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’
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.

<table>
<thead>
<tr>
<th>Females</th>
<th>Males</th>
</tr>
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<tbody>
<tr>
<td>---------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>30</td>
<td>0.44 Sv</td>
</tr>
<tr>
<td>40</td>
<td>0.48 Sv</td>
</tr>
<tr>
<td>50</td>
<td>0.54 Sv</td>
</tr>
<tr>
<td>60</td>
<td>0.64 Sv</td>
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**Deterministic**
Dose limits for Short-Term or Career Non-Cancer Effects (in mGy-Eq. or mGy)

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


**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**

- Gamma
- Neutron

Volumetric Heating Rate (W/cm$^3$) vs. Depth in liquid hydrogen (cm)

- 3E-3
- 2E-3
- 1E-3
- 5E-4
- 0E+0

0 50 100 150 200 250
Overview

i. Radiation Environments (Brief recap)
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Ares V NTP Configuration (from executive summary)
Mission timeline (from addendum 1)

1. Cargo and Habitat Landers and 2 NTR TMI stages delivered to LEO using 5 Ares-V launches. Vehicle assembly via EOR&D.

2. Habitat Lander aerocaptures into Mars orbit and awaits crew arrival.

3. Cargo Lander deploys NSPS, ISRU plant produces ascent propellant for MAV.

4. Crewed MTV components (1) NTR propulsion stage, (2) “in-line” tank, (3) long saddle truss & drop tank, and (4) short saddle truss, docking module, TransHab & Orion/SM delivered to LEO using 4 Ares-V launches. Assembled via EOR&D. CLV launches crew in 2nd Orion/SM which R&D with MTV.

5. TMI drop tanks jettisoned. Crew travels to Mars in “0-g” using “fast conjunction” transfers (~130-210 days). Propulsively captures into Mars orbit.

6. Crew MTV remains in Mars orbit.

7. Crew lands on Mars begins 500-day exploration phase.

8. MAV lift-off and rendezvous with orbiting crew MTV and TransHab.

9. Contingency consumables & DM jettisoned before TEI. Crew returns to Earth in “0-g” using “fast conjunction” transfers (~130-210 days).

10. Orion capsule entry at Earth. MTV targeted for Earth flyby & disposal.

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 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
  - 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
- Distance Truss
- Conical Tank
- Thermal ‘Buffer’ 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
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$_2$O than required by life ECLSS

- **Cockpit**
  - In-line seats
  - Situational awareness
- **Berth**
  - More time in cover
  - No sleeping protection
  - May be redundant
  - 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’ (< 2\pi)
- f. Water/food/waste ‘Hab-shelter’ (>3\pi)
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 determined 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)

<table>
<thead>
<tr>
<th>Per-engine shield mass</th>
<th>Crew Hab H2O</th>
<th>Estimated Total Dose</th>
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<tbody>
<tr>
<td>Case 1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case 2</td>
<td>0</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Case 3</td>
<td>170 kg</td>
<td>0.05 Sv (5 rem)</td>
</tr>
<tr>
<td>Case 4</td>
<td>630 kg</td>
<td>0.01 Sv (1 rem)</td>
</tr>
<tr>
<td>Case 5</td>
<td>170 kg</td>
<td>1.7 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diameter (m)</th>
<th>Water ‘slab’ thickness (m)</th>
<th>Mass of H2O (mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 m</td>
<td>1 m</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>1.7 m</td>
<td>5.3</td>
</tr>
<tr>
<td>3 m</td>
<td>1.0 m</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>2.0 m</td>
<td>21.4</td>
</tr>
<tr>
<td>4 m</td>
<td>1.7 m</td>
<td>28.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48.1</td>
</tr>
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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

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

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