Marshall Space Flight Center

Integrated NTP Vehicle Radiation Design

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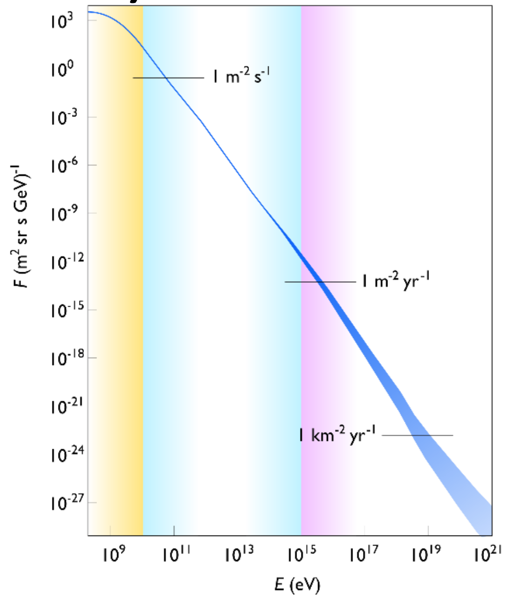
Overview

i. Radiation Environments (Brief recap)
ii. DRA5 Design Assumptions
iii. Integrated Mitigation Strategies
iv. Conclusion
v. Future Considerations

Galactic Cosmic Rays (GCR)

- Broad distribution of energy and mass
- Can be very energetic (> GeV)
- Shielding is relatively ineffective
- High-Z shields can worsen the effects
- Always present from all directions
- Dominant dose contributor outside of LEO



Solar Energetic Particles

- Lighter ions, especially protons
- Broad energy distribution, skews to lower energy
- Max energy much lower than GCR
- Can be shielded
- Sporadic occurrence in the form of ‘storms’

From SLS-SPEC-159 (DSNE)

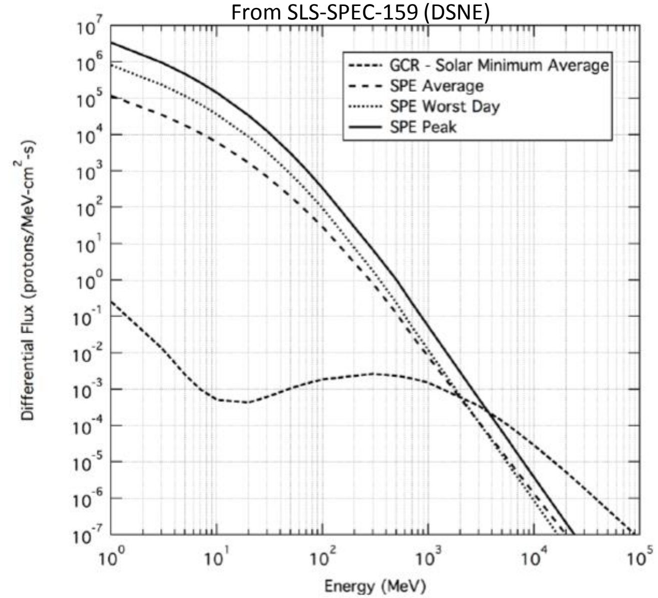
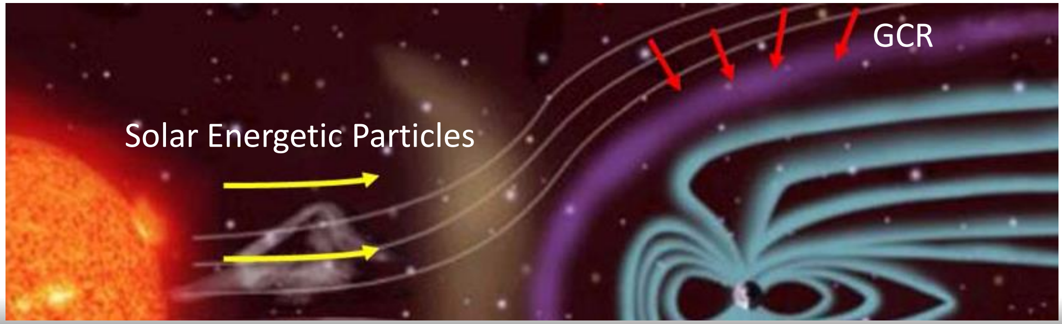
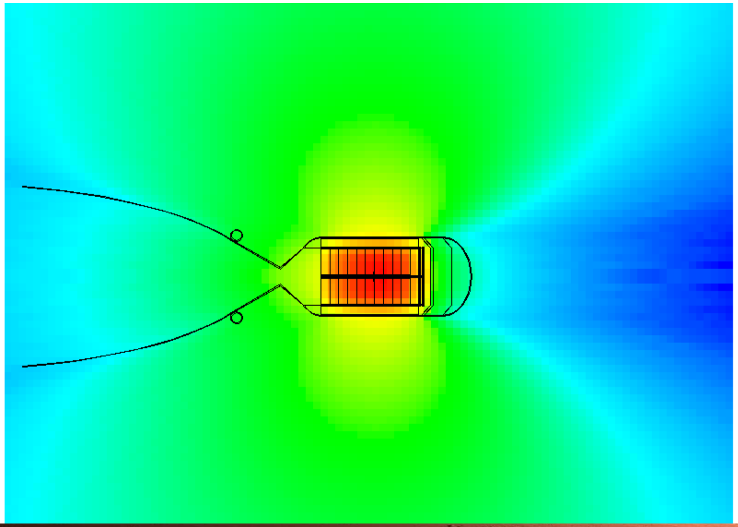


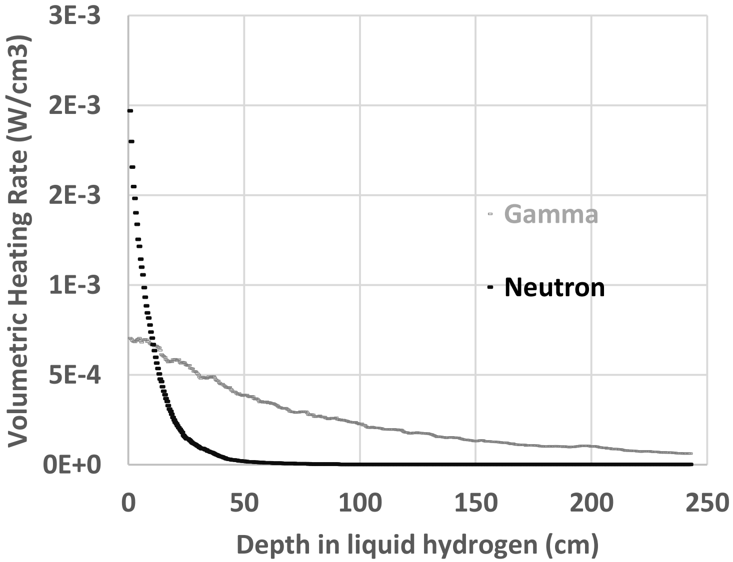
Figure 3.3.2.10.2-4. Differential Proton Flux for SPE and Solar Minimum GCR



Nuclear Reactor Operations

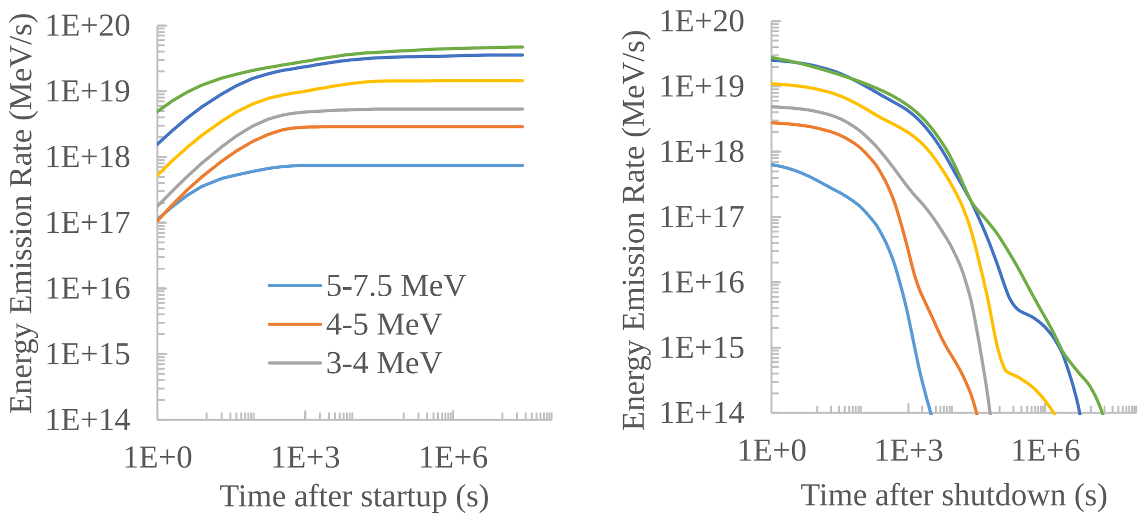
- Emits gamma photons and neutrons
- Both neutral particles – penetrates more readily
- Neutrons slow down by collision with light nuclei
- Captured neutrons can produce secondary gamma (prompt or delay)
- Gammas are attenuated by any matter





Nuclear Reactor Shutdown

- Fission products are unstable and emit gamma photons
- Decays quickly after shutdown, especially for high energies
- Activation also contributes gammas, but is dwarfed by fission products if reactor stays in place



Fission product gamma sources build-up and decay (after 1hr operation) in a 560 MW reactor

Summary

1) GCR

- Low rate
- Higher Energy
- Mostly 'unshieldable'
- High-Z shields make it worse

2) Solar Energetic Particles

- Sporadic
- In a storm: High rate
- Lower Energy
- 'Shieldable'

3) Engine Operations

- Short impulse (< 20min)
- Neutrons shielded by low-Z material
- Gammas shielded by either high-Z or low-Z material

4) Engine Shutdown

- Decays quickly
- Gammas shielded by either high-Z or low-Z material

Radiation Limits

Human Dose Limits

Stochastic

Example effective dose limits for 1-yr missions resulting in 3% REID. Assume equal dose to all tissue. No prior occupational exposure.

	Females		Males	
Age (yr)	**Avg US Adult Population**	**Never-Smoker**	**Avg US Adult Population**	**Never-Smokers**
30	0.44 Sv	0.60 Sv	0.63 Sv	0.78 Sv
40	0.48 Sv	0.70 Sv	0.70 Sv	0.88 Sv
50	0.54 Sv	0.82 Sv	0.77 Sv	1.00 Sv
60	0.64 Sv	0.98 Sv	0.90 Sv	1.17 Sv

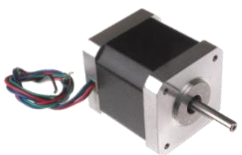
Deterministic

Dose limits for Short-Term or Career Non-Cancer Effects (in mGy-Eq. or mGy)

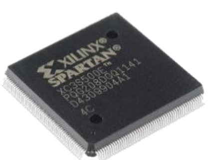
Organ	30-day limit	1-year limit	Career
Lens	1,000 mGy-Eq	2,000 mGy-Eq	4,000 mGy-Eq
Skin	1,500	3,000	6,000
BFO	250	500	N/A
Circ syst	250	500	1000
CNS	500 mGy	1,000 mGy	1,500 mGy
CNS (Z≥10)	-	100 mGy	250 mGy

NASA, 2014. Space Flight Human-System Standard Volume 1, Revision A: Crew Health (No. NASA-STD-3001).

Material Dose Limits



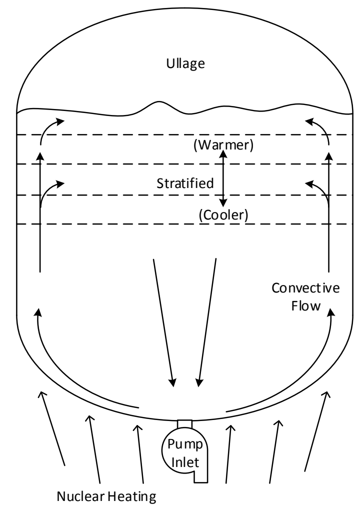
Stepper Motors – 10^9 Rad

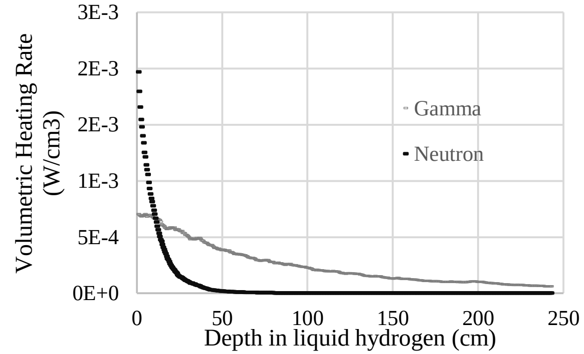


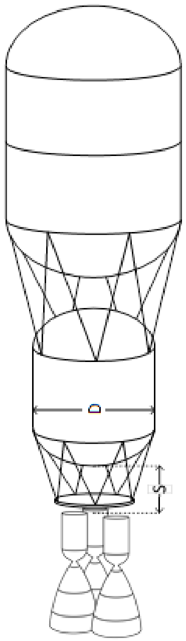
FPGA – 10^4 Rad
ASIC – 10^5 Rad

Teflon < 10^5 Rad
Rubber – 10^7 Rad

Thermal Limits







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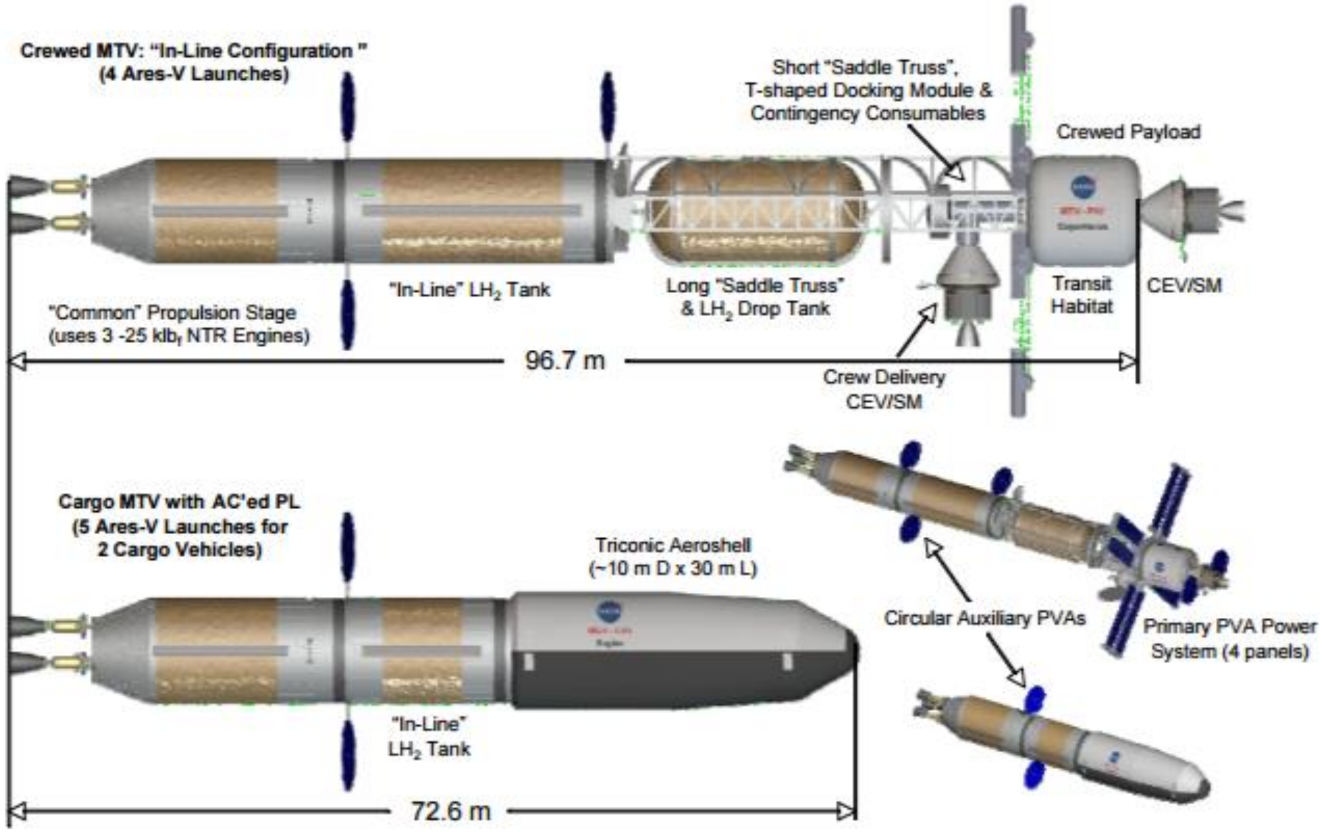
Ares V NTP Configuration (from executive summary)



Mission timeline (from addendum 1)

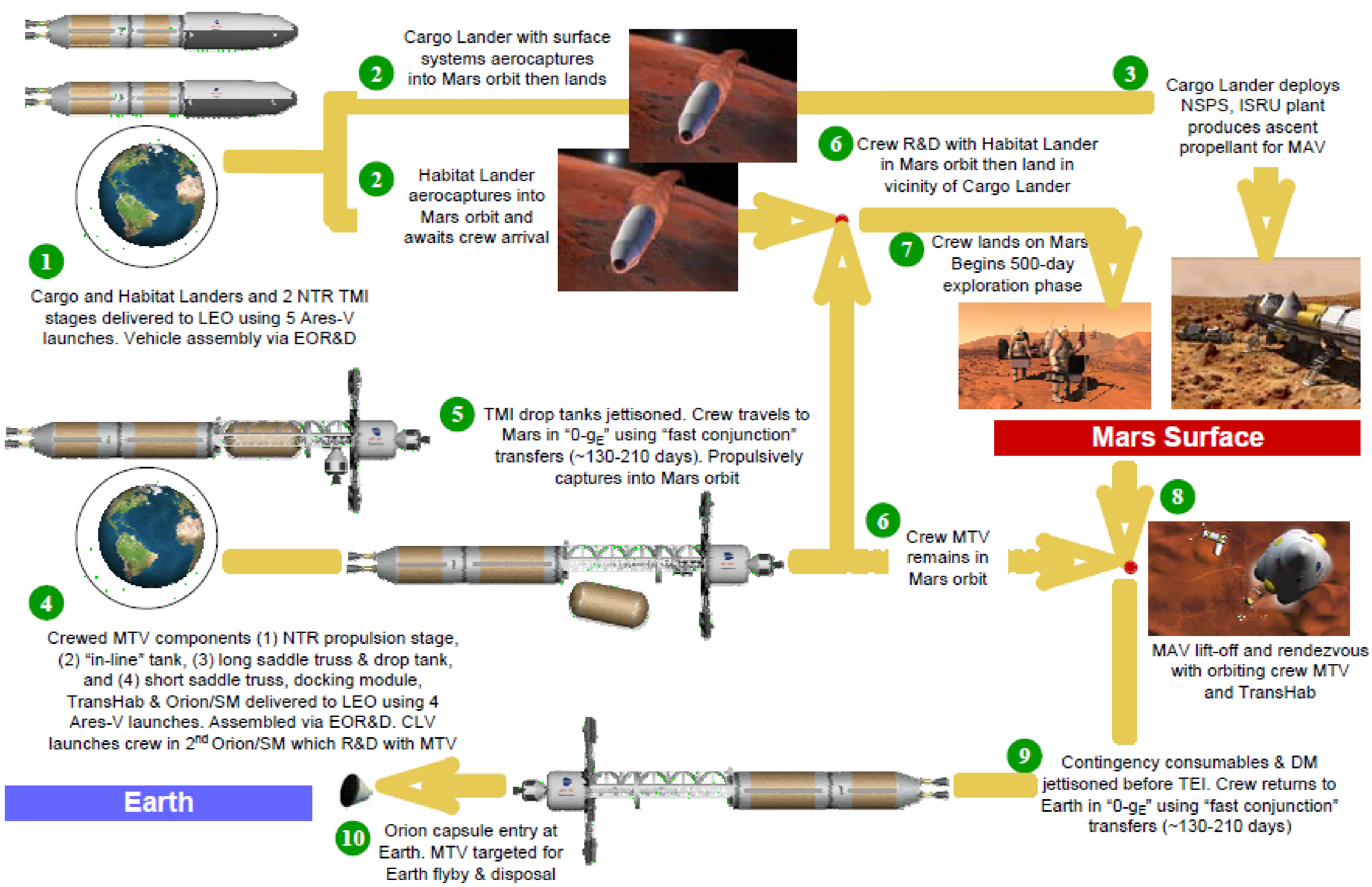


Figure 5-36. DRA 5.0 long-stay Mars mission overview: alternative NTR crewed MTV.

Background

- From the Report (NASA-SP-2009-566)
  - NTP option used 25klbf engines, predeployed lander and single crew stack ypical configuration includes the hab, at least 2 tanks (1 core, 0-1 inline and 1+ drop tanks) and an engine assembly with 3 25klbf engines
  - The stage LH2 tank has an inner diameter of 8.9 m and a propellant capacity of 59.4 t. The short in-line tank has a launch mass of 46.6 t and an overall length of 13.3 m including the forward and rear adaptor sections, and it holds 34.1 t of LH2.
  - It includes two saddle trusses that are open on the underside for jettisoning of the drained LH2 drop tank and unused contingency consumables at the appropriate points in the mission
  - Design includes additional external radiation shielding on each engine for crew protection during engine operation.
  - Total mass allocation for shielding was 6.45-7.31 mT, depending on assumptions used.
  - Shielding material was not explicitly mentioned in detail, but is expected to be some combination of plastics, lead, and metal carbides.
- From team members participating in study
  - From Addendum 2 in DRA 5, total mass shielding was
    - 7.31 mt (30% mass margin) - ~2.43 mT/engine
    - 6.45 mT (15% mass margin) - ~2.14 mT/engine
    - 5.625 mT, (0% mass margin) - ~1.88 mT/engine
  - The original DRA 5.0 baselined three 25 klbf GC fueled “Pewee-class” engines using HEU. Each engine had an internal dome shield, and included a forward external radiation shield (~1.5 t per 25 klbf engine) plus some additional localized spot shielding
  - The shielding that we’ve provided for our vehicles to date have been geared around limiting the crew dose to no more than ~5 rem over the course of the mission. The analysis presented at the 2/9/17 NTP team meeting showed the need for an ~1.4 mT external shield* on each 25 klbf engine to maintain a 5 rem limit, so DRA 5.0 was on the conservative side with 1.5 t shields and additional spot shielding

    *yielded 5 rem total dose to an otherwise entirely unshielded astronaut at 80m from the engine (accounting for tanks plus LH2 rundown).

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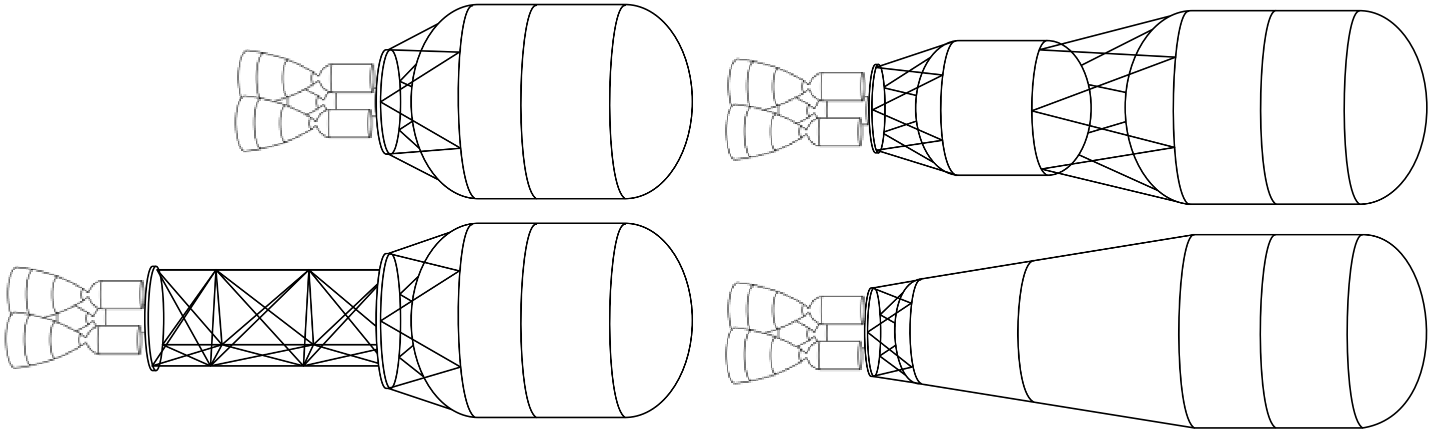
Mitigation Strategies (MS)

1) Geometry
   A) Distance – Increase engine standoff
      - Fixed or extendable engine truss
      - Crew habitat location
   B) Shadowing/Scattering – Reduce solid-angle of exposure
      - Conical tanks
      - Core stage stack sizing
2) Material
   A) Propellant
   B) Food/water/equipment (in habitat)
   C) Dedicated shield:
      - Internal to engine
      - External to engine
      - Aft face of propellant tank or thrust takeout
      - Spot shielding for components

Staging Considerations

Standard Core Stage

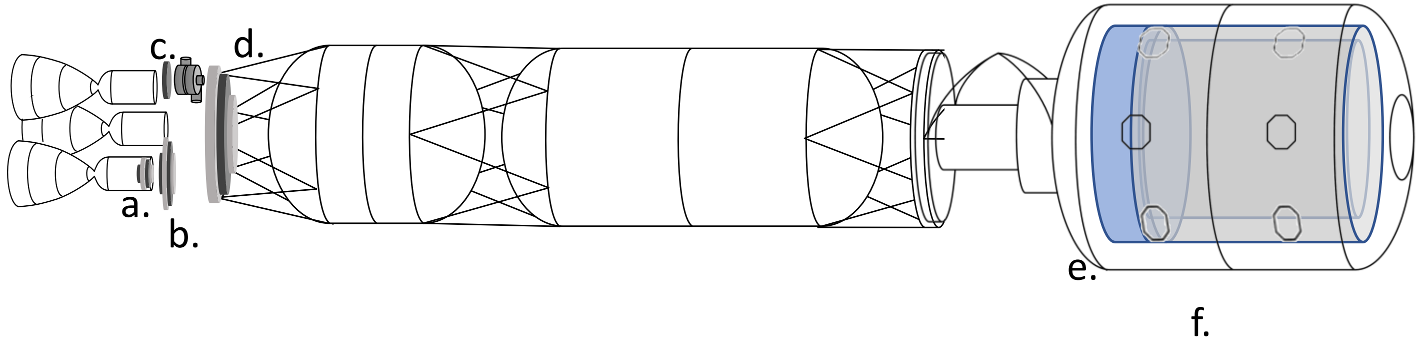
Thermal ‘Buffer’ Tank



Distance Truss

Conical Tank

Potential Shielding Locations



a. Internal shielding (per engine)

b. External shielding (per engine)

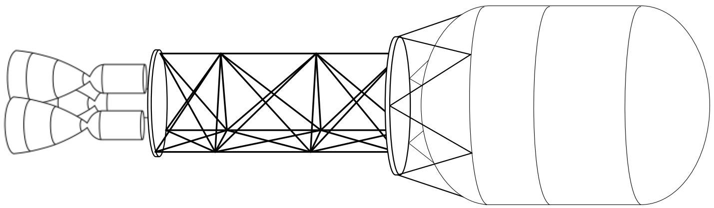
c. External spot shielding (per component)

d. External shielding (cluster)

e. Water/food/waste 'Hab-slab' ($< 2\pi$)

f. Water/food/waste 'Hab-shelter' ($>3\pi$)

MS 1A) Distance Truss



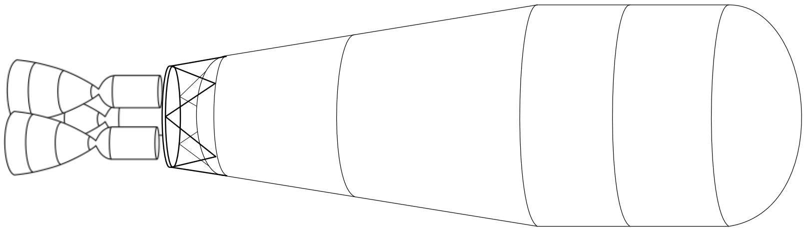
PRO

- Distance is effective (view factors)
- No major redesign
- Reduces tank heating
- Smaller shadow shield

CON

- Longer feedlines and docking attachments
    - Thermal conditioning
    - Pump location(s)?
- Packaging constraints
- Control authority (RCS)
- Increased complexity
    - Retractable truss
    - In-space deployment
- Diminished returns:
    - First meter of distance has dramatic reduction in view factor
    - Benefit drops off rapidly with added distance

MS 1B) Geometry



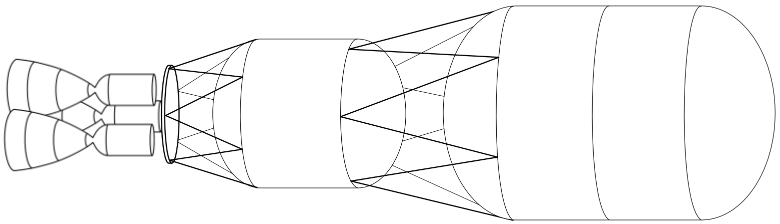
PRO

- Reduces ‘view-factor’ b/w engine and tank
- Smaller shadow shield, less thermal heating
- For equivalent mass of propellant, greater ‘thickness’ and intrinsic shielding

CON

- More mass
- Packaging efficiency in payload shroud
- Manufacturing
- Control authority (RCS)

MS 2A) Buffer/Run Tank



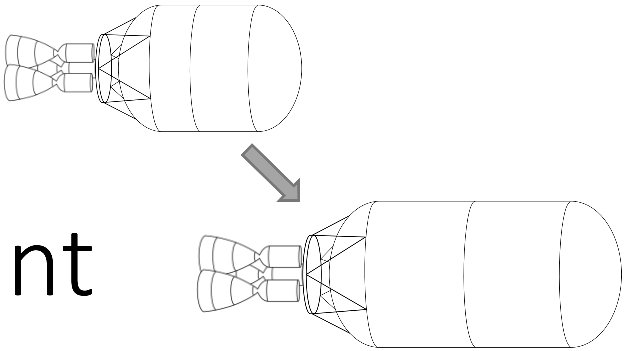
PRO

- Uses propellant mass to absorb radiation and conducted heat
- Reduces shadow shield diameter (If smaller profile tank is used)
- Permits higher pressure with reduced mass penalty
- As run-tank:
  - Isolates thermal stratification effects to smaller volume
- As buffer-tank:
  - Route boiloff as ullage pressurant
- Expands pressure-fed operating envelope in shutdown/startup transient
- Possibly lends itself to a small/inexpensive FTD Option (e.g run tank and single engine)

CON

- 2 tanks: mass/shells, ducts, valves, TPS
- Added structure mass
- Significant complexity
- Packaging inefficiency
- May require separate launch (smaller vehicle is OK)

MS 2A) Bigger tanks/ More ‘reserve’ propellant



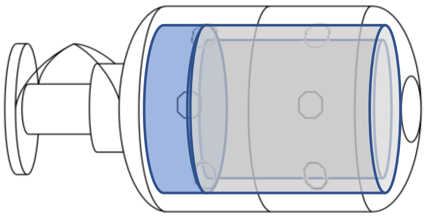
PRO

- Reserve propellant nearly eliminates neutron dose concern
- Distance bonus for crew dose
- More propellant allows more contingency
- Better margins for propellant losses or off-nominal operation

CON

- More surface area
- More mass
- Packaging limitations
- Only helps crew dose
- If prop. margin is used, crew dose increases
- Post-shutdown: ‘Slosh’ makes an unreliable shield

MS 2B) Hab Design: Storm Shell-tube



PRO

- Can use water
- Dirty water/brine is OK
- Improves ECLSS margin
- Handles GCR/SPE

CON

- May use more H_2O than required by life ECLSS

Cockpit

- In-line seats
- Situational awareness

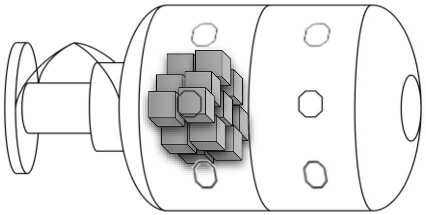
- No sleeping protection
- May be redundant

Berth

- More time in cover

- More room required

MS 2B) Hab Design: Food/water/equip.



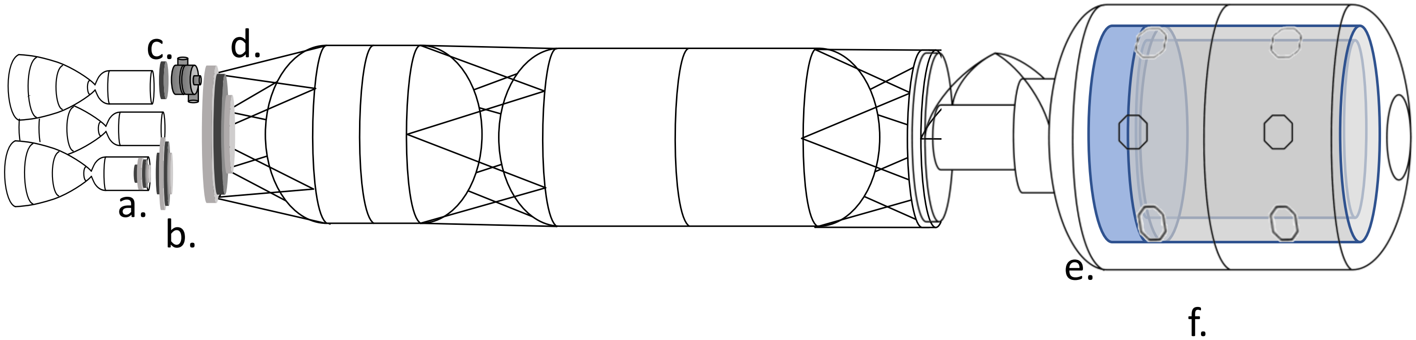
PRO

- Uses existing mass (nothing added)
- Handles GCR/SPE

CON

- Repackaging complexity
  - CONOPS
  - Must mitigate streaming radiation paths (no holes)

MS 3C) Dedicated Shielding



a. Internal shielding (per engine)

b. External shielding (per engine)

c. External spot shielding (per component)

d. External shielding (cluster)

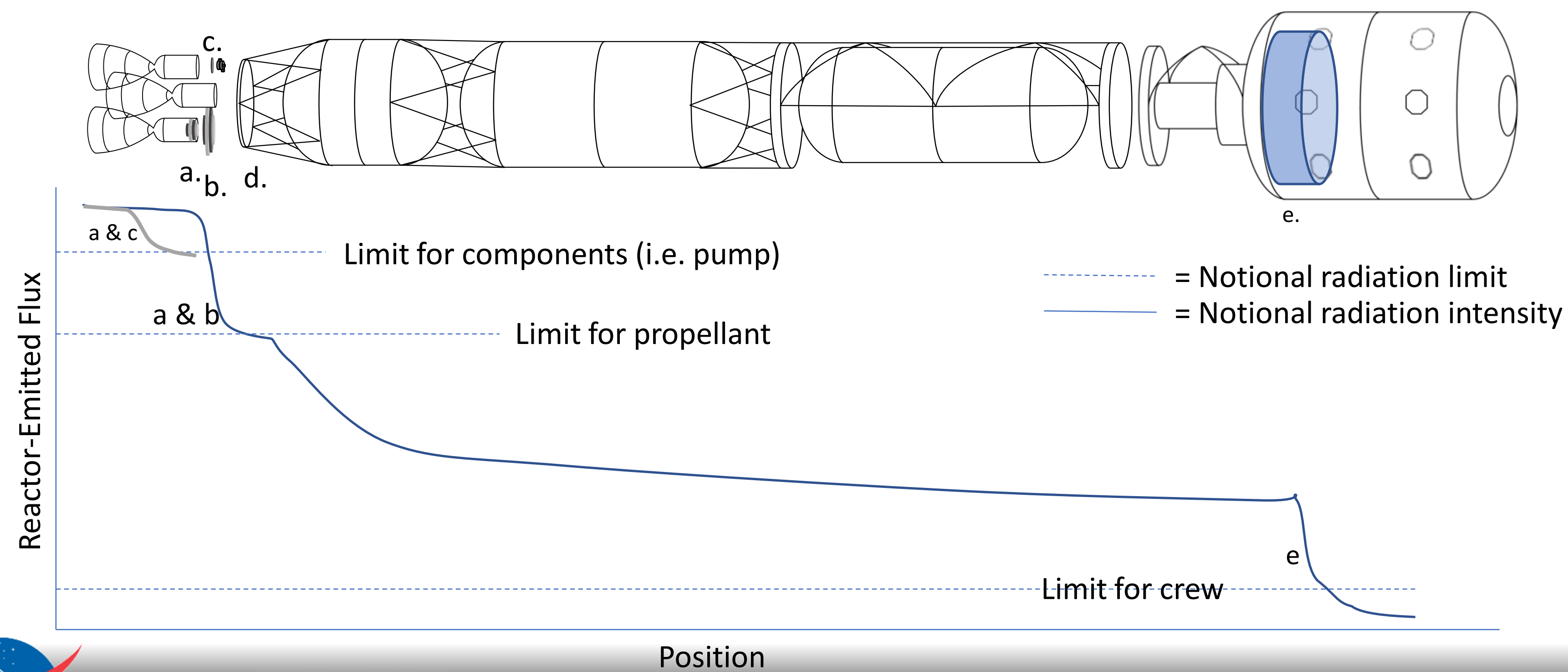
e. Water/food/waste ‘Hab-slab’ (< 2π)

f. Water/food/waste ‘Hab-shelter’ (>3π)

Comparison: Shielding Scheme A

- **Internal shield** and **spot shielding** provide adequate protection for core-adjacent **components**
- **Internal shield** and **external shield** provide adequate protection for **propellant** systems
- **Water/food/etc** in habitat provide adequate protection for **crew** (eliminates any deficit from other shields)

PRO: **Only the required mass** is applied to shield each sensitive region. **Crew hab shield also reduces space radiation.**
CON: Requires collaborative shield design with habitat architecture. Must be configurable for this application.

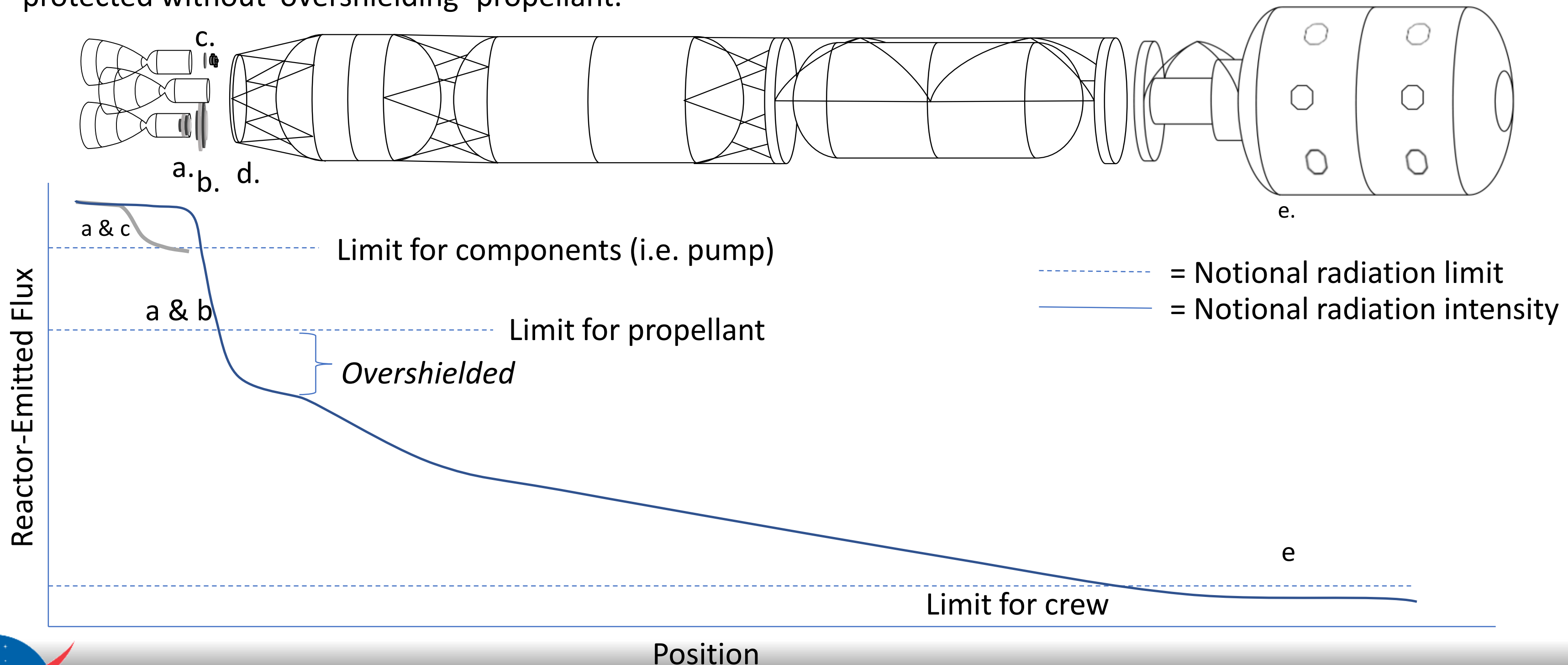


Comparison: Shielding Scheme B

- **Internal shield** and **spot shielding** provide adequate protection for core-adjacent **components**
- **Internal shield** and **external shield** provide adequate protection for **propellant** systems **AND crew**

PRO: Crew dose limits are met with **no modification to habitat**.
CON: Possibly results in **more shield mass** than is required. **No additional protection from space radiation**.

The notional diagram shown below assumes external shield size is driven dose limit to crew, implying propellant can handle high dose. If propellant is instead determed to be limiting factor, crew habitat may be adequately protected without 'overshielding' propellant.



Conclusions

- Shield design at or near the engine should only account for effects to components and propellant. Any additional mass required for crew (if any) should be allocated to the crew hab and can be dual use for other purposes (water, food, GCR/SPE shielding) wherever possible.
- When performing shielding trades, it should be possible to take credit for mass in the crew hab (and even add to it if required) when designing the stage. (e.g. shielding design may be an iterative/integrated process with the hab).
- All concepts will need some localized shielding at the engines.
- Think outside the box – Use existing mass as shielding wherever possible
- Think integrated – Design to the environment
- Think 'Big Picture' – Remember existing space radiation dose environment

Future Considerations

Near-term

- Establish thermal limits to propellant
- Explore optimal propellant-use options (esp. buffer tank)
- Radiation and MMOD Shielding:
  - Composites
  - Additive Mfg
  - Metal Foams

Long-term

- Split launch (SLS/FH/Delta)
- Single engine contingency

Spare Slides

Water shielding dose comparisons

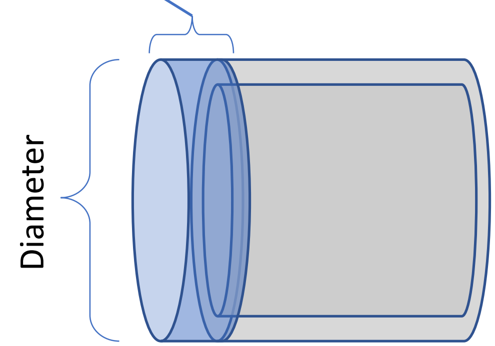
(Summary slide from 2/9/17)

	Per-engine shield mass	Crew Hab H2O	Estimated Total Dose
Case 1	0	0	7 Sv (700 rem)
Case 2	0	1.0 m	0.2 Sv (20 rem)
Case 3	170 kg	1.0 m	0.05 Sv (5 rem)
Case 4	630 kg	1.0 m	0.01 Sv (1 rem)
Case 5	170 kg	1.7 m	0.01 Sv (1 rem)

Water 'slab' thickness (m)

Diameter (m)	1 m	1.7 m
2 m	3.1	5.3
3 m	12.6	21.4
4 m	28.3	48.1

Mass of H2O (mt)



Background

- DRA 5.0 examined several transportation options: All-chemical, NTP, NEP, and Solar electric
- Executive summary discusses NTP configuration using Ares V, addendum includes the NCPS NTP variant using SLS
- NTP option used 25klbf engines, predeployed lander and single crew stack
  - Typical configuration includes the hab, at least 2 tanks (1 core, 0-1 inline and 1+ drop tanks) and an engine assembly with 3 25klbf engines
- Aggregation orbit was LEO, Mars aggregation at a 1-sol orbit
- Six crew members

Comparison to EMC

	DRA 5.0	EMC
Aggregation orbit	LEO (407 km circular)	LDRO (cislunar)
Transportation options	Chem, NTP, NEP, SEP/Chem	SEP/Chem, Hybrid
Predeployment	Cargo only	Cargo + return propellant
Mission class	"Fast conjunction" Type-I Long-stay	Type-II Long-stay
Crew stack mass (DRA NTP vs EMC SEP/Chem)	~356 mT (Ares V) / 360 mT (SLS)	~270 mT
Launch Vehicle	4-5 Ares V / SLS	4-6 SLS

Time-series Dose

Linear Scales

	Dose Rate: Engine Ops + Shutdown	Cumulative Dose: Engine Ops + Shutdown	Cumulative Dose: GCR (1 Sv/yr*)

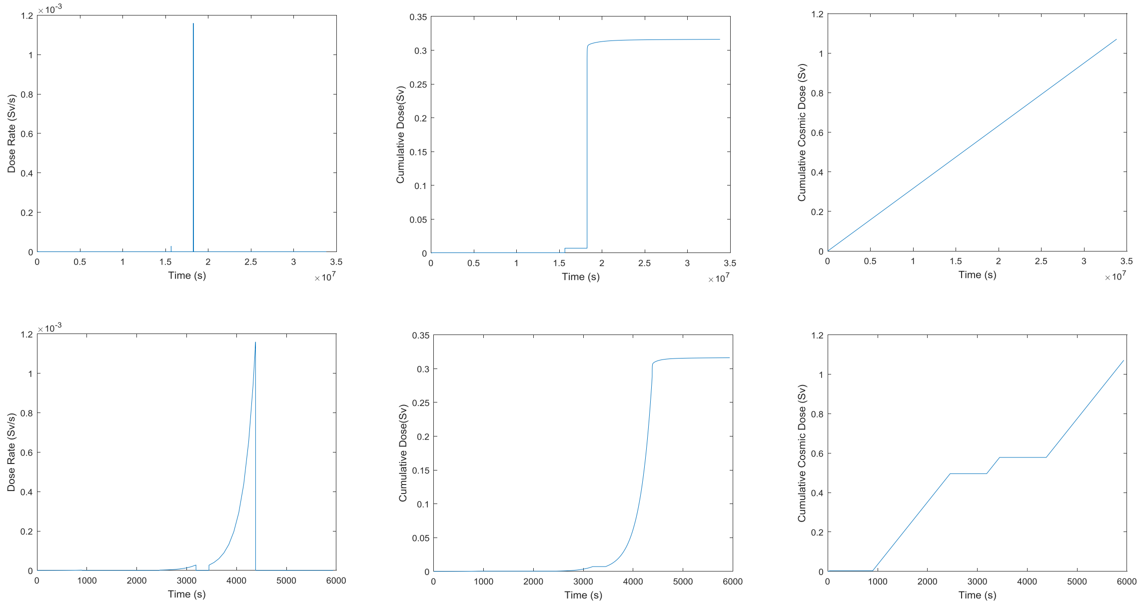
Y-axis: Linear

X-axis: Standard

Y-axis: Linear

X-axis: Condensed

(Coast phase x10000)



All doses shown here are only for demonstration and not necessarily representative of expected dose rates.

Time-series Dose

Semilog Scales

Dose Rate: Engine Ops + Shutdown | Cumulative Dose: Engine Ops + Shutdown | Cumulative Dose: GCR (1 Sv/yr*)

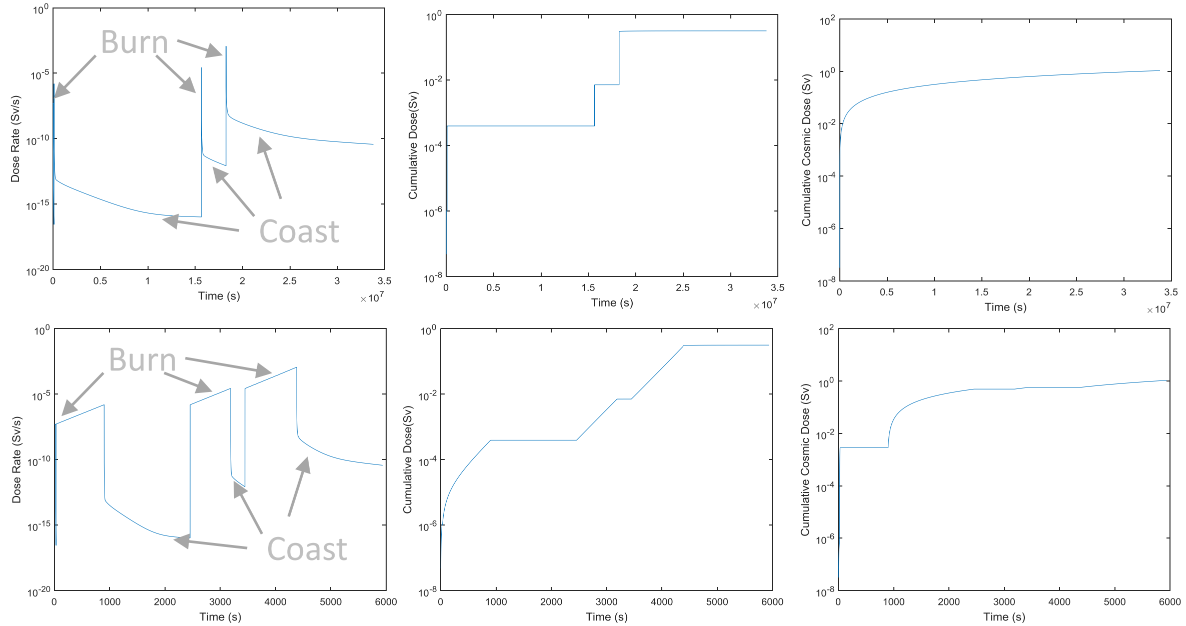
Y-axis: Log

X-axis: Standard

Y-axis: Log

X-axis: Condensed

(Coast phase x10000)



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