Mission Segment:	**HRP recommendation:**	**Rationale:**
Time in Microgravity Pre-Lunar Surface	45-105 days, 75 days minimum preferred.	45 days is the minimum time for the environment. Previous spaceflight Spaceflight-associated Neuro-ocula manifest in 80% of susceptible peo
Time on Lunar Surface	30-60 days	30 days minimum corresponds to th RM surface ops. Due to the small gravity (1/6g) and microgravity, 60 detect a signal.
	Rapid return	Rapid return allows greater evaluat

Human Exploration and Operations (HEO) Systems Engineering and Integration (SE&I) Decision Memorandum **Mars Mission Duration Guidance for Human Risk Assessment and Research Planning Purposes** HEO-DM-1002

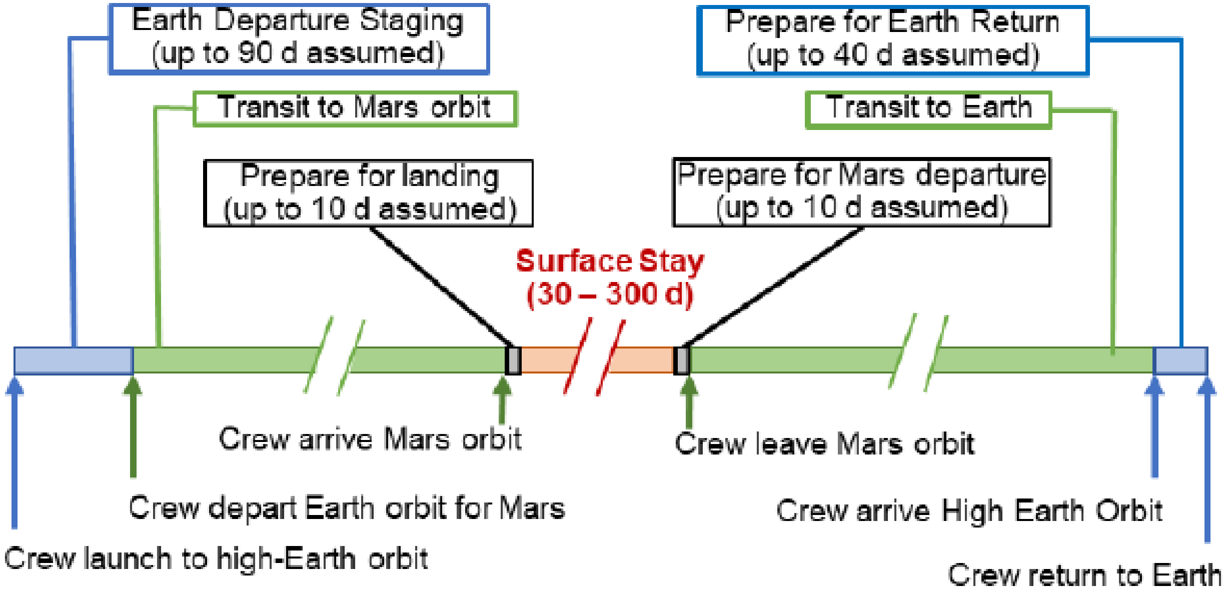

Figure 1. Mars Mission Timeline Overview

SOME EQUIPMENT CONCEPTS FOR REPOSITIONING REGOLITH

- **Surface construction video publicly released by NASA :**
  https://youtu.be/mpXdY2v5FDI

- **Some concepts in development at NASA:**
  - Excavator: RASSOR
  - Bulldozer: LANCE on a mobile platform
  - Scoop on a Crane: LSMS on a mobile platform
- **Welcome you to invite the respective principal investigators and key developers of those equipment concepts to present at LSIC E&C FG**

CONCLUSIONS

- **Current proxy limit of 150 mSv lifetime effective dose makes Radiation the largest crew health hazard for humans on Mars**
  - **In all cases, shielding of surface habitats would be required to allow the proxy limit to be applied fully to the in-space phases**
- **Regolith with 20% poly binder performs better than bulk "as is" regolith for thicknesses below ~1200 g/cm^2 (divide by material density to obtain physical thickness)**
- **Fast transit mission class that uses advanced propulsion for high Isp and high thrust may offer a solution (but these advancements are still in development)**
- **Other mission classes require overcoat thicknesses and masses for the in-space interplanetary habitat that may not be feasible to push to/from Mars and will require further study**
- **** Relaxing the proxy dose limit allows the trade study to consider current propulsion technologies and other mission scenarios**
- **Several equipment concepts appear viable for repositioning regolith for shielding needs**