Radiation Shielding for Space Nuclear Propulsion

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Overview

• Shielding for Nuclear Propulsion
• Time Series Dose Calculator
• Optimization Methodology
• Example Optimizations
• Material Comparison
• Conclusions
Shielding for Nuclear Propulsion
Compartamental Design

• Separate geometry into component parts
• Generalize inputs for each compartment
• Match inputs with output from preceding compartment
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>Age (yr)</th>
<th>Females</th>
<th>Males</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.44 Sv</td>
<td>0.60 Sv</td>
</tr>
<tr>
<td>40</td>
<td>0.48 Sv</td>
<td>0.70 Sv</td>
</tr>
<tr>
<td>50</td>
<td>0.54 Sv</td>
<td>0.82 Sv</td>
</tr>
<tr>
<td>60</td>
<td>0.64 Sv</td>
<td>0.98 Sv</td>
</tr>
</tbody>
</table>

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>
</tr>
</thead>
<tbody>
<tr>
<td>Lens</td>
<td>1,000 mGy-Eq</td>
<td>2,000 mGy-Eq</td>
<td>4,000 mGy-Eq</td>
</tr>
<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 – $10^9$ Rad
ASIC – $10^8$ Rad
Pumps - ??

Heat in Cryo

Volumetric Heating Rate (W/cm³)
Depth in liquid hydrogen (cm)
- Gamma
- Neutron
Time-Series Dose Calculation

• **MCNP6 Model:**
  • Import surface source generated from criticality run
  • Construct representative model of vehicle:
    • Structure (bulkheads)
    • Tank walls
    • Propellant
    • Nozzle

Crew compartment excluded:
  → Dose measured at fixed distance 80 m (after drop tank)

• Variable propellant load corresponding to mission profile
MCNP calculated dose response functions

MCNP6 dose response for varying propellant loads due to prompt neutron and gamma during engine operation (left) and due to delayed gammas from fission products across six energy groups (right).
Empirical fission product gamma terms

\[ \Gamma_j(t_o, t_s) = P_o \sum_{i=1}^{N_j} \frac{\alpha_{ij}}{\lambda_{ij}} e^{-\lambda_{ij}t_s} [1 - e^{-\lambda_{ij}t_o}] \]

Empirical model \cite{1,2} of fission product buildup during operation (left) and decay after shutdown (right).

Mission profile

Combine source and response functions, controlled by mission parameters: \( D(E, t) = S(E, t)R(E, t) \)
Evolutionary Algorithms

- AKA: *Genetic algorithms*
- Parameters of a design are encoded as a vector
- Population of designs are tested
- Best performing designs are more likely to pass traits to next generation
- Occasional random mutation of traits is permitted
- Both **Fitness** and **Diversity** are important!
Multiobjective Optimization

- Non-dominated solutions comprise the ‘Pareto set’
- Hypothetical curve of non-dominated solutions is true ‘Pareto front’
The ‘genome’ of a shield

- Parameters of shield candidate are stored in a vector
- Sorted to preserve some correlation for individual layers

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Material</th>
<th>Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>3</td>
<td>56.3</td>
</tr>
<tr>
<td>1.7</td>
<td>3</td>
<td>98.1</td>
</tr>
<tr>
<td>5.3</td>
<td>3</td>
<td>74.3</td>
</tr>
<tr>
<td>3.4</td>
<td>2</td>
<td>30.9</td>
</tr>
</tbody>
</table>

Layer 1 | Layer 2 | Layer 3 | Layer 4
Visualized...

- Generate Shield
- Calculate Dose & Mass
- Repeat for $N$ individuals

Aggregate and Score Performance

Dose vs. Mass

<table>
<thead>
<tr>
<th>Mass</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>2.0</td>
</tr>
<tr>
<td>4.5</td>
<td>3.0</td>
</tr>
<tr>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>2.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Fitness Scoring

• Measure distance between each point and its nearest line

\[ d = \min \begin{cases} d_{ap} = \text{norm}(a, P) \\ d_{bp} = \text{norm}(b, P) \end{cases} \]

The point is past the orthogonal bounds of the segment... if \((a - b) \cdot (P - b) \times ([b - a] \cdot [P - a]) < 0\)

Otherwise...

\[ d = \frac{1}{d_{\text{ab}}} \begin{vmatrix} x_a & y_a & 1 \\ x_b & y_b & 1 \\ x_P & y_P & 1 \end{vmatrix} \]

Or in English: distance is the absolute value of the determinant of the matrix shown above, divided by the distance between points \(a\) and \(b\).
Diversity Scoring

• Measure distance between each point and its nearest neighbor point

\[ P_i = (x_i, y_i) \]

\[ Diversity_i = \min_{k=1 \rightarrow N} [\text{norm}(P_k, P_i)] \]
Selection

• Preferentially select for reproduction based upon performance scoring

\[ S_i = W_F(F_i) + W_D(D_i) \]

\[ P_i = \frac{S_i}{\sum S} \]

<table>
<thead>
<tr>
<th>Fitness (F)</th>
<th>Diversity (D)</th>
<th>Score (S)</th>
<th>Repr. Prob (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1</td>
<td>2.5</td>
<td>0.22</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>3</td>
<td>0.26</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>2</td>
<td>0.17</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>4</td>
<td>0.35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fitness (F)</th>
<th>Diversity (D)</th>
<th>Score (S)</th>
<th>Repr. Prob (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>3</td>
<td>91.2</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>95.1</td>
<td>3.4</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>45.8</td>
<td>3</td>
</tr>
<tr>
<td>2.5</td>
<td>3</td>
<td>83.9</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>58.1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>84.2</td>
<td>2.2</td>
</tr>
<tr>
<td>2.5</td>
<td>3</td>
<td>83.9</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>58.1</td>
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<td>84.2</td>
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</tr>
<tr>
<td>2.5</td>
<td>3</td>
<td>83.9</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Reproduction – Split and recombination

• Split the two ‘genomes’ at a random location and recombine

• Allow chance for mutation:

• Add to the next generation of candidate designs:
The Algorithm (as implemented)

- Includes a secondary ‘archive’ population of high-performers
- Allows greater mutation rates and diversity without losing ground
Progression of the Multiobjective Evolutionary Algorithm (MOEA)

- Begins with random selection that fills the design space
- Converges toward the Pareto front within ~40 generations
- Thereafter, gradually pushes $\text{PF}_{\text{known}}$ toward $\text{PF}_{\text{true}}$ (mutation is important here)
Interpreting The Results

• All of parameter space is collapsed into each point displayed in objective space
• Requires some creative methods of visualization...
Example Case: 40 kW limit to Core Stage Tank

1) Generate Source:

2) Embed in Problem Geometry:

3) Execute Optimization Code:

4) Apply Constraint for Evaluation
Example Case: 0.2 Sv Entering Crew Compartment

Step 1) Evaluate time-series profile of a reference case, e.g. no-shield
Example Case: 0.2 Sv (continued)

Step 2) Determine terminal dose rate and cumulative dose:

\[
\dot D_{EOB} = 4.2E - 2 \frac{Sv}{s}
\]

\[D_{tot} = 7.0 \text{ Sv}\]
Example Case: 0.2 Sv (continued)

Step 3) Determine *Scaled* terminal dose ($\dot{D}'_{EOB}$) required to satisfy the imposed dose constraint ($D'_\text{tot}$)

$$
\dot{D}'_{EOB} = \dot{D}_{EOB} \frac{D'_\text{tot}}{D_{tot}}
$$

$$
\dot{D}'_{EOB} = (4.2E - 2 \text{ Sv/s}) \frac{0.2 \text{ Sv}}{7.0 \text{ Sv}} = 1.2E - 3 \text{ Sv/s}
$$
Example Case: 0.2 Sv (continued)

Step 4) Perform shield optimization using terminal dose rates only

Step 5) Select Appropriate Shield using Scaled Terminal Dose Rate ($\tilde{D}'_{EOB}$)
Material mass comparison

<table>
<thead>
<tr>
<th>Heating from single engine</th>
<th>M1 = LiH</th>
<th>M2 =   W</th>
<th>M3 = B₄C</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 kW</td>
<td>Mass (kg) : LiH + B₄C + W : B₄C + W</td>
<td>Ratio : 1.15</td>
<td>Δ Mass (kg) : 61</td>
</tr>
<tr>
<td>50 kW</td>
<td>Mass (kg) : 185 : 205</td>
<td>Ratio : 1.11</td>
<td>Δ Mass (kg) : 20</td>
</tr>
<tr>
<td>70 kW</td>
<td>Mass (kg) : 87 : 101</td>
<td>Ratio : 1.16</td>
<td>Δ Mass (kg) : 14</td>
</tr>
</tbody>
</table>

LiH Permitted (B₄C forced in first layer)

B₄C and W only
Conclusions

• Created a set of methods and tools to aid design and analysis of shielding for space nuclear propulsion

• Time-series dose calculator
  • Necessary tool for calculating integral dose
  • Highlights the importance of shielding for final burn

• Optimization code
  • Permits flexible design optimization, including ‘hot-swappable’ materials
  • Unconstrained multiobjective approach is ideal for facilitating design trades
  • Can be re-implemented in entirely new ways, e.g. add traits, change geometry
Future Work

• Additional complexity for design space
  • Slower convergence (more ‘noise’)
  • More possibilities for efficiency improvement

• Extension to greater than two objectives
  • Refactor some portions of code for higher-order solutions
  • Visualization and interpretation become much harder

• Implement improved ‘exploitation’ methods
  • Further narrows design space toward $P_{F_{true}}$ using other methods
  • Hastings Metropolis, Simulated Annealing, etc.
Acknowledgments

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  • Omar Mireles as my Pathways Mentor at MSFC

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  • Michael Eades
  • Paolo Veneri
  • Vishal Patel
  • Wes Deason

Opinions and recommendations expressed are my own and do not necessarily represent the opinions of NASA.
Contours

• MCNP6 FMESH Tallies:
  • Neutron flux
    • Fast – Epithermal - Thermal
  • Dose
    • Silicon (electronics)
    • Tissue (dosimetry)

• GNUPlot:
  Ugly scripts → Pretty plots
Engine Offset without Correction
Engine Offset with Correction
Time-series Dose (w/ Cosmic dose)

Y-axis: Linear
X-axis: Standard

Y-axis: Linear
X-axis: Condensed
(Coast phase x10000)
Time-series Dose (w/ Cosmic dose)

Log Scales

Y-axis: Log
X-axis: Standard

Y-axis: Log
X-axis: Condensed
(Coast phase x10000)