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DESIGN OPTIMIZATION OF SATELLITE ELECTRON/PROTON SHIELDS

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PRESENTED BY

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SAND???

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CONTEXT

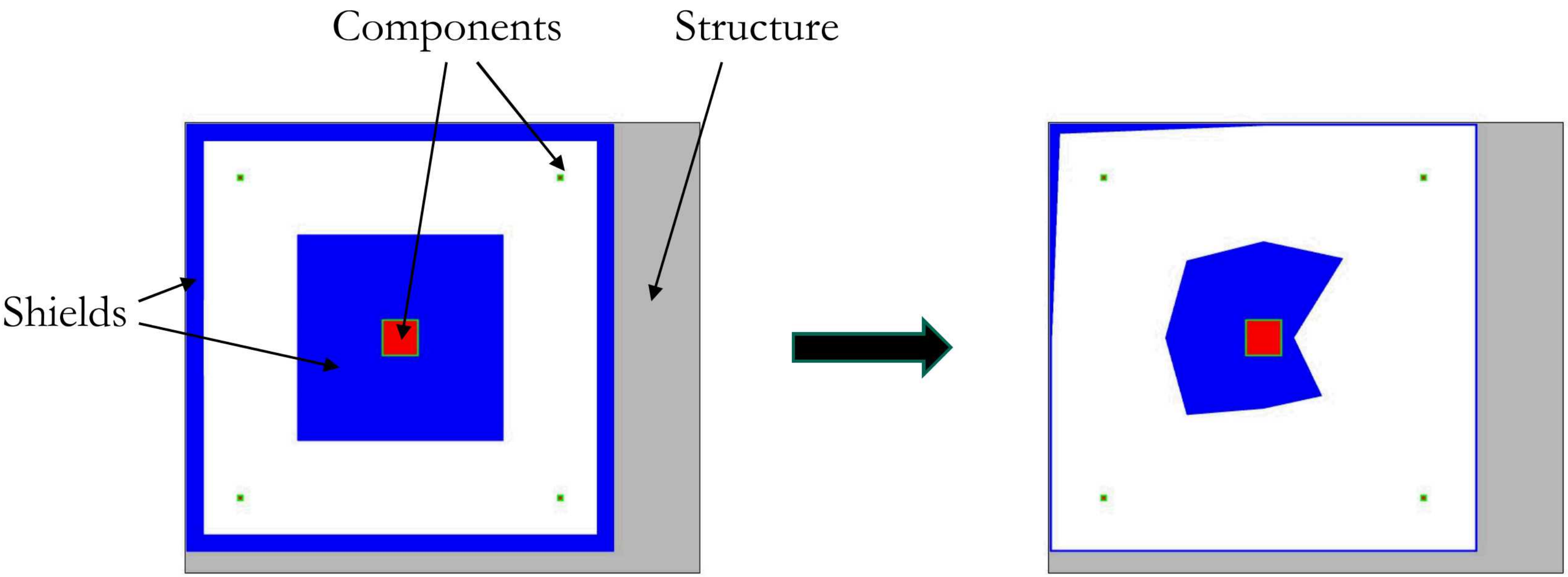
- Increased demand for optimization and UQ
- Increasing interest in advanced materials/manufacturing
- Recent advances in transport community with adjoint-based sensitivities

Opportunity: use adjoint-based transport methods to efficiently determine parameter sensitivities, which will be used to drive design optimization and/or UQ calculations in high-dimensional spaces.

- Enable consideration of larger design/trade space
- Provide greater insight to designers

END OBJECTIVE

We are interested in satellite electron/proton shielding applications. Mass is at a premium for space missions due to launch costs and/or mass limits. We want to perform design optimization to achieve the required level of protection with the minimum amount of mass. For example, we want to be able to transform the initial design below to a mass-saving one while still meeting the same requirements. This may entail material and/or geometric changes.



Initial design

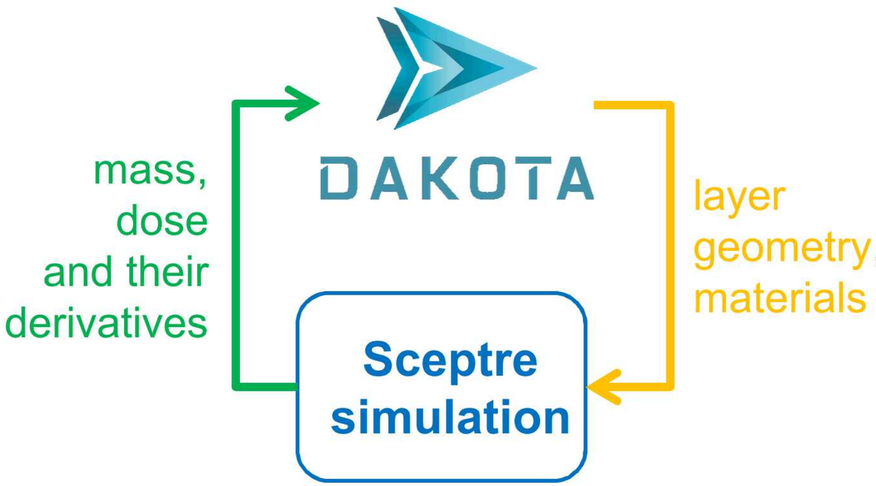
Final design

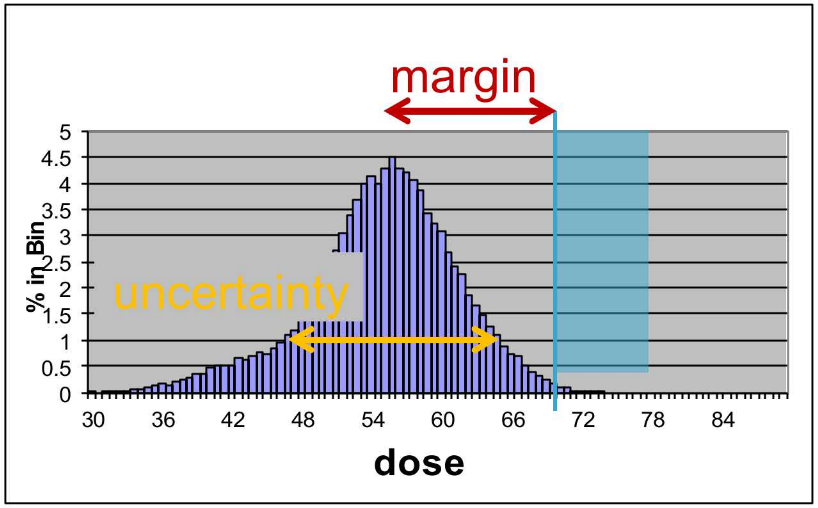
SIMULATION-BASED DESIGN EXPLORATION AND ANALYSIS

- Use Dakota with Sceptre (deterministic transport solver) to systematically ask what-if questions: sensitivity, design, uncertainty analyses

- Optimization: What component materials, composite material fractions, and shield layer geometries yield the lightest shield meeting strength and dose requirements?

- Uncertainty Quantification (UQ): Given variability in manufacturing (mixtures, layer geometry) and state of knowledge (transport cross sections), with what probability will a proposed design meet dose requirements?



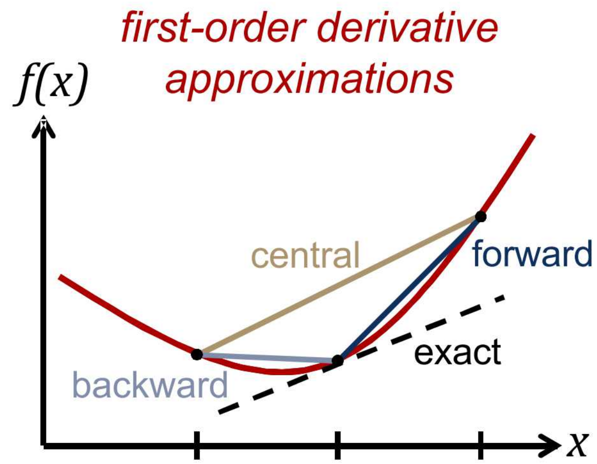


GRADIENTS FOR DERIVATIVE-BASED OPTIMIZATION METHODS

- Akin to Newton's method for root-finding, minimize the objective by going "downhill" based on the gradient of the objective function:

$$\nabla f_x(x) = \left[\frac{\partial f(x)}{\partial x_1}, \ldots, \frac{\partial f(x)}{\partial x_N} \right]$$

- Most simulations don't calculate derivatives
- Dakota approximates gradients (and Hessians if needed) by running the simulation at $x \pm \Delta x$ as needed



First-order Forward Difference	Second-order Central Difference
$\frac{\partial f}{\partial x} \approx \frac{f(x+\Delta x) - f(x)}{\Delta x}$	$\frac{\partial f}{\partial x} \approx \frac{f(x+\Delta x) - f(x-\Delta x)}{2\Delta x}$

`responses`
`  numerical_gradients`
`    forward`
`    fd_step_size 1.0e-3`
	`responses`
	`  numerical_gradients`
	`    central`
	`    fd_step_size 1.0e-3`

THEORY: TRANSPORT SENSITIVITIES

If the following equations are satisfied:

$$(L + C - S)\psi = q \qquad \text{(forward Boltzmann problem)}$$

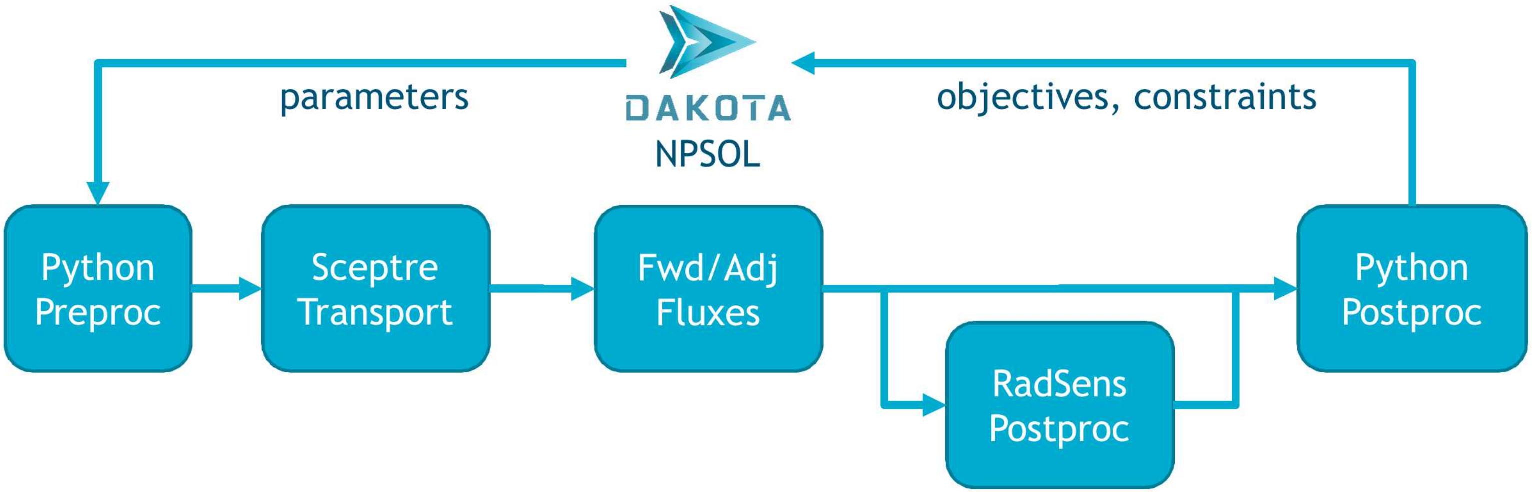
$$\left(L^\dagger + C^\dagger - S^\dagger\right)\psi^\dagger = q^\dagger \qquad \text{(adjoint Boltzmann problem)}$$

then the sensitivity (gradient) of a transport response *R* (e.g. dose) is given by:

$$\frac{dR}{dp} = \left[\left\langle \psi, \frac{\partial q^\dagger}{\partial p} \right\rangle + \left\langle \psi^\dagger, \frac{\partial q}{\partial p} \right\rangle - \left\langle \psi^\dagger, \left(\frac{\partial}{\partial p}(L + C - S)\right)\psi \right\rangle\right]$$

The sensitivities of *any* *R* to *any* *p* are obtained by various inner products involving the forward solution ψ, the adjoint solution $\psi^\dagger$, and derivatives of *input* (i.e. known) quantities.

OPTIMIZATION



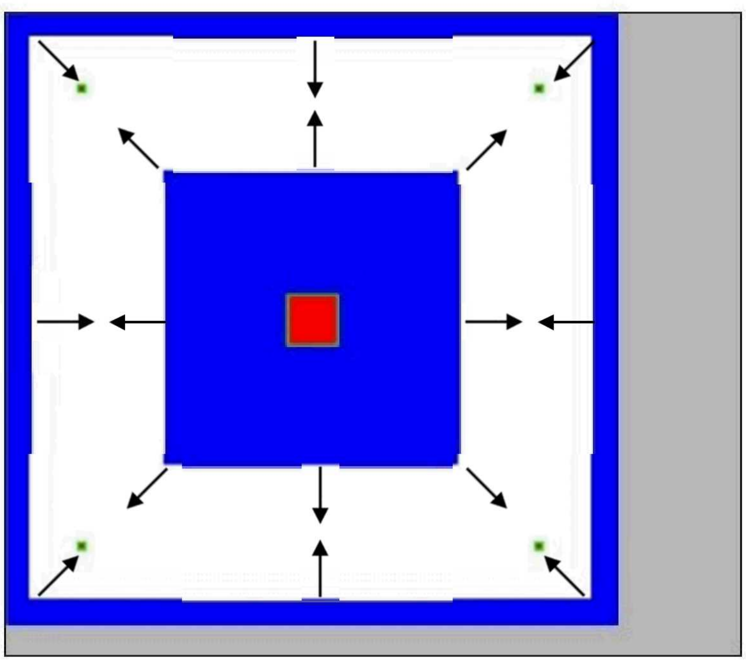
- Dakota NPSOL optimization drives the process
- Python tools translate between Dakota and Sceptre
- Sceptre deterministic transport produces forward and adjoint angular flux fields
- Material and geometric sensitivities are post-processed from these fields

APPLICATION: ELECTRON AND/OR PROTON SATELLITE SHIELDING

We are interested in satellite shielding applications. The problems we will study are:

- 2000 km circular equatorial orbits (arbitrarily chosen to demonstrate optimization)
- Proton and/or electron environments as defined by the AP8 and AE8 models in Spenvis
- Various components to be protected to various levels
- Multiple shielding regions of arbitrary geometry and/or materials

APPLICATION: ELECTRON AND/OR PROTON SATELLITE SHIELDING

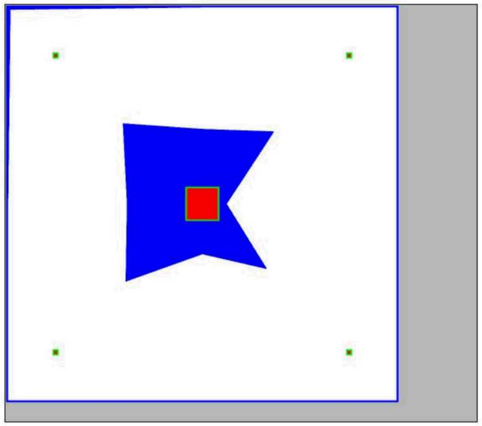


Initial design

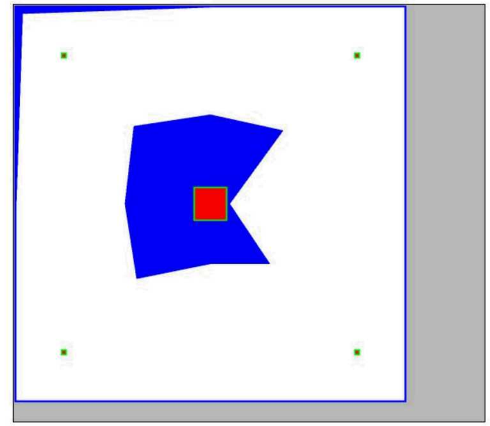
We want to protect components in a satellite. The electron/proton flux is isotropic, but asymmetric aluminum structure produces an asymmetric internal environment. The thick region on the right is an approximation to the satellite structure. The region on the bottom represents other instruments. There are four components in the corners, and a larger fifth component in the middle. Nominal shields are in blue. The location and allowed movement of control points is represented by arrows.

EXAMPLE: PROTON SHIELDING WITH POLYETHYLENE REQUIREMENTS: 100 KRAD/YR AT CORNERS, 40 KRAD/YR AT CENTER

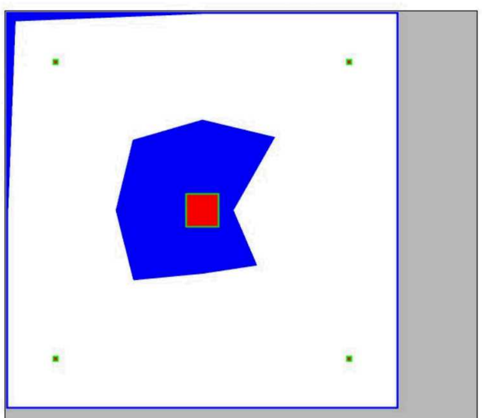
(The initial design is overdesigned and requires 225 g/cm)



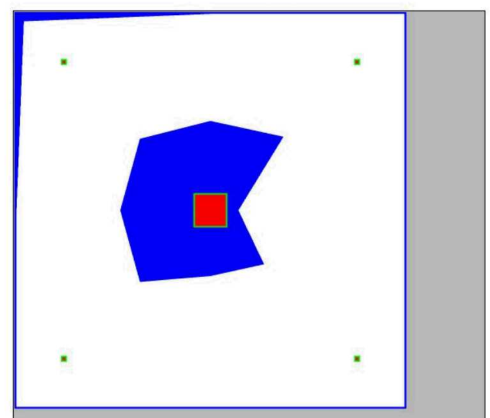
Second design iteration



Third design iteration

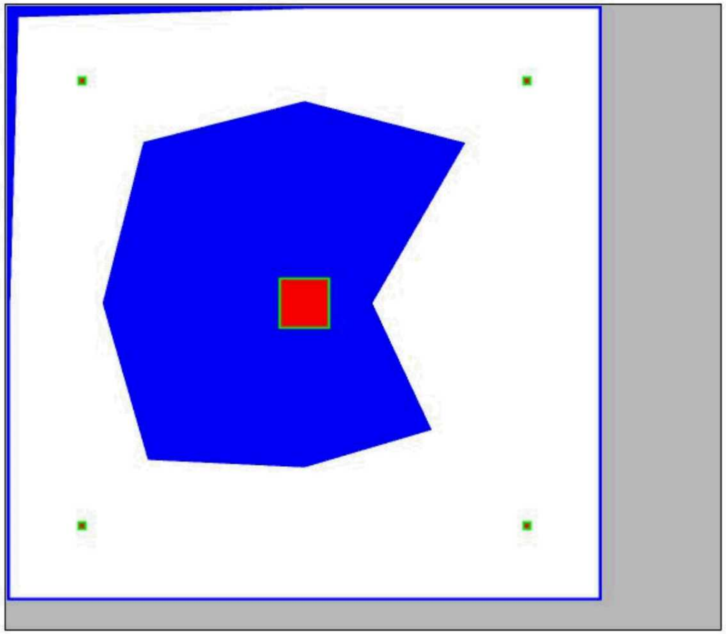


Fourth design iteration



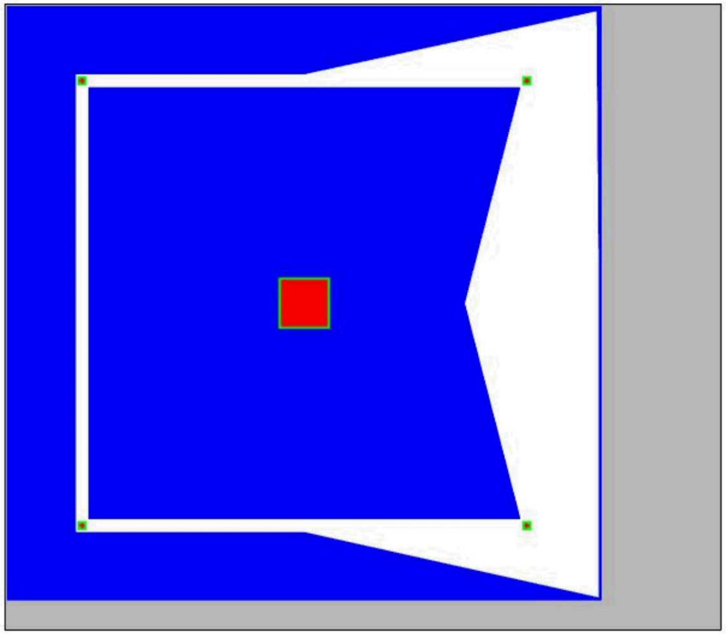
Final design: 82 g/cm

DESIGNS WITH OTHER DOSE CONSTRAINTS



Center dose requirement: 30 krad/yr

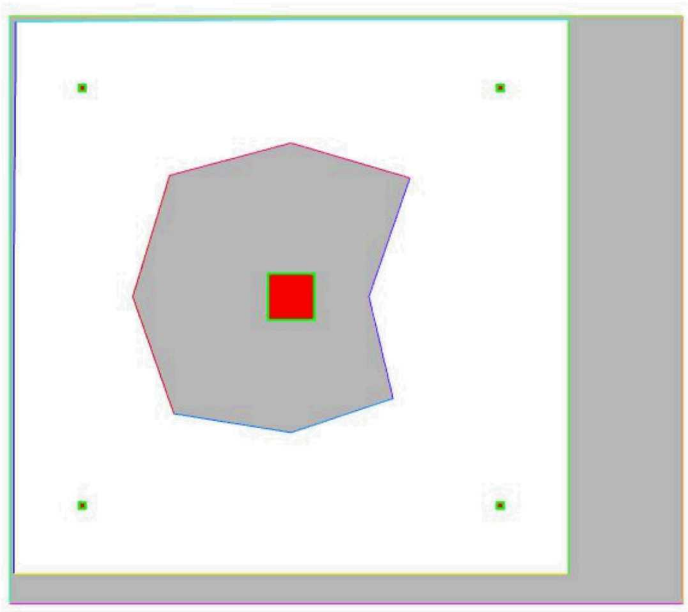
Final design: 174 g/cm



Center dose requirement: 20 krad/yr

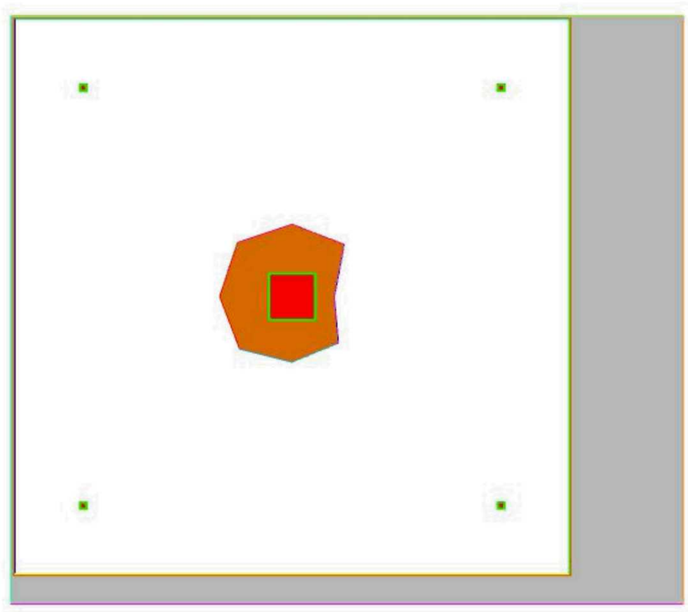
Final design: 450 g/cm

DESIGNS WITH OTHER MATERIALS



Aluminum shields, 20 krad/yr

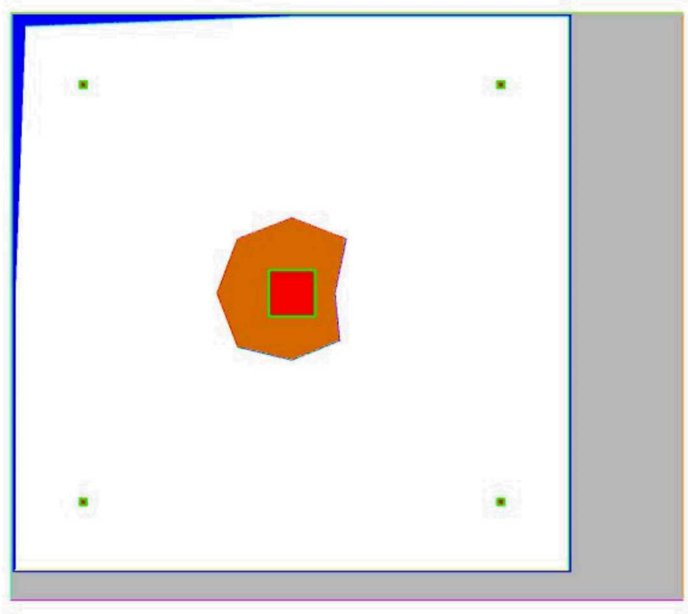
Final design: 357 g/cm



Copper shields, 20 krad/yr

Final design: 289 g/cm

COMBINED MATERIAL AND GEOMETRY OPTIMIZATION

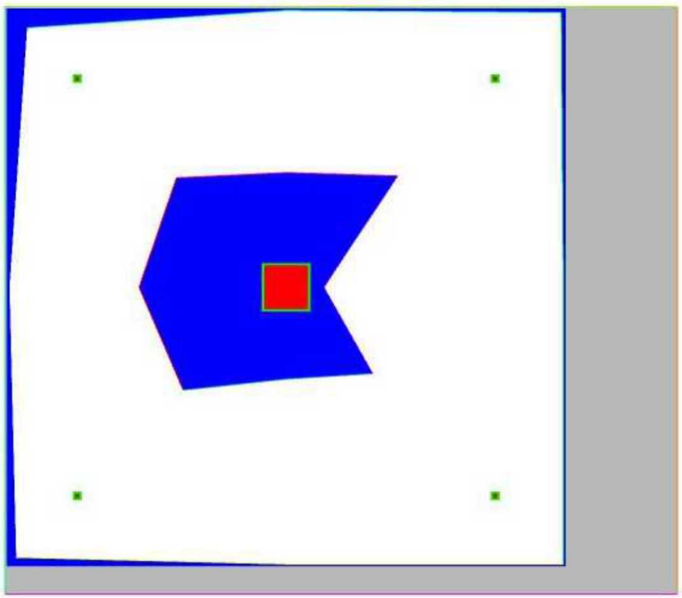


Requirement: 20 krad/yr

For this design we arbitrarily allowed for the use of polyethylene, aluminum, copper, molybdenum, and/or tantalum

Final design: Polyethylene outer shield, copper inner shield, 226 g/cm

COMBINED PROTON/ELECTRON ENVIRONMENT



Requirement: 40 krad/yr

For this design we only allowed for the use of polyethylene

Final design: 97 g/cm

CONCLUSIONS

- We have derived the sensitivities of satellite component doses to geometric and material changes in electron/proton shields.
- We have incorporated these sensitivities into satellite shield design tools that use the Sceptre deterministic transport code and Dakota optimization algorithms
- We have demonstrated the use of these tools for a variety of satellite problems:
  - combined environments
  - multiple materials
  - numerous control points
- Future work:
  - More combined environment studies with multiple materials
  - 3D sensitivities/optimization
  - Robust design