Marshall Space Flight Center

Oregon State UNIVERSITY OSU College of Engineering

Radiation Shielding for Space Nuclear Propulsion

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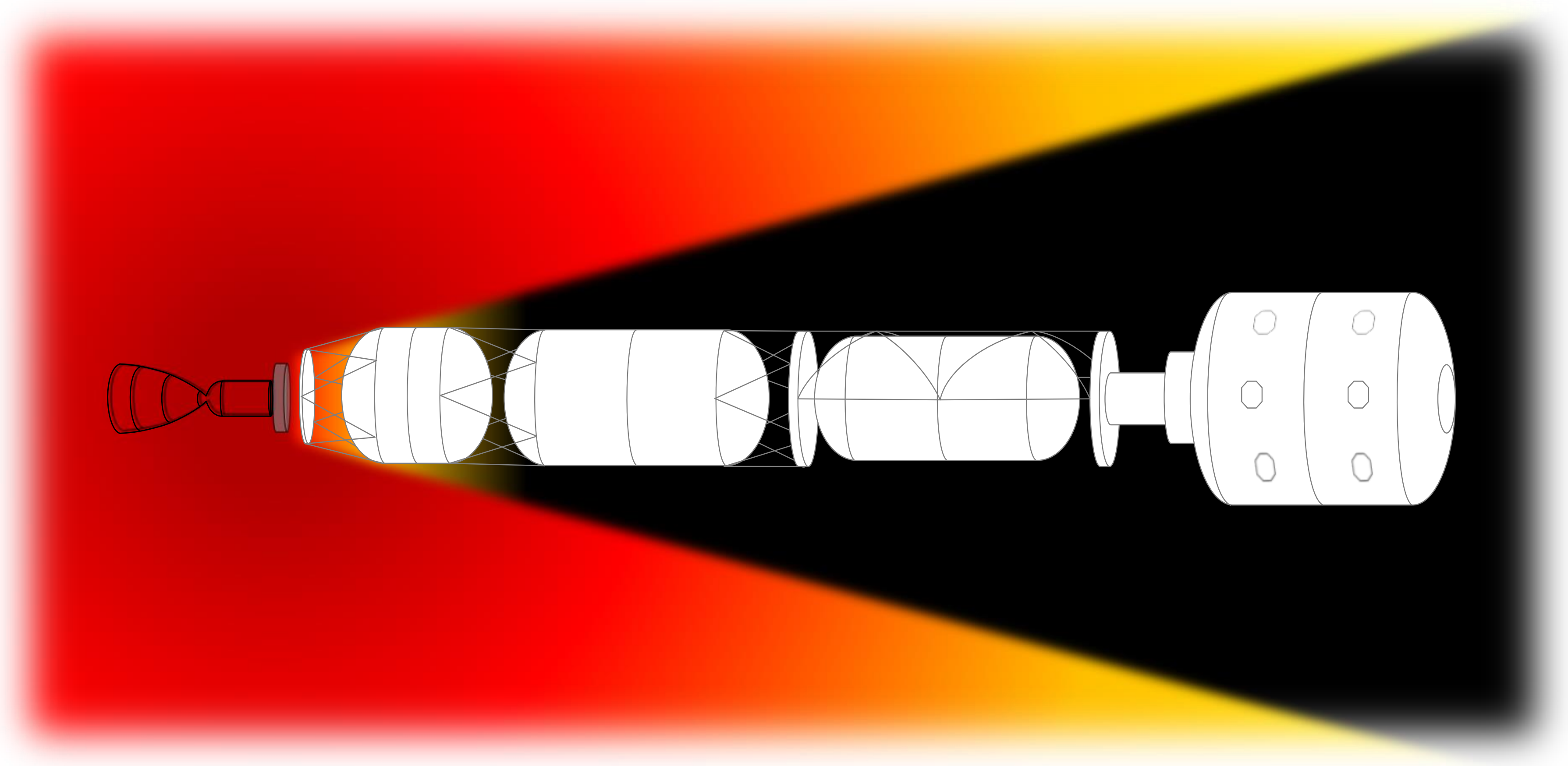
Overview

- Shielding for Nuclear Propulsion
- Time Series Dose Calculator
- Optimization Methodology
- Example Optimizations
- Material Comparison
- Conclusions

Shielding for Nuclear Propulsion



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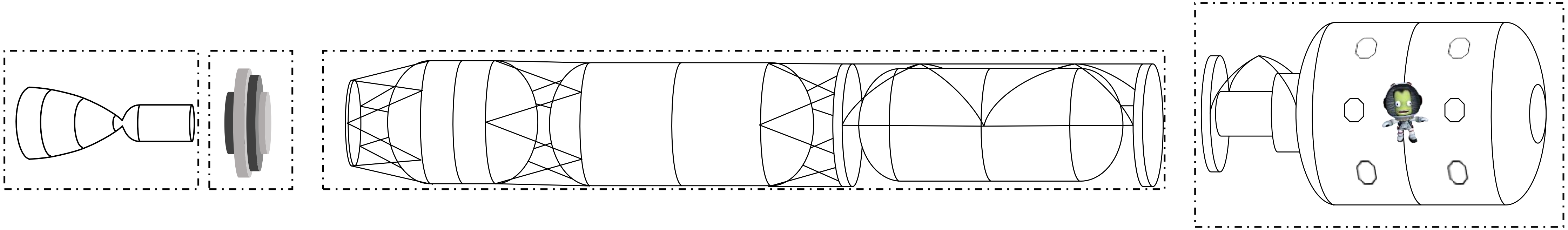
Compartmental Design

- 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.

	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

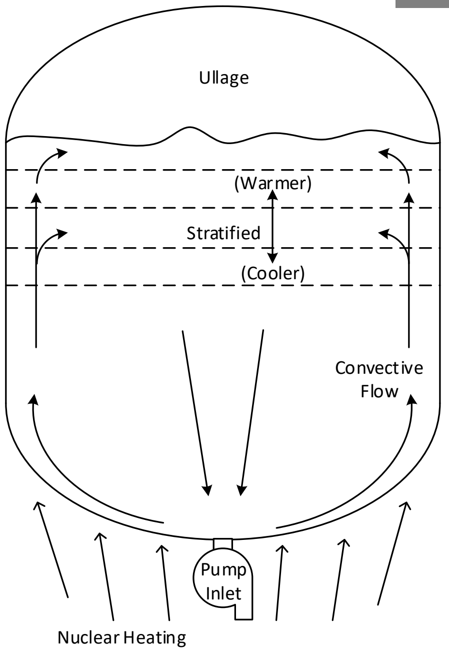
Material Dose Limits

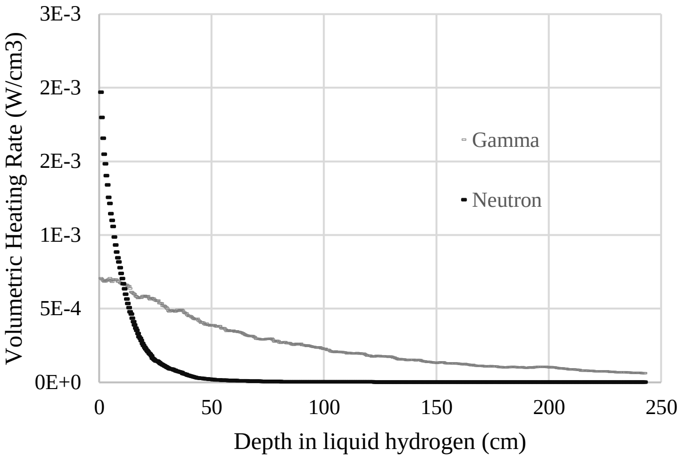
Stepper Motors – 10^9 Rad

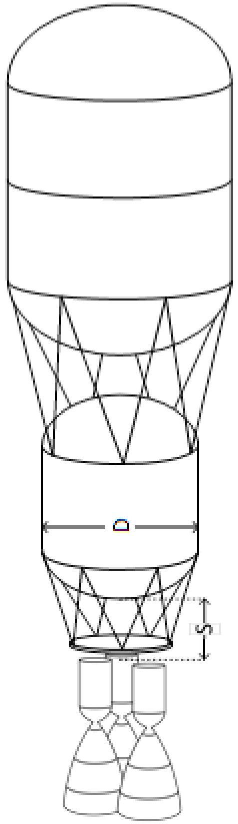
FPGA – 10^4 Rad
ASIC – 10^5 Rad

Pumps - ??

Heat in Cryo

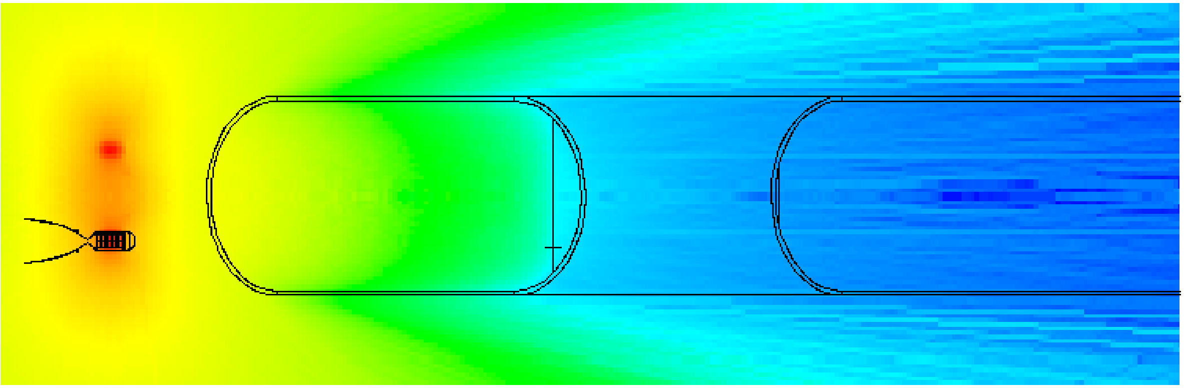






Time-Series Dose Calculation

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

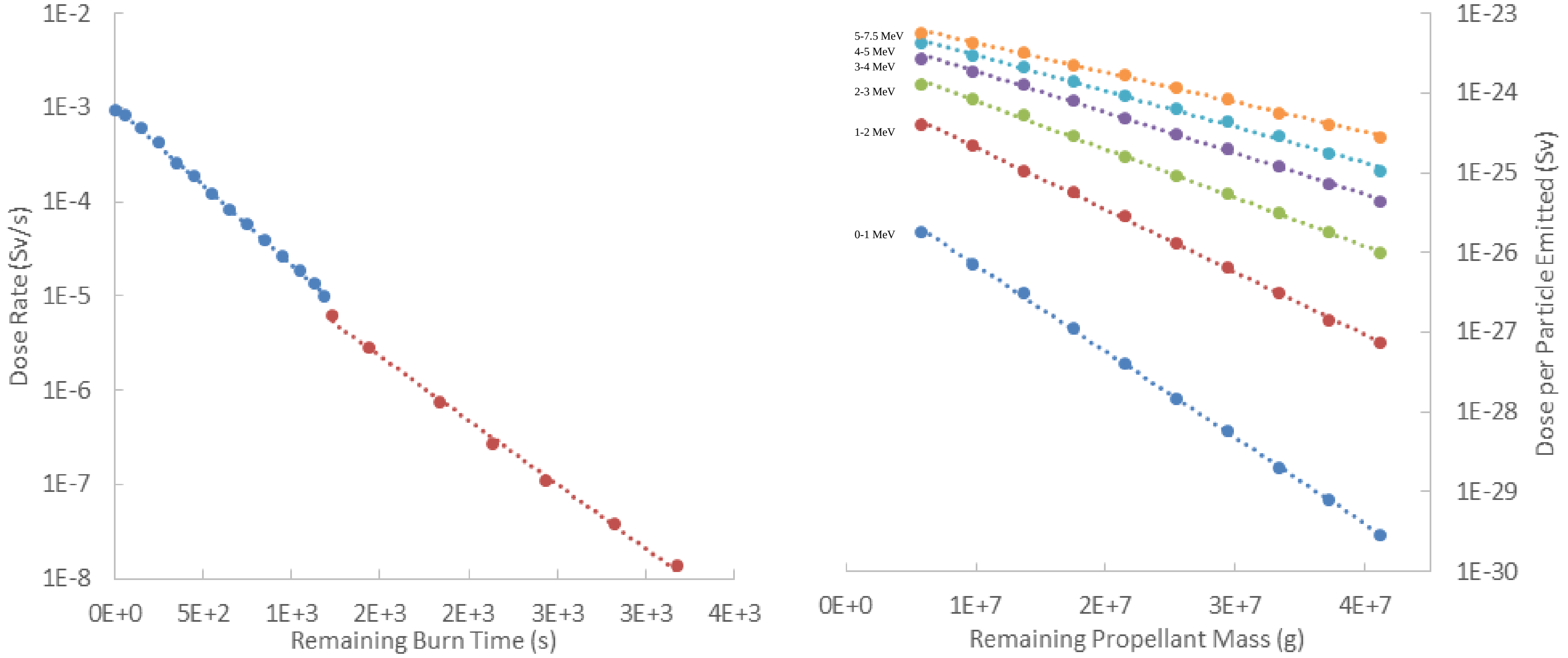


Crew compartment excluded:

→ Dose measured at fixed distance 80 m (after drop tank)

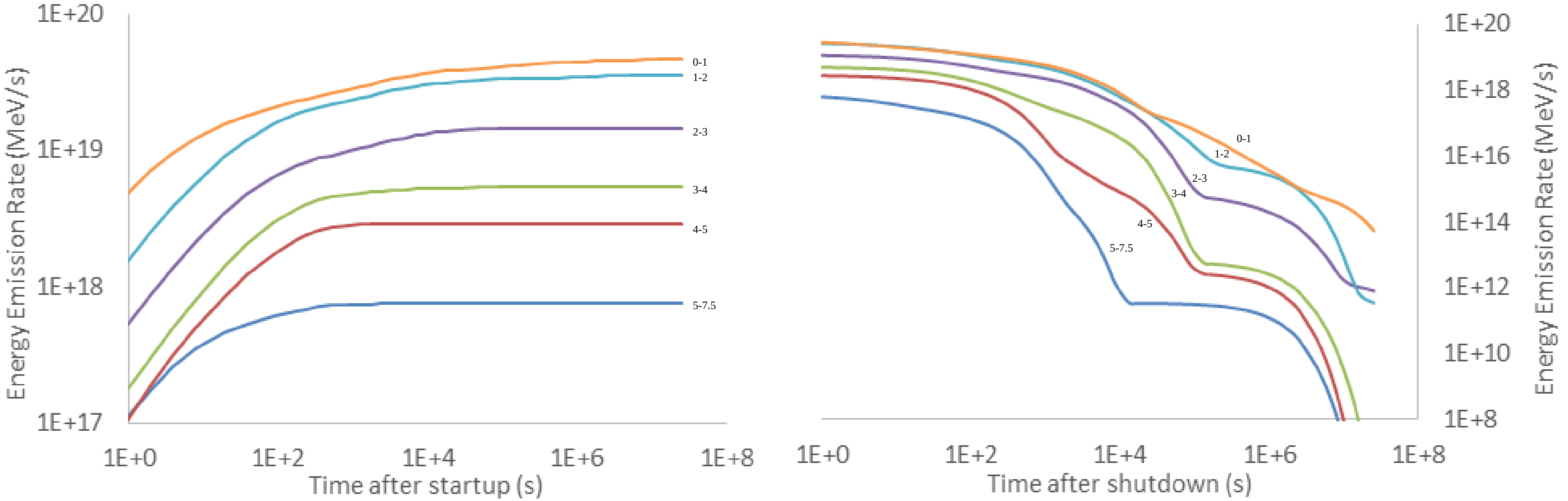
- Variable propellant load corresponding to mission profile

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



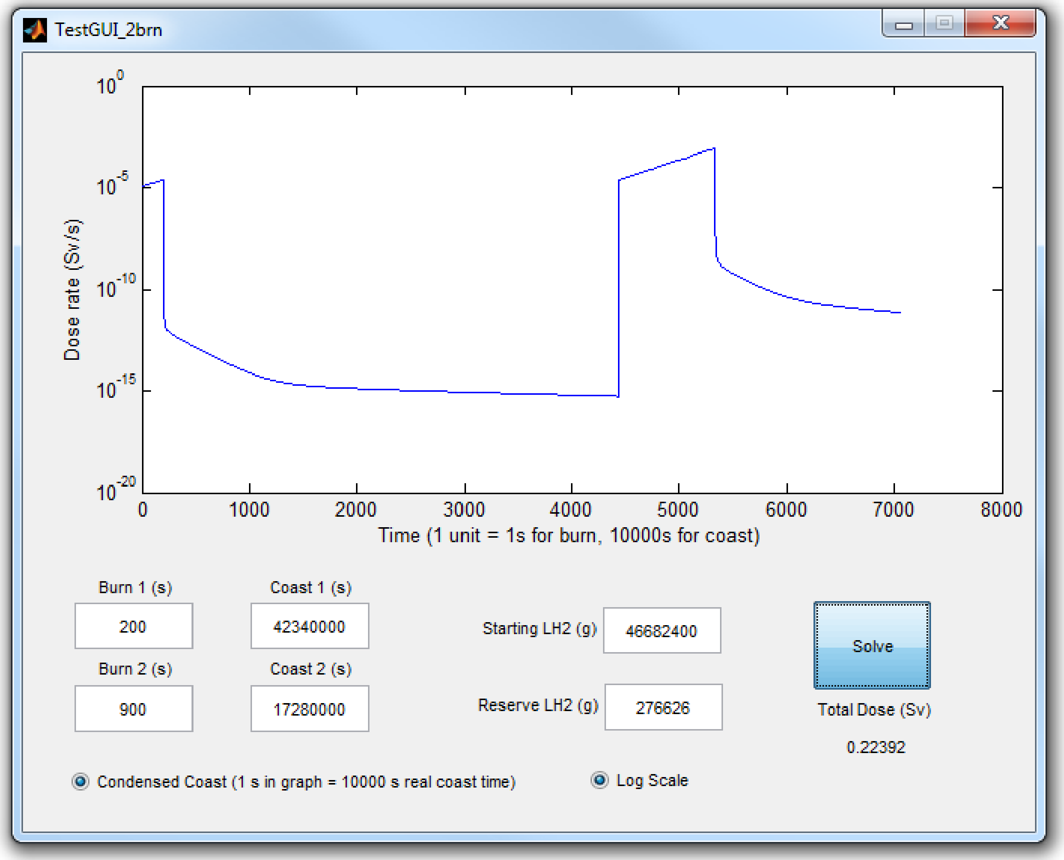
Empirical model[1,2] of fission product buildup during operation (left) and decay after shutdown (right).

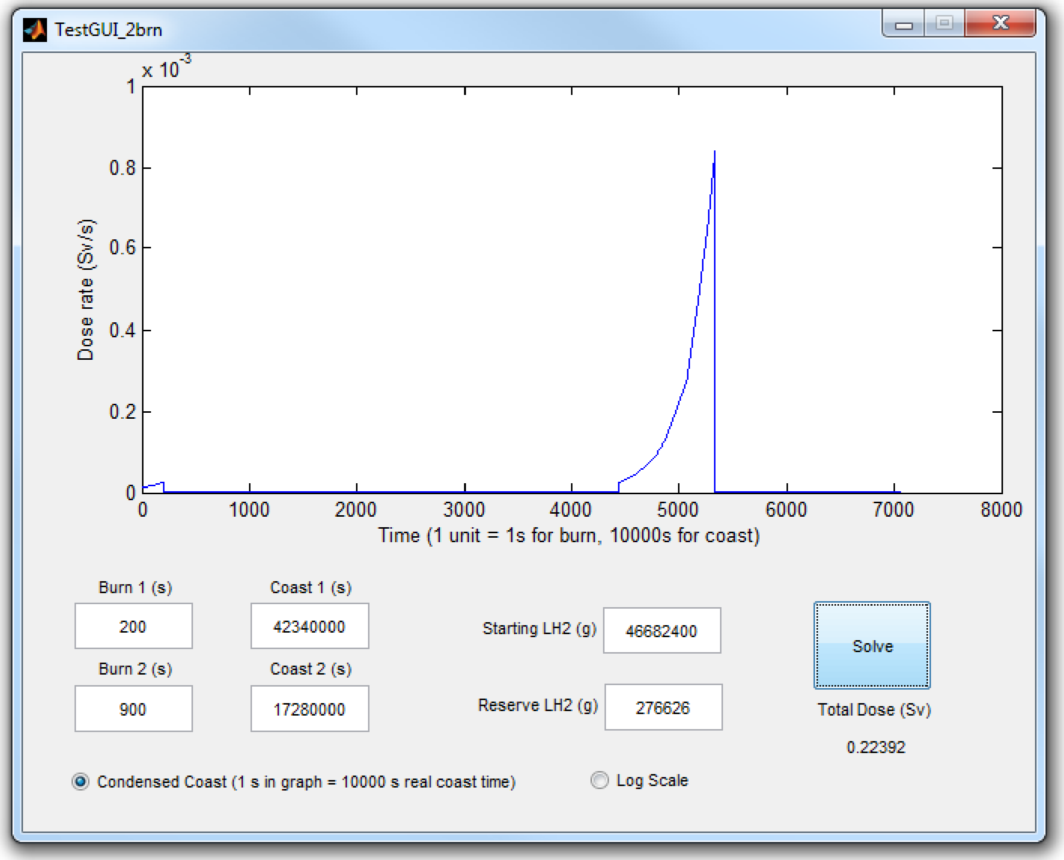
$$\Gamma_j(t_o, t_s) = P_o \sum_{i=1}^{N_j} \frac{\alpha_{ij}}{\lambda_{ij}} e^{-\lambda_{ij} t_s} [1 - e^{-\lambda_{ij} t_o}]$$

1. George, D.C., et al., "Delayed photon sources for shielding applications," *Trans. Am. Nucl. Soc.*, **35**, 463 (1980).
2. LaBauve, R.J., England, T.R., George, D.C., Maynard, C.W., "Fission product analytic impulse source functions," *Nucl. Technol.*, **56**, 322-339 (1982).

Mission profile

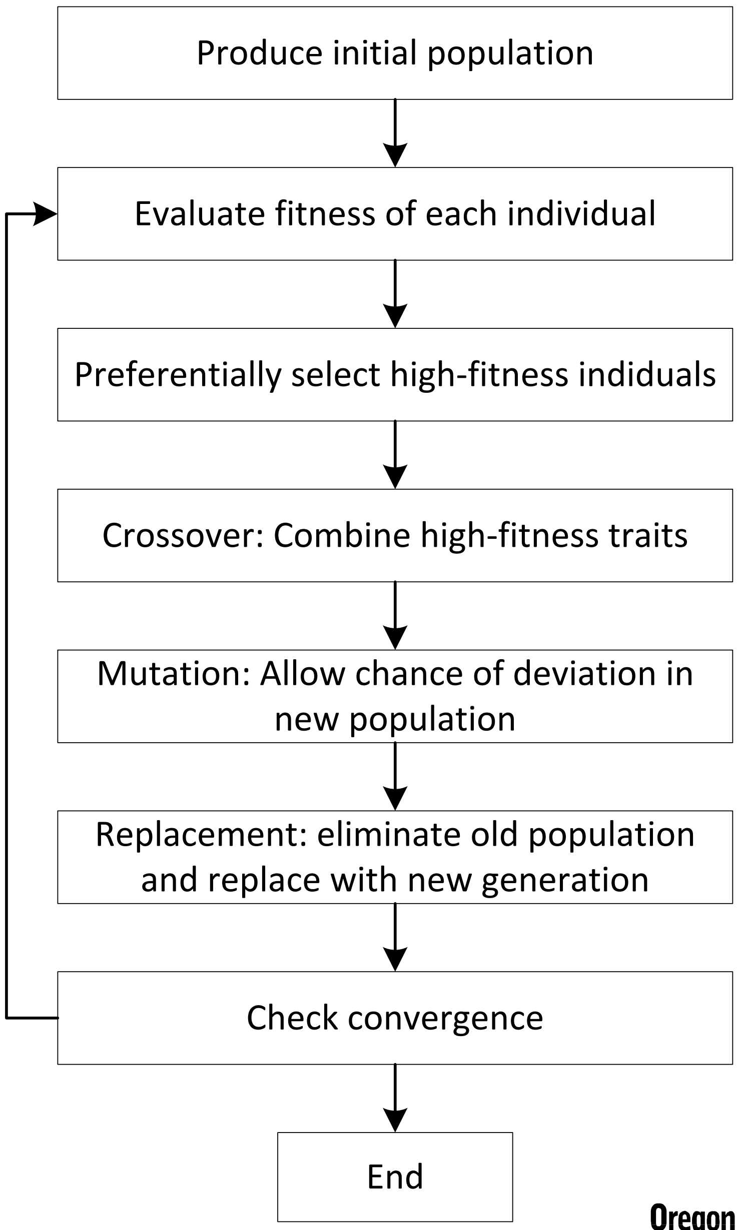
Combine source and response functions, controlled by mission parameters: $D(E,t) = S(E,t)R(E,t)$





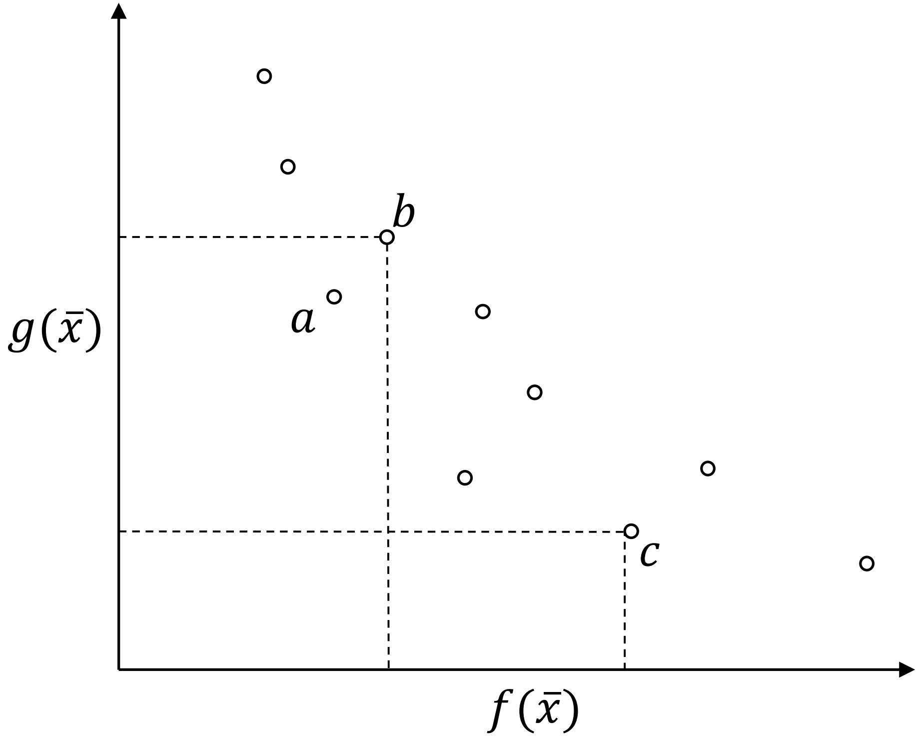
Evolutionary Algorithms

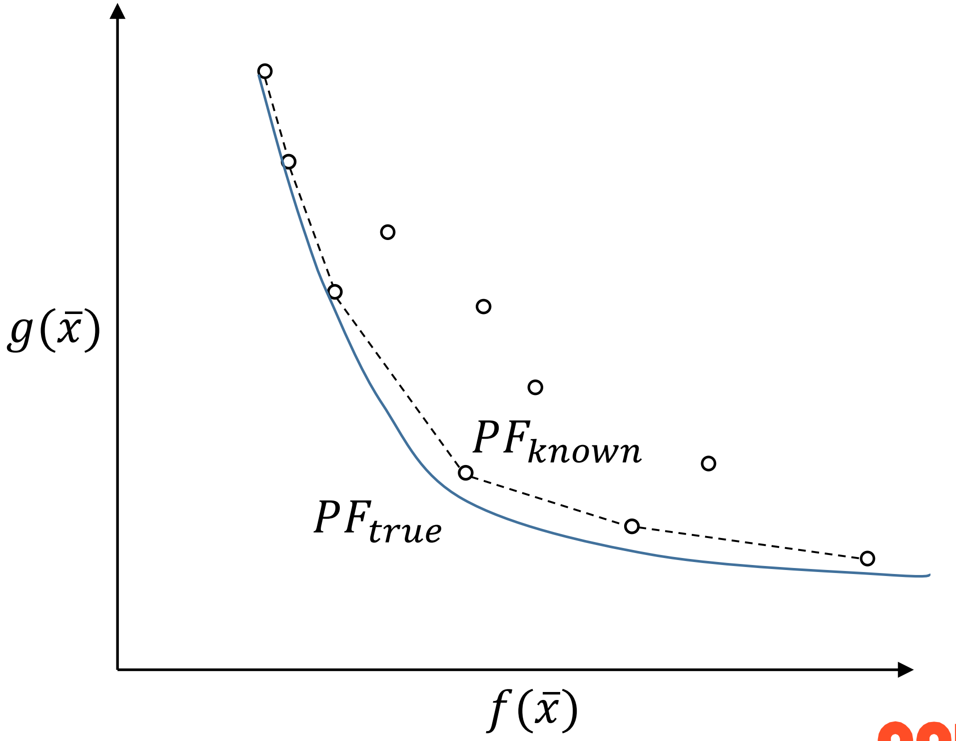
- AKA: *Genetic algorithms*
- Parameters of a design are encoded as a vector
- Population of designs are tested
- Best performing designs are more likely to pass traits to next generation
- Occasional random mutation of traits is permitted
- Both **Fitness** and **Diversity** are important!



Multiobjective Optimization

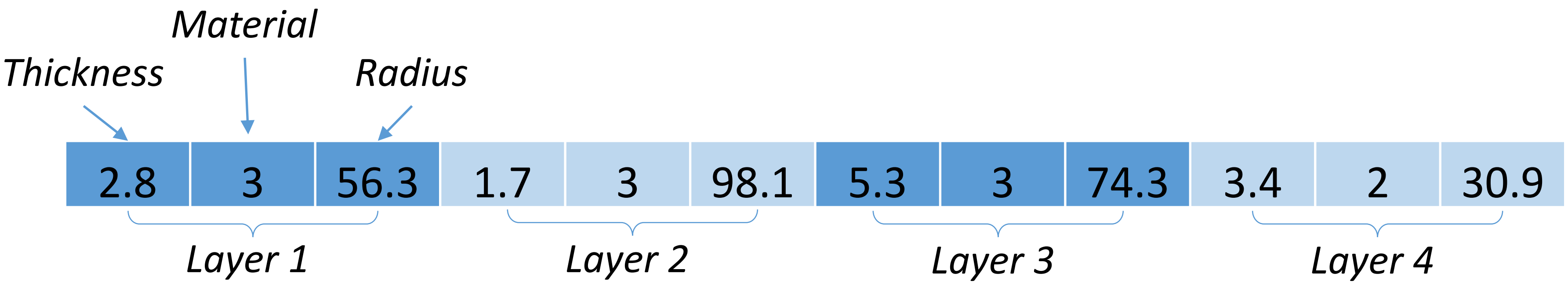
- Non-dominated solutions comprise the 'Pareto set'
- Hypothetical curve of non-dominated solutions is true 'Pareto front'





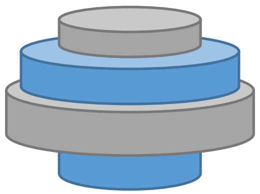
The 'genome' of a shield

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



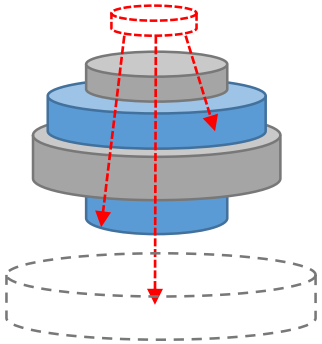
Visualized…

Generate Shield

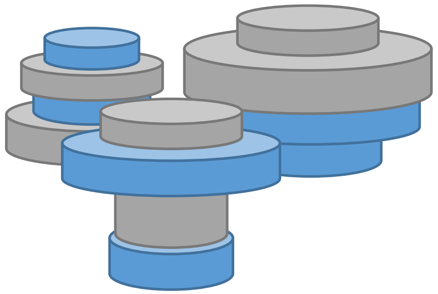


2.8	3	56.3	1.7	2	98.1	5.3	3	74.3	3.4	2	30.9

Calculate Dose & Mass

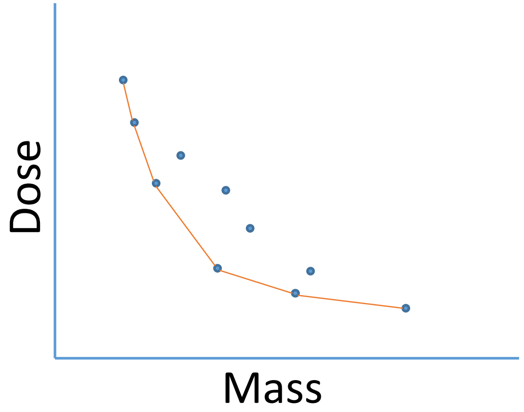


Repeat for *N* individuals



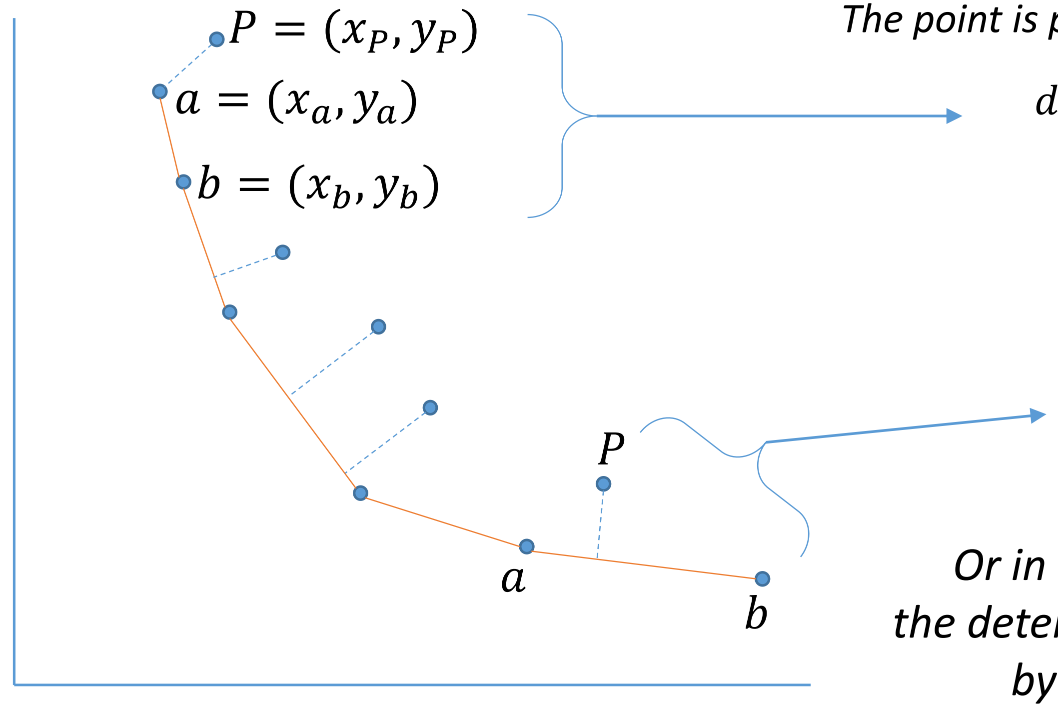
3.1	3	52	2.5	2	60.4	5.8	3	32.2	5.5	2	31.9
2.5	3	83.9	3.5	3	58.1	2	3	84.2	2.2	1	38.5
4.2	3	91.2	3.3	2	41.3	3.4	2	45.8	2.6	3	94.1

Aggregate and Score Performance



Fitness Scoring

- Measure distance between each point and its nearest line



$$if \; ([a-b]\cdot[P-b]) \times ([b-a]\cdot[P-a]) < 0$$

The point is past the orthogonal bounds of the segment…

$$d = \min \begin{bmatrix} d_{aP} = norm(a, P) \\ d_{bP} = norm(b, P) \end{bmatrix}$$

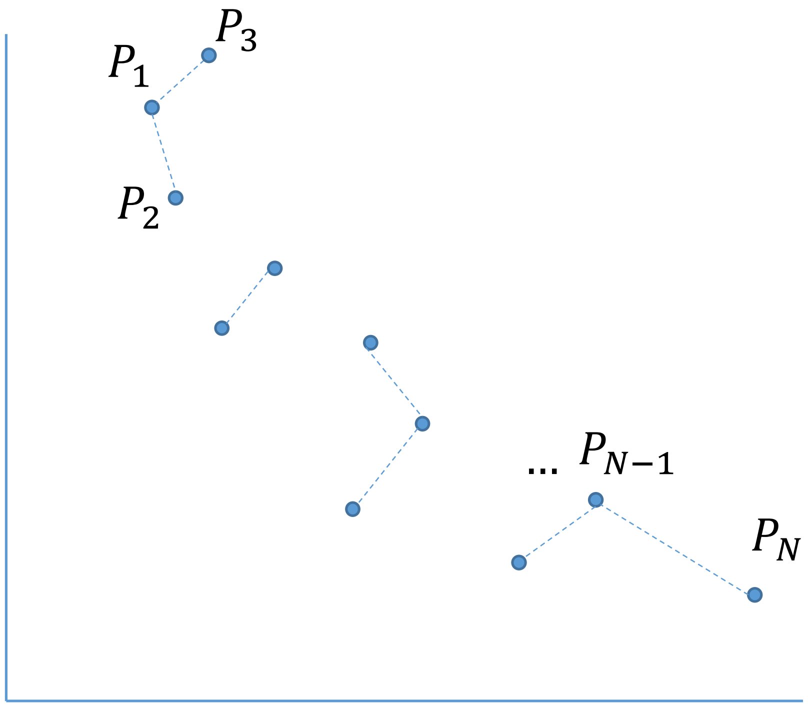
Otherwise…

$$d = \frac{1}{\mathrm{d_{ab}}} \begin{vmatrix} x_a & y_a & 1 \\ x_b & y_b & 1 \\ x_P & y_P & 1 \end{vmatrix}$$

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



$$P_i = (x_i, y_i)$$

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

Selection

- Preferentially select for reproduction based upon performance scoring

$$S_i = W_F(F_i) + W_D(D_i)$$

$$P_i = \frac{S_i}{\sum S}$$

W_F	W_D
1	2

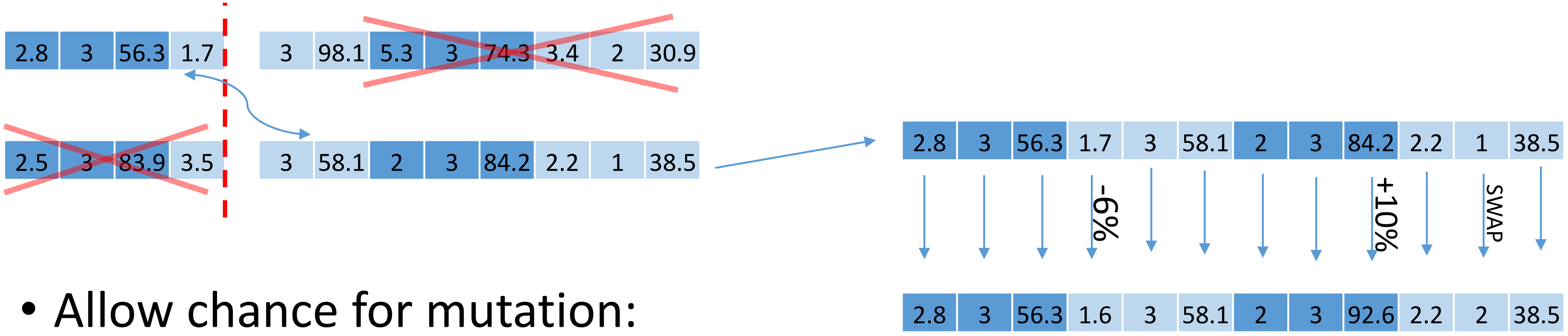
Fitness (F)	Diversity (D)	Score (S)	Repr. Prob (P)
0.5	1	2.5	**0.22**
2	0.5	3	**0.26**
1	0.5	2	**0.17**
2	1	4	**0.35**

2.8	3	56.3	1.7	3	98.1	5.3	3	74.3	3.4	2	30.9
3.1	3	52	2.5	2	60.4	5.8	3	32.2	5.5	2	31.9
2.5	3	83.9	3.5	3	58.1	2	3	84.2	2.2	1	38.5
4.2	3	91.2	3.3	2	41.3	3.4	2	45.8	2.6	3	94.1

2.8	3	56.3	1.7	3	98.1	5.3	3	74.3	3.4	2	30.9
2.5	3	83.9	3.5	3	58.1	2	3	84.2	2.2	1	38.5

Reproduction – Split and recombination

- Split the two 'genomes' at a random location and recombine



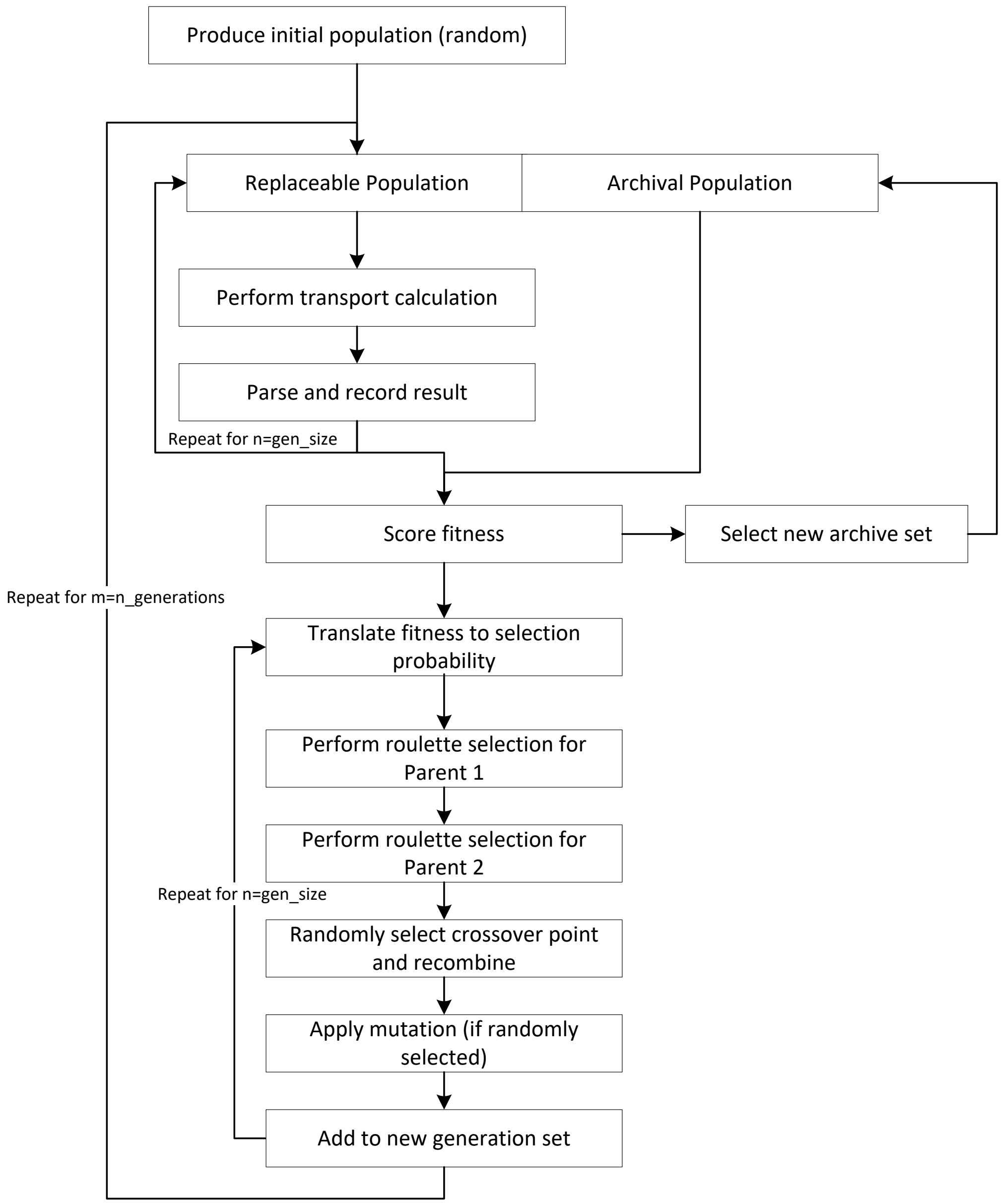
- Allow chance for mutation:

- Add to the next generation of candidate designs:

3.1	3	52	2.5	2	60.4	5.8	3	32.2	5.5	2	31.9
2.5	3	83.9	3.5	3	58.1	2	3	84.2	2.2	1	38.5
4.2	3	91.2	3.3	2	41.3	3.4	2	45.8	2.6	3	94.1

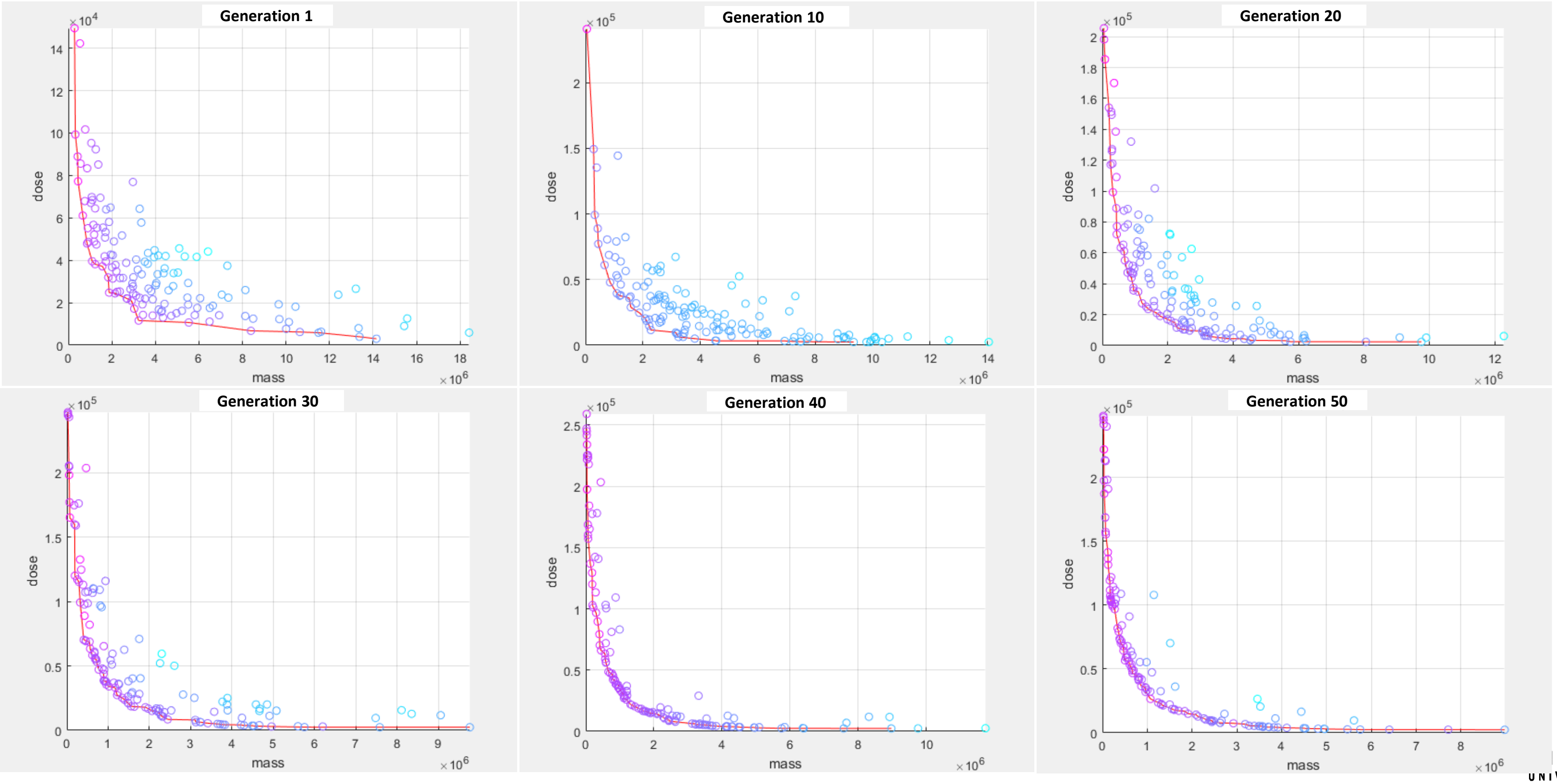
The Algorithm (as implemented)

- Includes a secondary ‘archive’ population of high-performers
- Allows greater mutation rates and diversity without losing ground



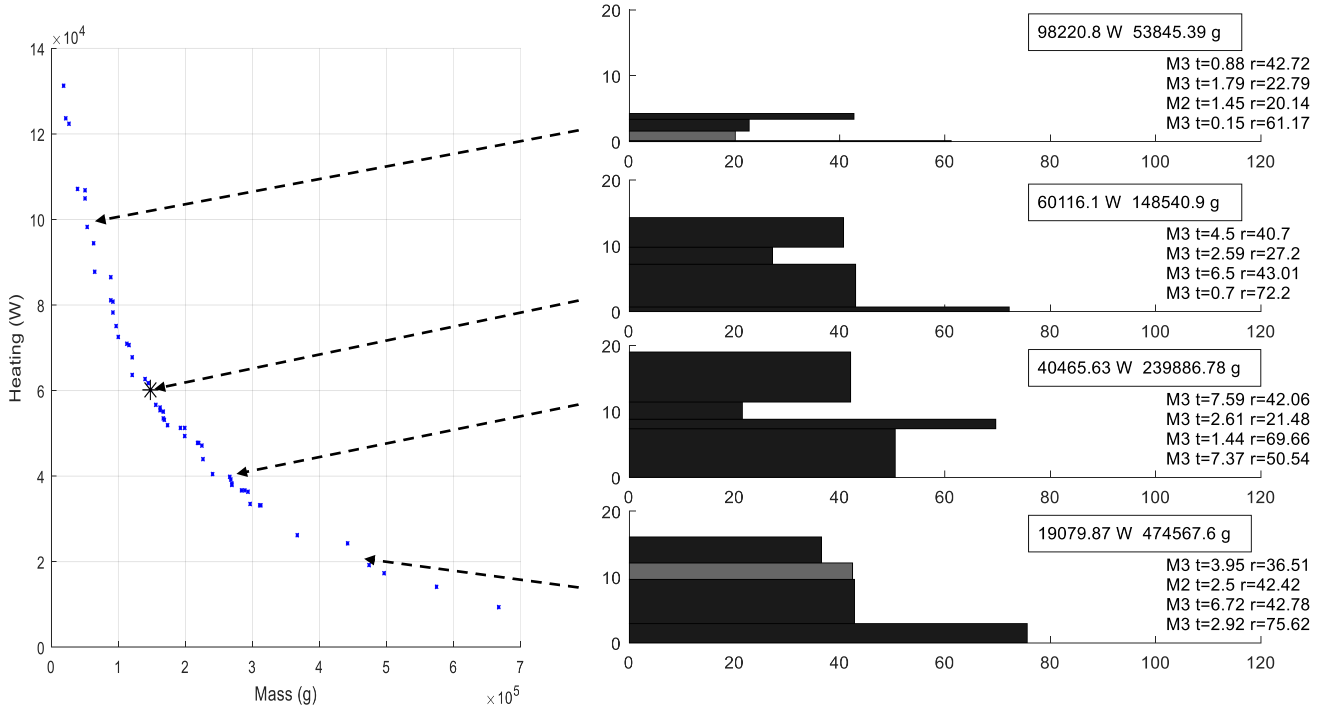
Progression of the Multiobjective Evolutionary Algorithm (MOEA)

- Begins with random selection that fills the design space
- Converges toward the Pareto front within ~40 generations
- Thereafter, gradually pushes PF_{known} toward PF_{true} (mutation is important here)



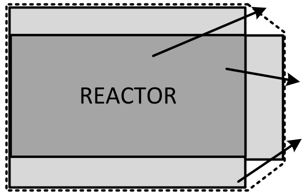
Interpreting The Results

- All of *parameter space* is collapsed into each point displayed in *objective space*
- Requires some creative methods of visualization…

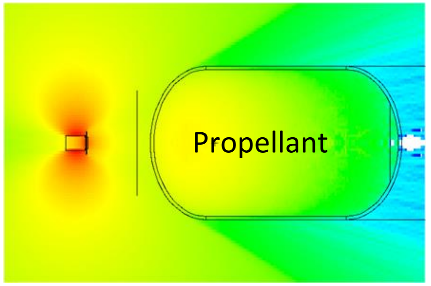


Example Case: 40 kW limit to Core Stage Tank

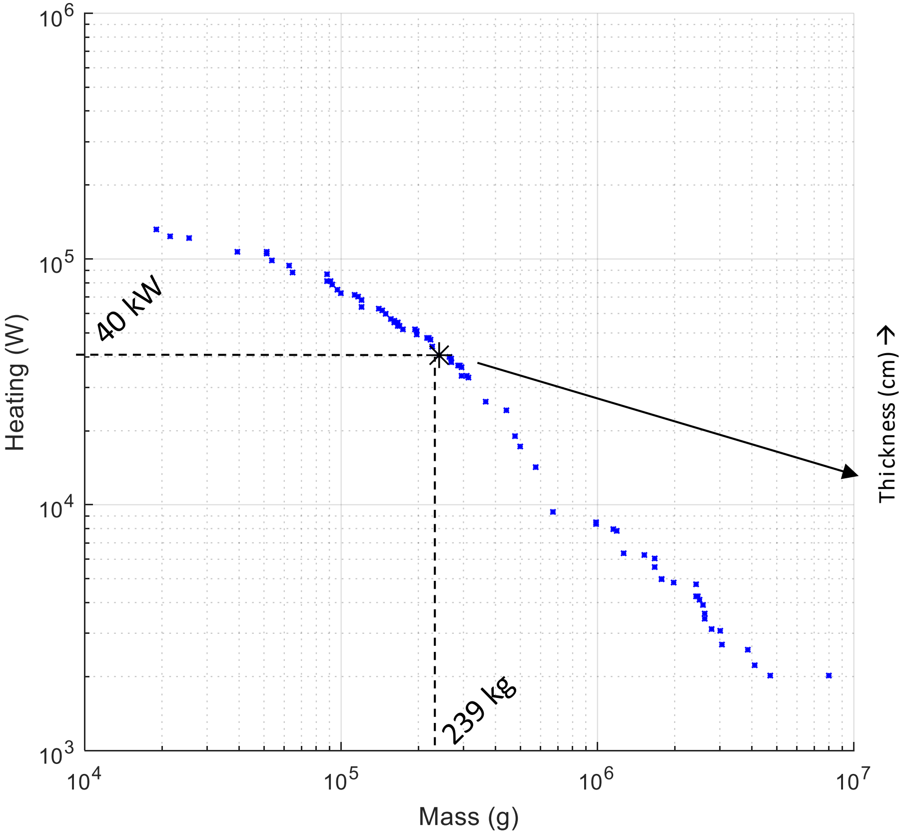
1) Generate Source:



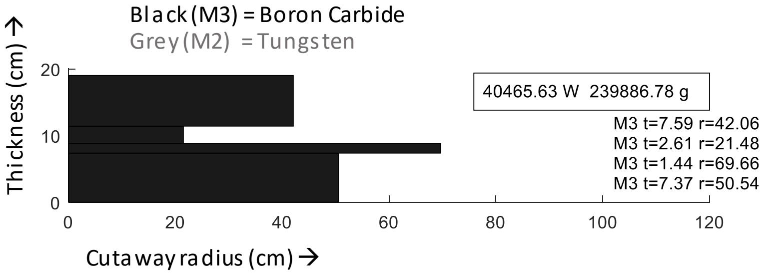
2) Embed in Problem Geometry:



3) Execute Optimization Code:

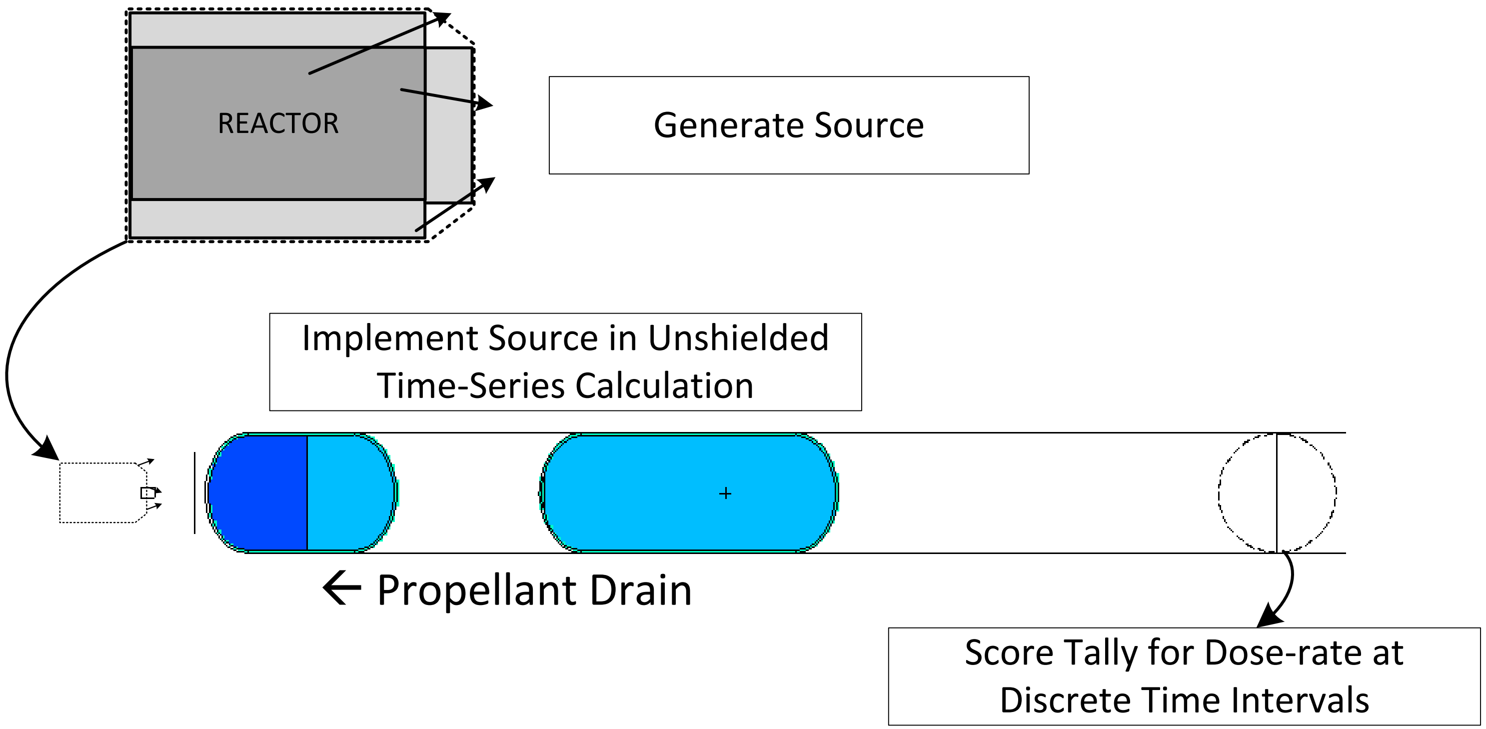


4) Apply Constraint for Evaluation



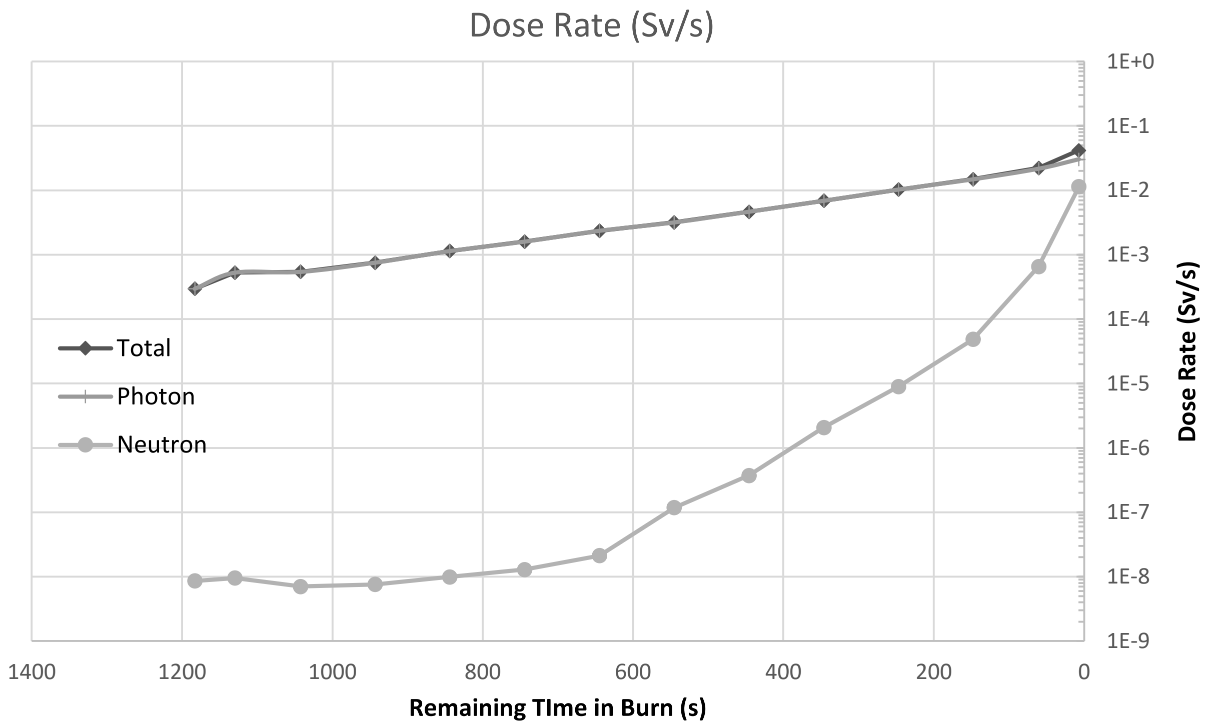
Example Case: 0.2 Sv Entering Crew Compartment

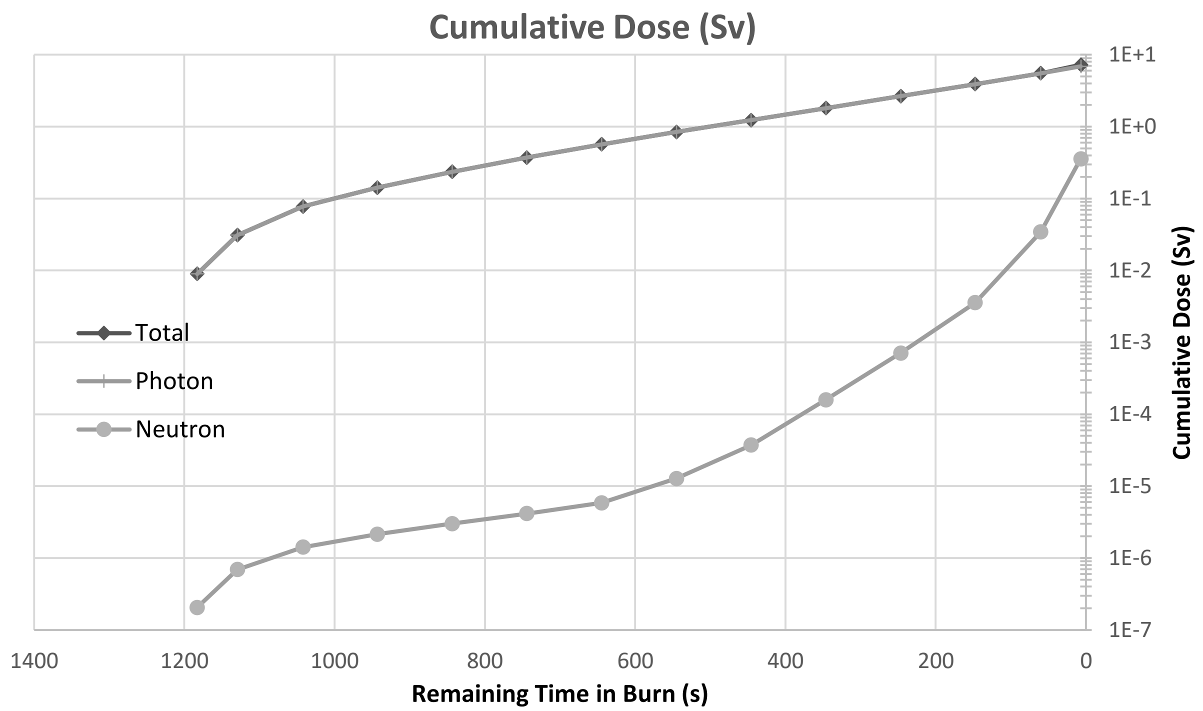
Step 1) Evaluate time-series profile of a reference case, e.g. no-shield



Example Case: 0.2 Sv (continued)

Step 2) Determine terminal dose rate and cumulative dose:





$$\dot{D}_{EOB} = 4.2E - 2\,\frac{Sv}{s}$$

$$D_{tot} = 7.0\ Sv$$

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Example Case: 0.2 Sv (continued)

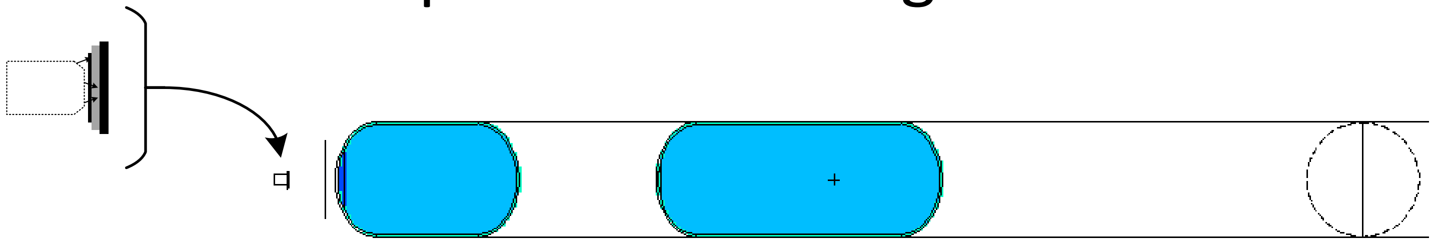
Step 3) Determine *Scaled* terminal dose ($\dot{D}'_{EOB}$) required to satisfy the imposed dose constraint (D'_{tot})

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

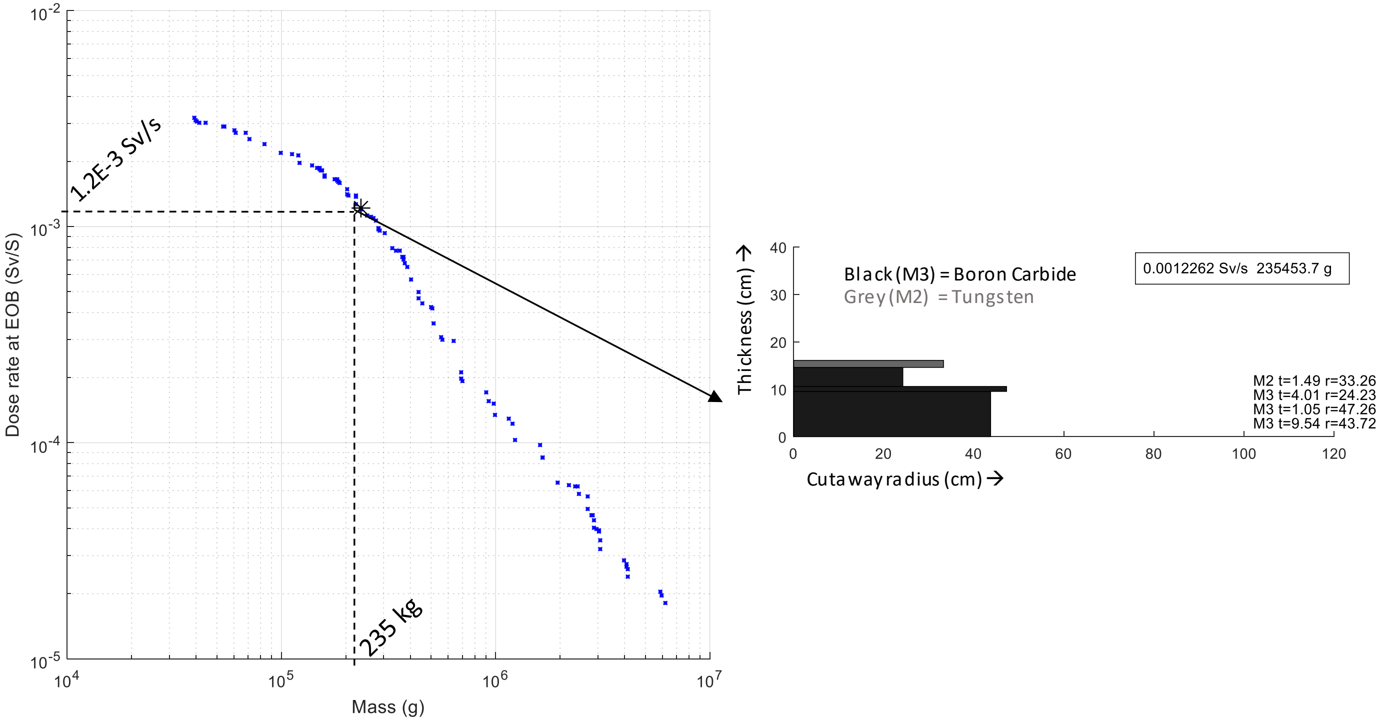
$$\dot{D}'_{EOB} = \left(4.2E-2\ {}^{Sv}/_{s}\right) \frac{0.2\ Sv}{7.0\ Sv} = \mathbf{1.2E-3}\ {}^{\boldsymbol{Sv}}/_{\boldsymbol{s}}$$

Example Case: 0.2 Sv (continued)

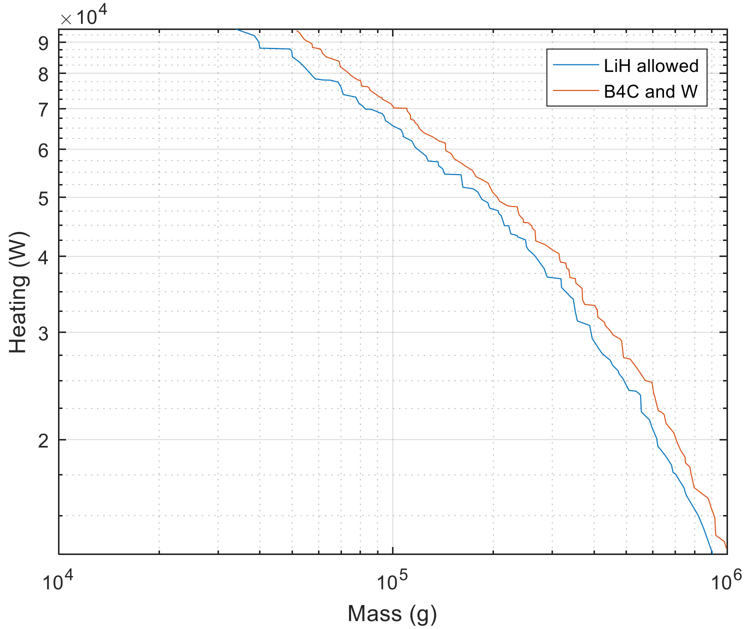
Step 4) Perform shield optimization using terminal dose rates only



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



Material mass comparison



LiH Permitted (B_4C forced in first layer)

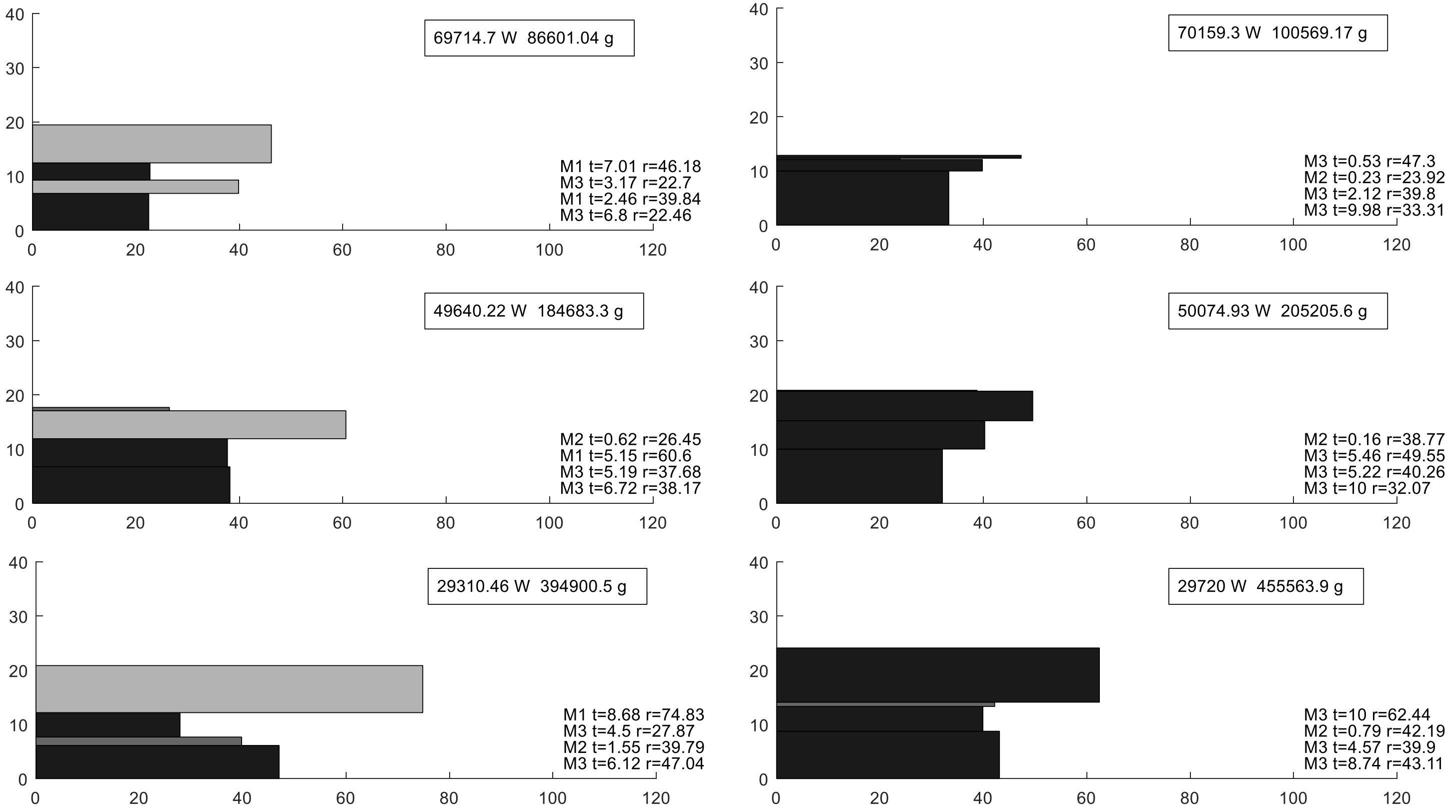
M1 = LiH
M2 = W
M3 = B_4C

B_4C and W only

70 kW

50 kW

30 kW



		Mass (kg)		Ratio	Δ Mass (kg)
		LiH+B_4C+W	B_4C + W		
Heating from single engine	30 kW	395	456	1.15	61
	50 kW	185	205	1.11	20
	70 kW	87	101	1.16	14

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 PF_{true} using other methods
  - Hastings Metropolis, Simulated Annealing, etc.

Acknowledgments

- Special thanks to :
  - Omar Mireles as my Pathways Mentor at MSFC
  - SCCTE Team from Center for Space Nuclear Research for providing relevant engine models for source term production:
    - Michael Eades
    - Paolo Veneri
    - Vishal Patel
    - Wes Deason

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

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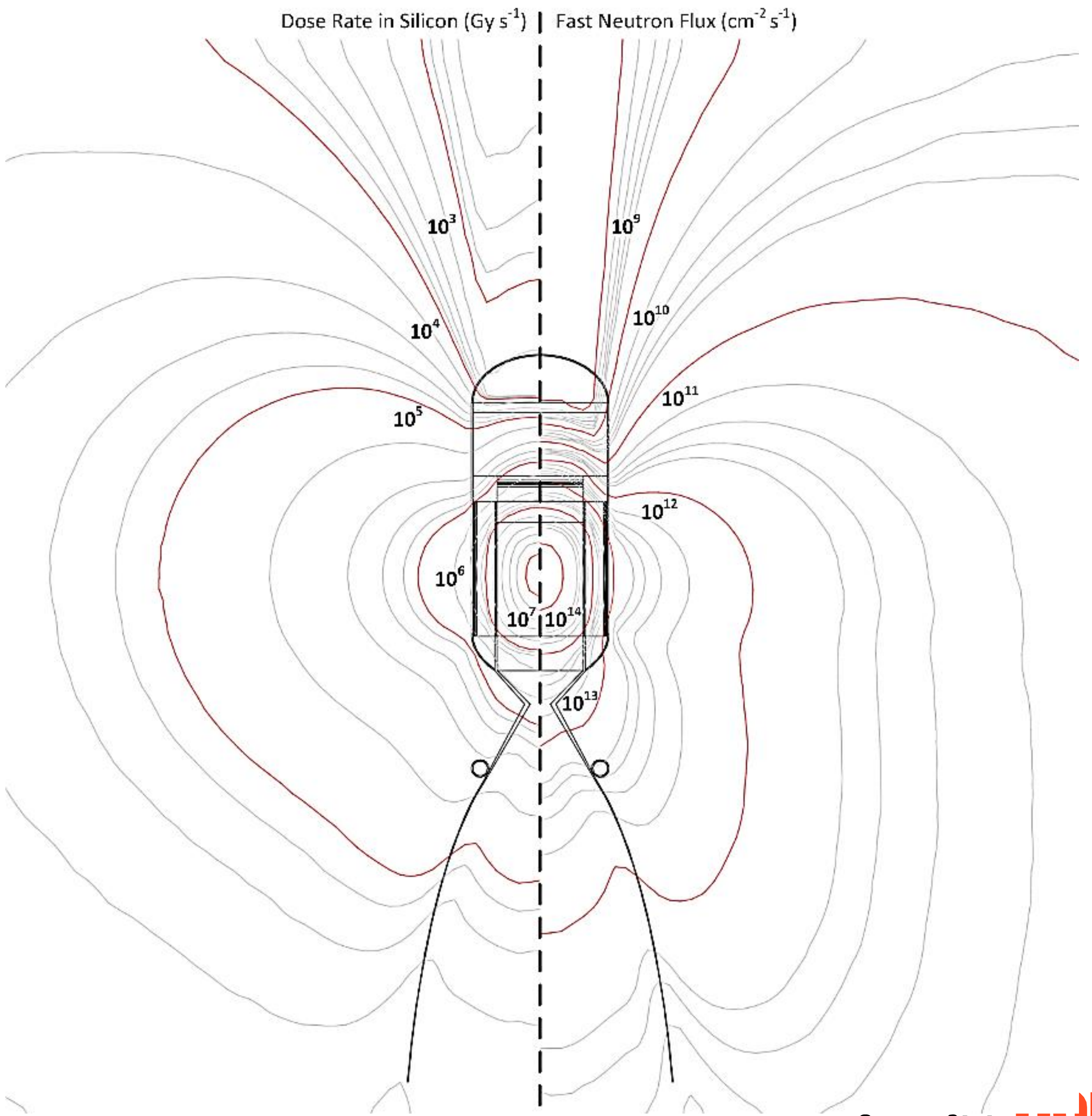
BACKUP

Contours

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

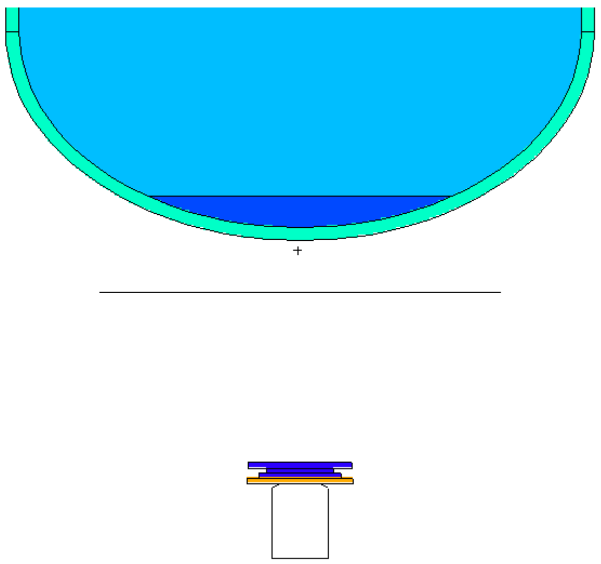
  - GNUPlot:

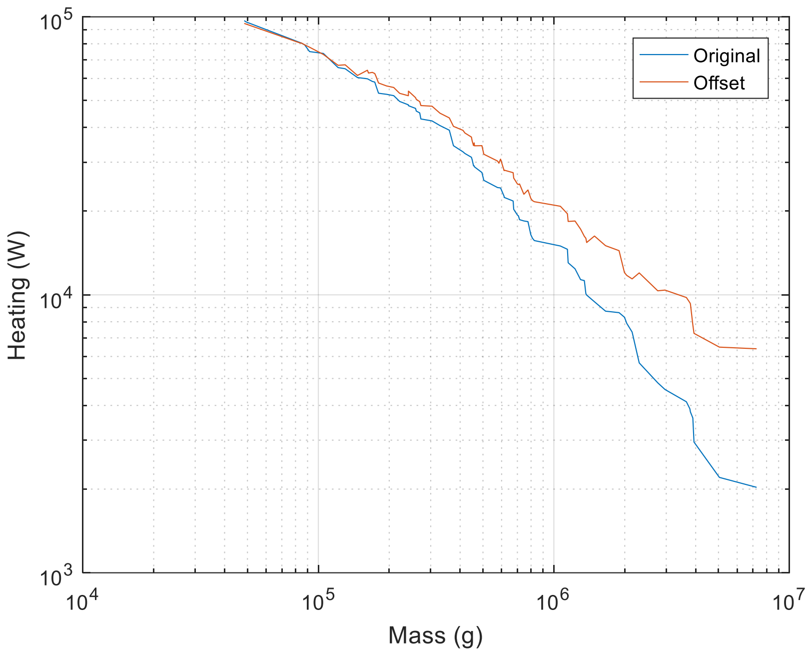
  Ugly scripts → Pretty plots



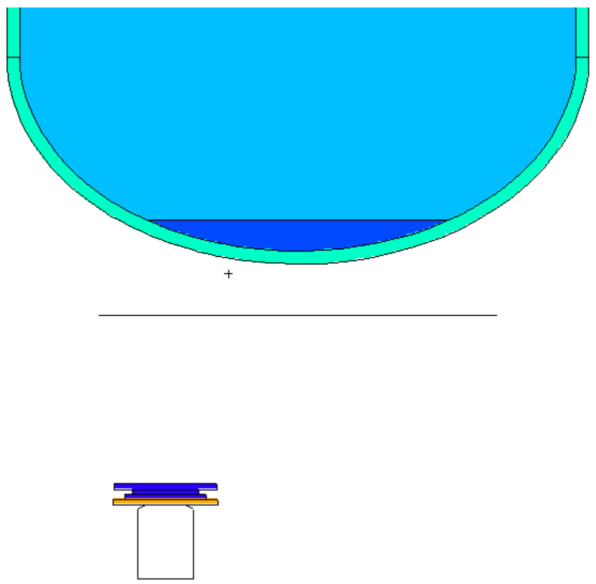
Engine Offset without Correction

ORIGINAL



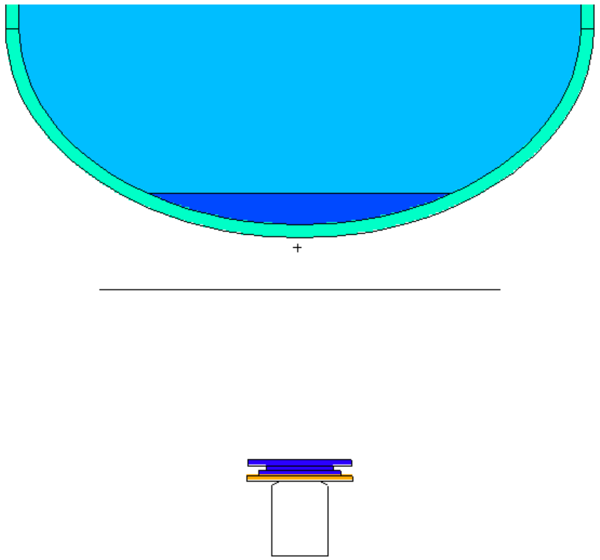


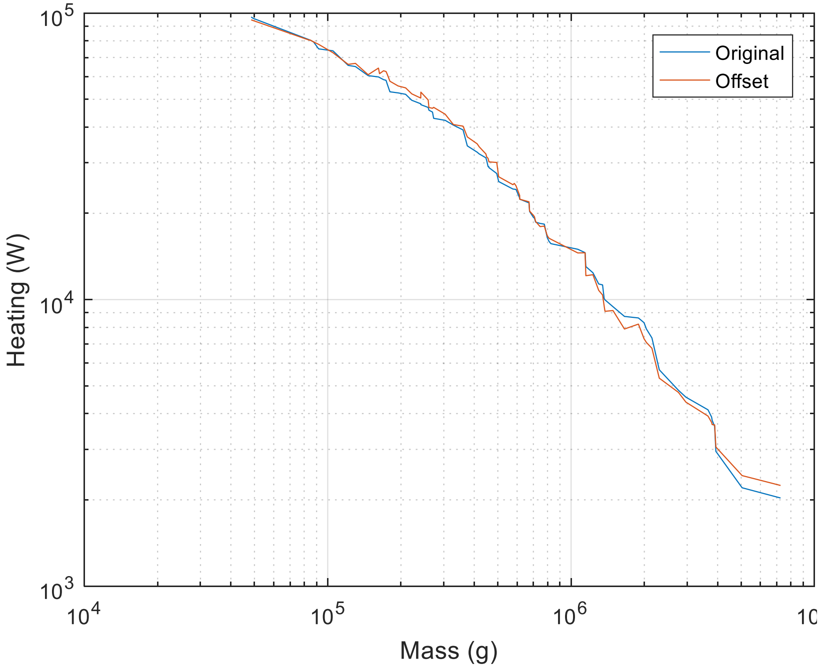
UNCORRECTED OFFSET



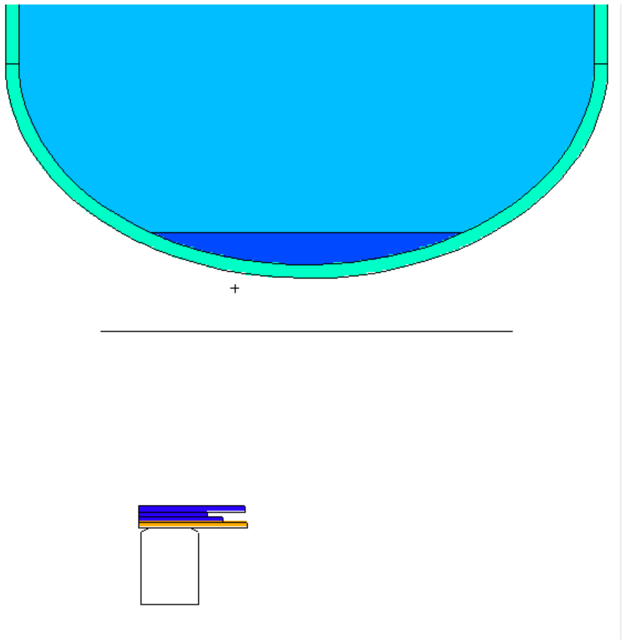
Engine Offset with Correction

ORIGINAL





CORRECTED OFFSET

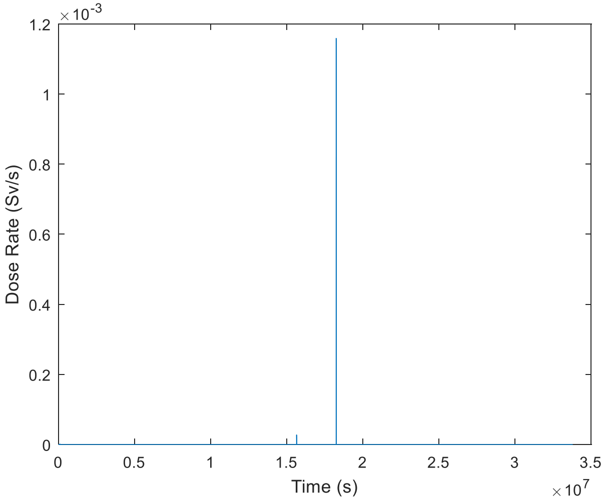


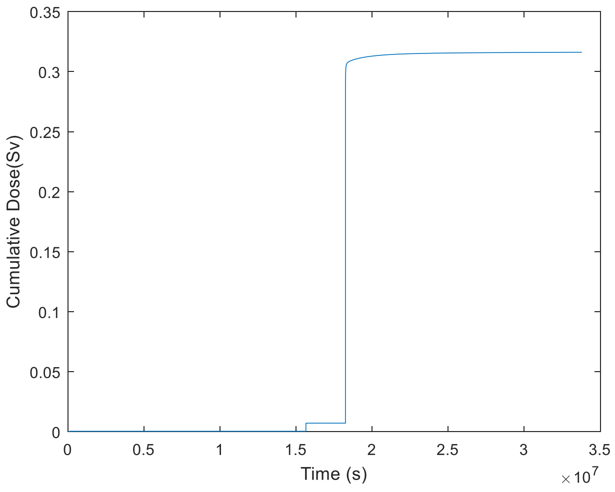
Time-series Dose (w/ Cosmic dose)

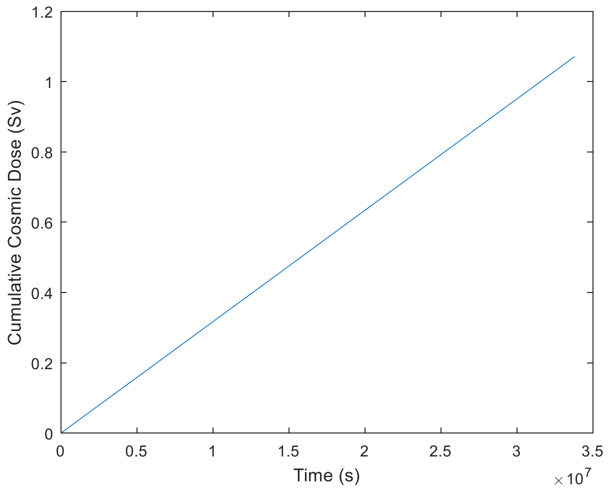
Linear Scales

Y-axis: Linear

X-axis: Standard



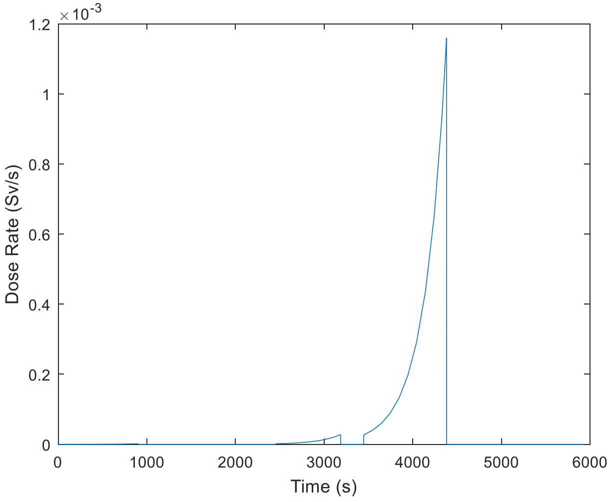


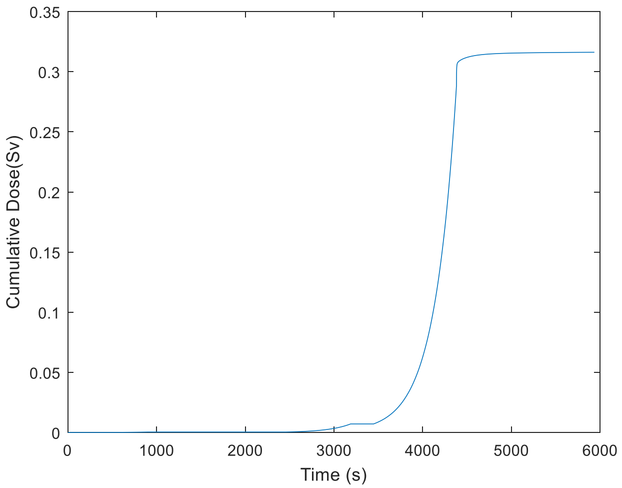


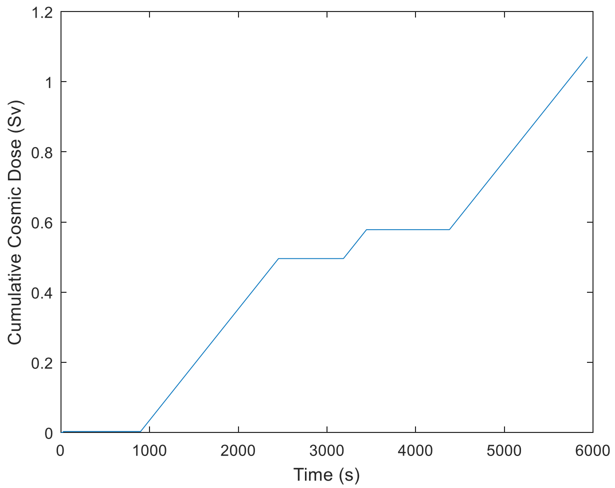
Y-axis: Linear

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)