Nuclear Thermal Propulsion Space Truss

Analysis and Optimization

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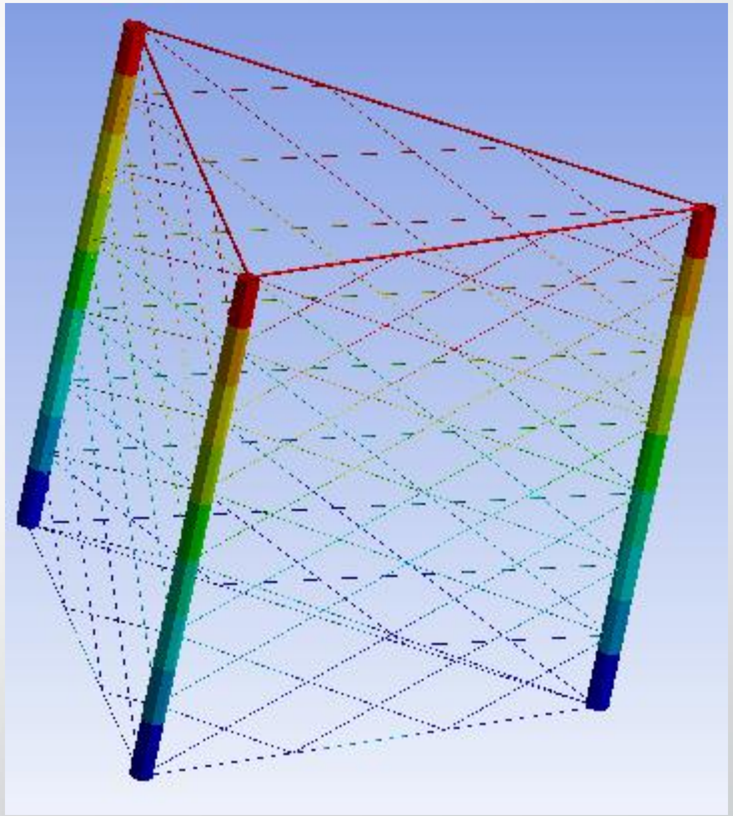
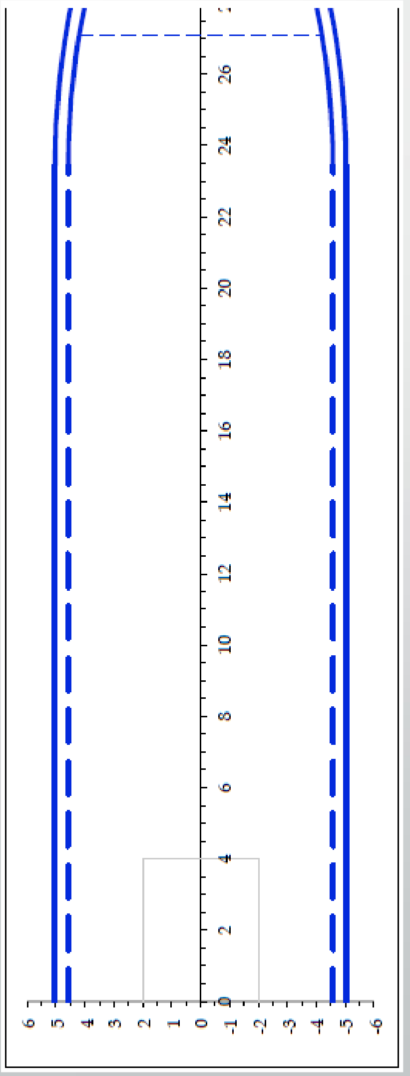


Overview

- Objective: Develop a mass vs length relationship for a truss structure capable of withstanding the loading brought on by proposed nuclear thermal rocket engines and launch.
- Use this derived relationship in conjunction with the mass vs distance relation of the gamma shielding mass to determine an optimal truss length range (or limit by design).
- Optimize mass savings from the generic truss structure, and establish procedure for more specified truss design as system capabilities solidify.

Constraints

- Develop the design constraints as normal and then compare and relate those to the capabilities of the optimization software.
- Select goals and limiting factors for the optimization capabilities.
- Reduce computational intensity of the design and constraining factors.



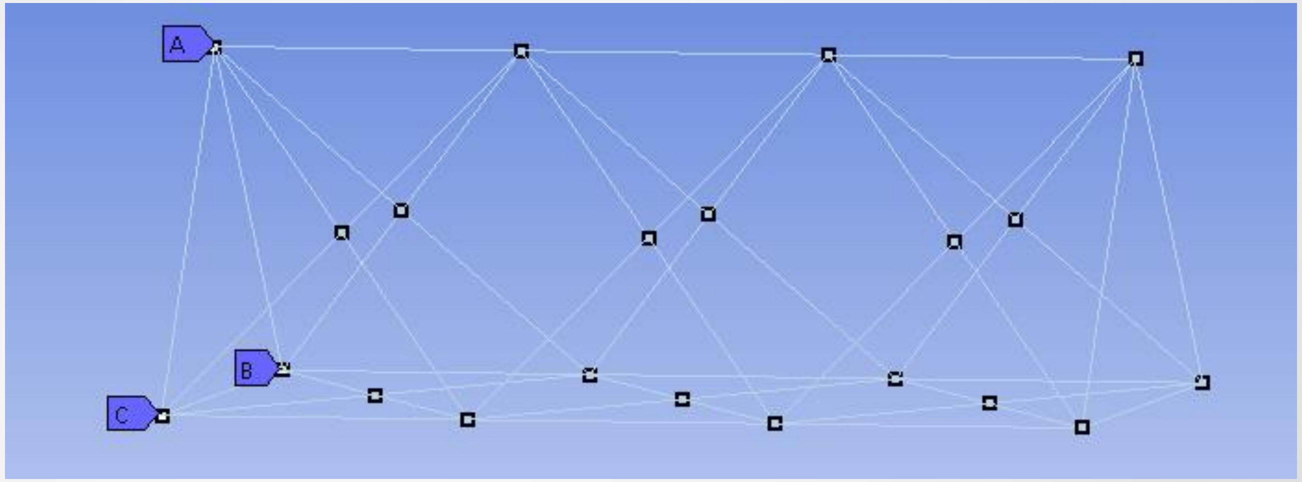
Constraints – Load and Launch

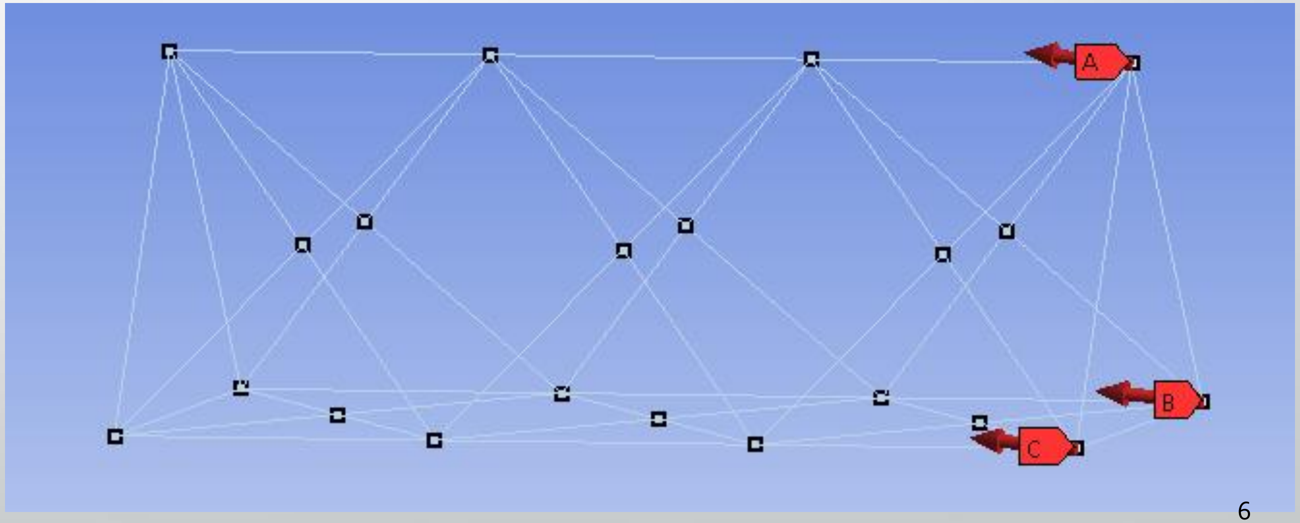
- Initial loads were based on launch loads (acceleration), max thrust, max gimbal, and one engine out scenarios.
- Varying shield mass (lowest estimate) was used in determining launch loads and was varied manually between runs.
- Length was also varied manually between optimization runs for simplicity avoiding difficult or impossible design shifts by the optimization software.
- Truss members were varied in both outer and inner diameter via the optimization software.
- The entire set up was created with parameterization in mind in order to be able to easily adjust for engine design changes or other system capability adjustments.

Loading

- The three points (marked blue) that are connected to the fuel tank are fixed.
- The three points (marked red) that are connected to the engines receive a total of 75,000 pounds of force (25,000 each) at a gimbal angle of 5°, determined to be the conservative loading choice. More recent iterations had the engines at 35,000 lbsf each.
- Acceleration loads were distributed between the 3 nodes via a point mass
- Each truss was analyzed using beam elements.
- Joints were assumed stiff by construction.

Truss 1- 6 meters





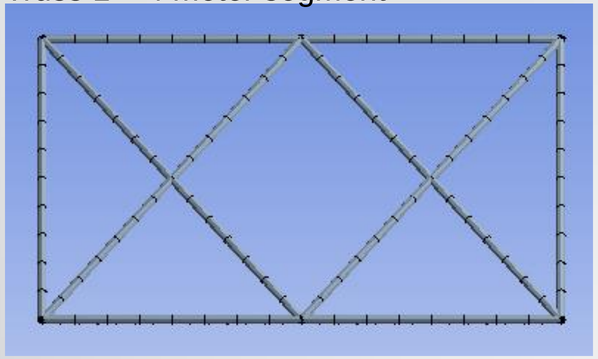
Truss Material and Environment

A variety of metals as well as Carbon Fiber were traded as initial materials for the support structure. Materials such as titanium and beryllium were eliminated for cost and feasibility, Steel was too heavy, and Carbon Fiber also was not ideal due to computational complexity and its behavior in a radioactive environment. For initial runs Aluminum was selected as it is a cost effective isotropic material that can be used at both cryogenic and slightly elevated temperatures. It also has a high strength-to-weight ratio which was paramount for this project.

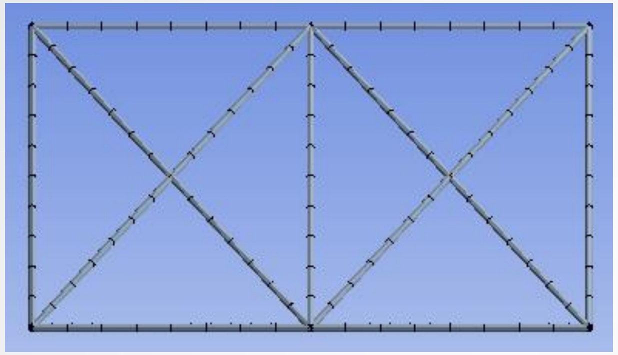
The thermal environment chosen for the truss mimicked that of a white painted structure on a trans-lunar path executing a “bbq roll”, as provided by Marshall Space flight centers ER43. The heating from the engines was not considered.

Initial Simplified Truss Design

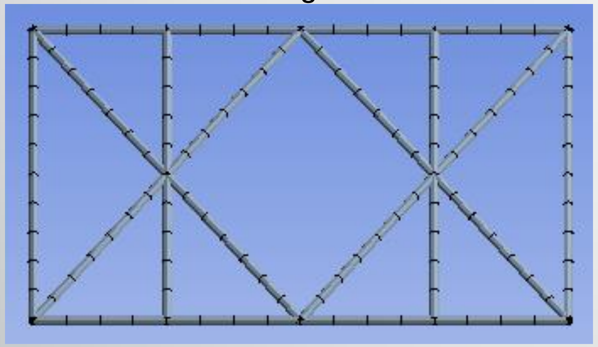
Truss 1 – 4 meter segment



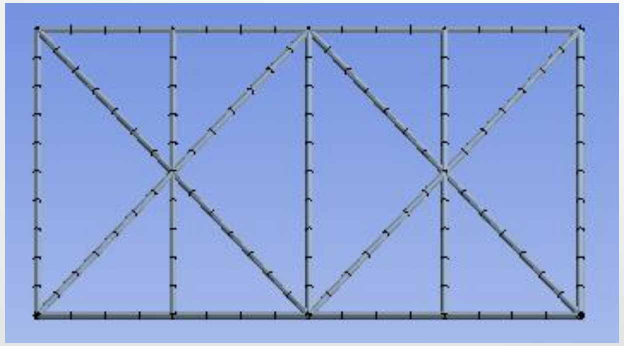
Truss 2 – 4 meter segment



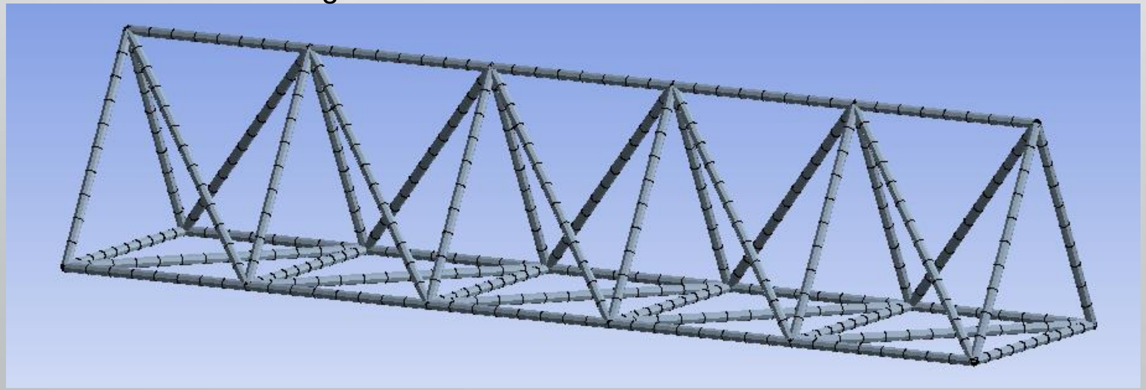
Truss 3 – 4 meter segment

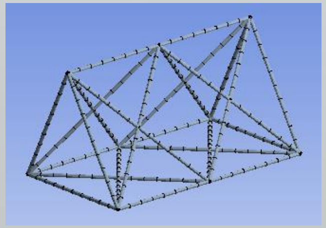


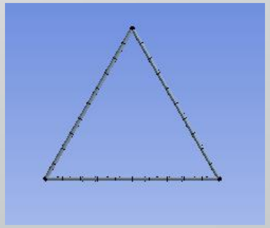
Truss 4 – 4 meter segment



Truss 5 – 10 meter segment

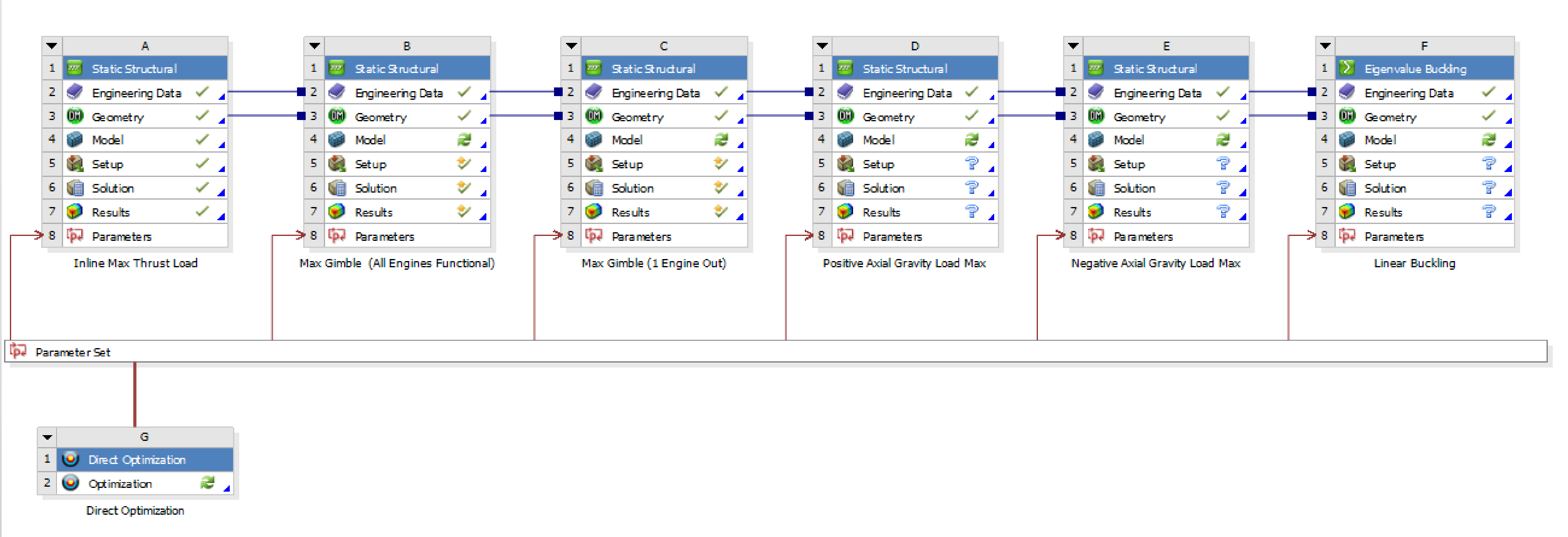






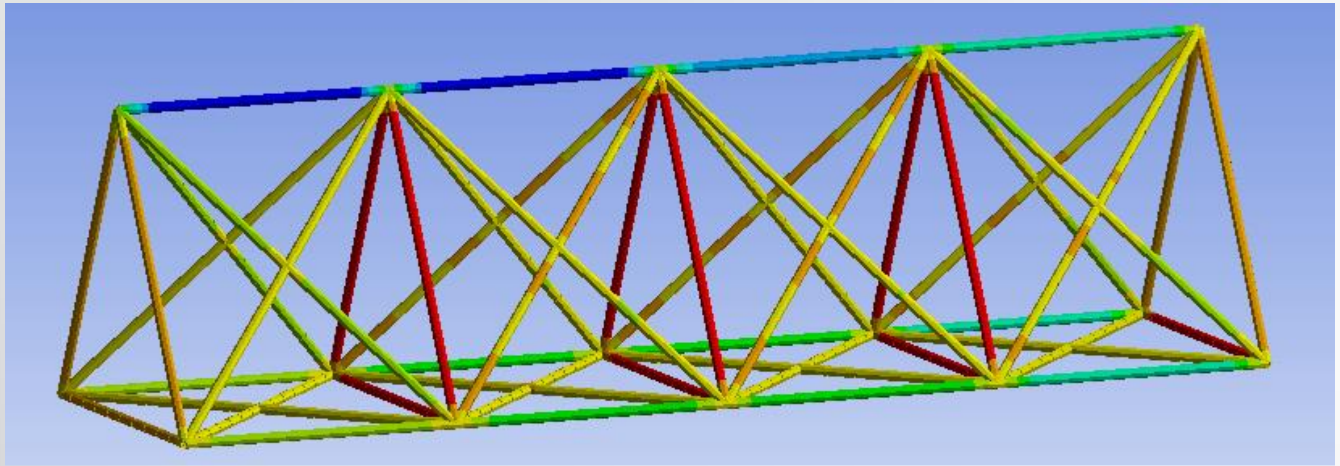
- The design of the truss was based on past successful designs capable of withstanding similar loading environments.
- 5 final designs were chosen, optimized, and analyzed in order to determine the most effective build.

Structural Analyses and Optimization

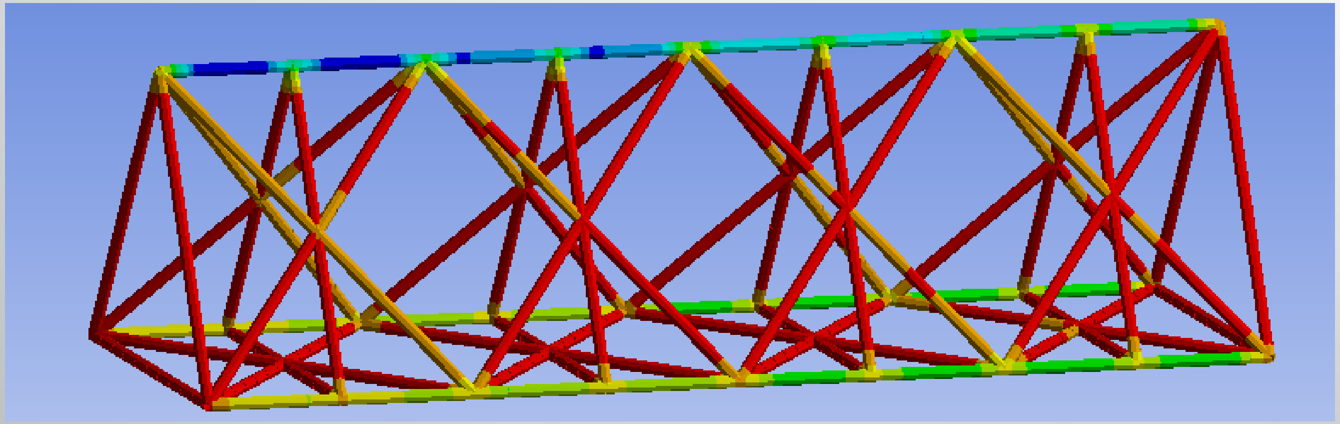


The optimization process was set up as shown. Analysis was conducted for the variety of applicable load cases simultaneously. The highest stresses and buckling strengths are then catalogued at which point the software modifies the geometry, in this case the inner and outer radii of the truss bar structure, and runs the process again.

Structural Analyses



Truss 2- 8 meters



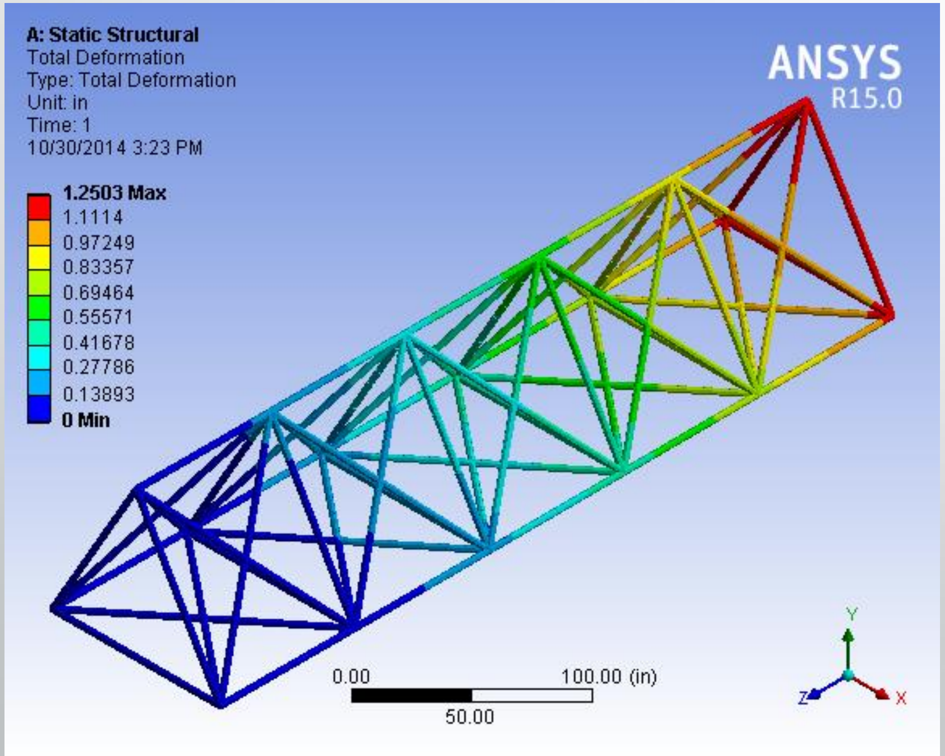
Truss 3- 8 meters

- Each truss design (5 in total) was assessed at 4 different lengths (4,6,8, and 10 meters respectively) under the same loading conditions, over 2500 different geometries were analyzed for each.
- All 50,000 cases were run in a day, the lightest weight options that had positive margin in all defined structural categories were reported.

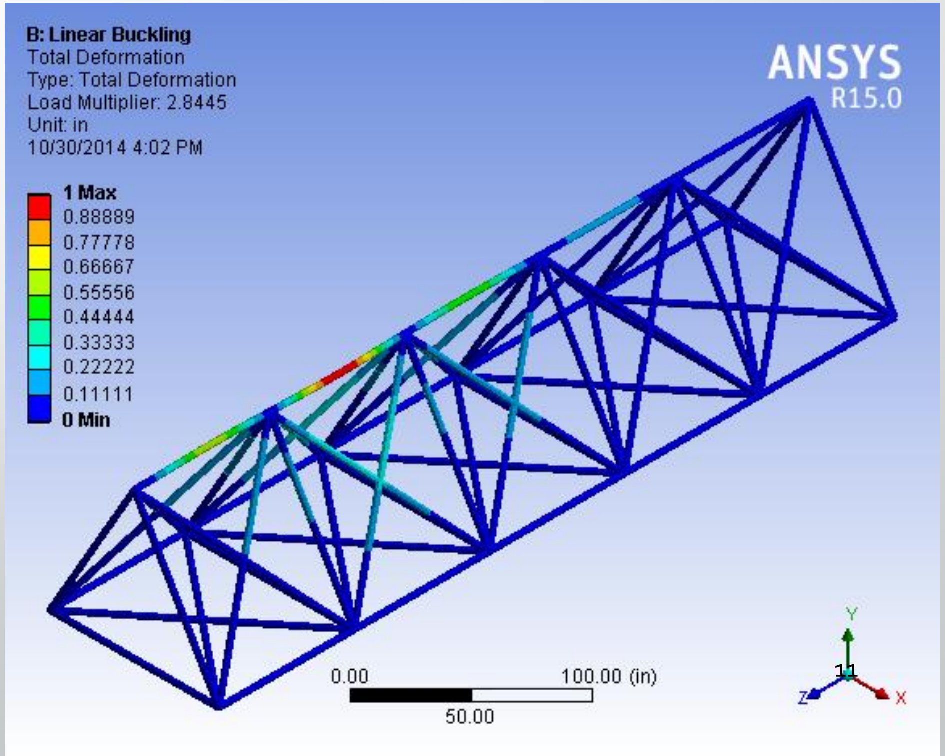
Post Optimization Checks: Deformation and Buckling Analysis

A max deformation of 0.03175 meters was found for the 10 meter truss of design 2 in a one engine out configuration.

ANSYS was used to perform a linear buckling analysis for each of the optimized designs.

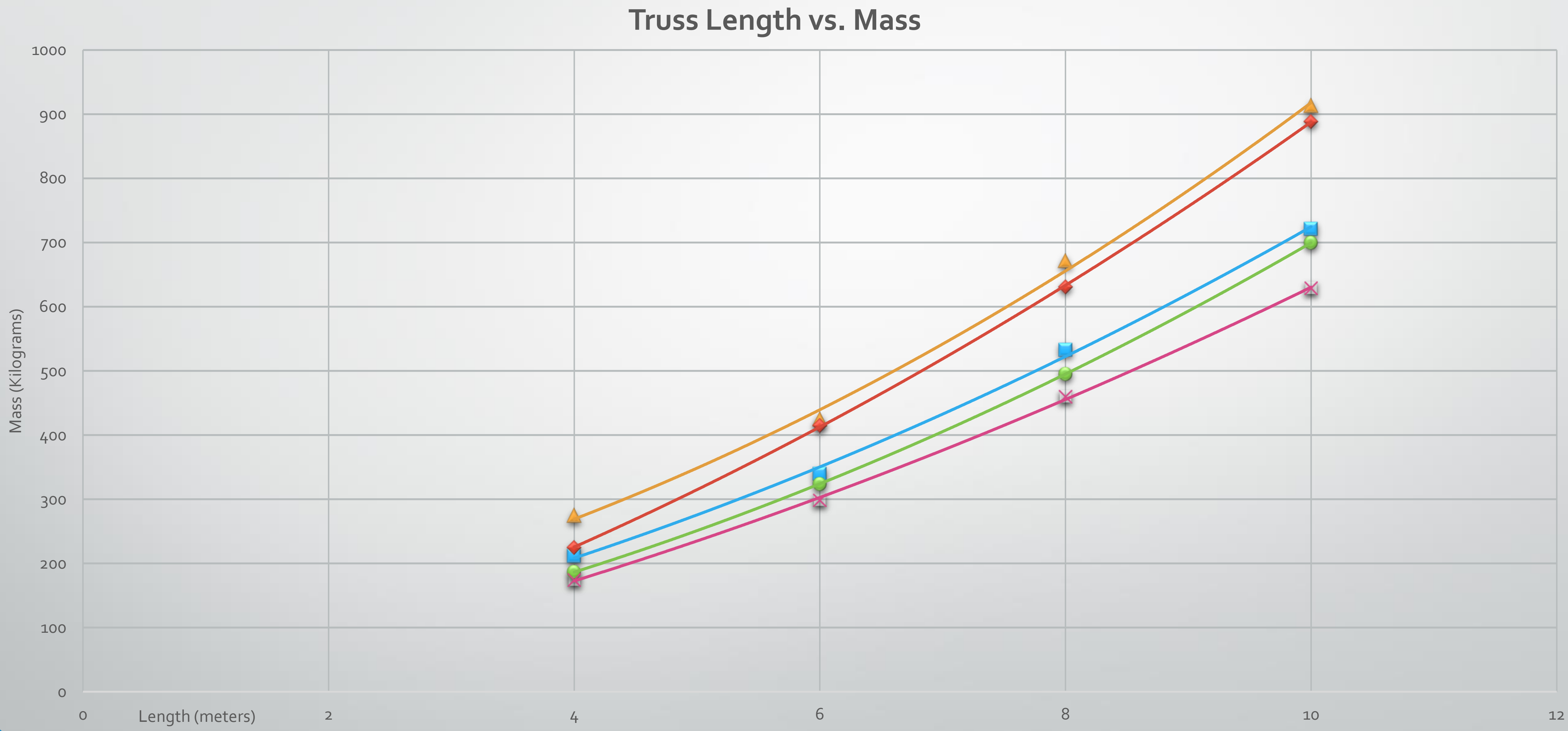


Truss 2 -10 meters
Deformation analysis



Truss 2 -10 meters
Buckling analysis

Initial Truss Mass Results



Truss 1
$y = 3.7585x^2 + 33.426x + 14.453$
$R^2 = 0.9983$

Truss 2
$y = 4.181x^2 + 26.992x + 11.527$
$R^2 = 1$

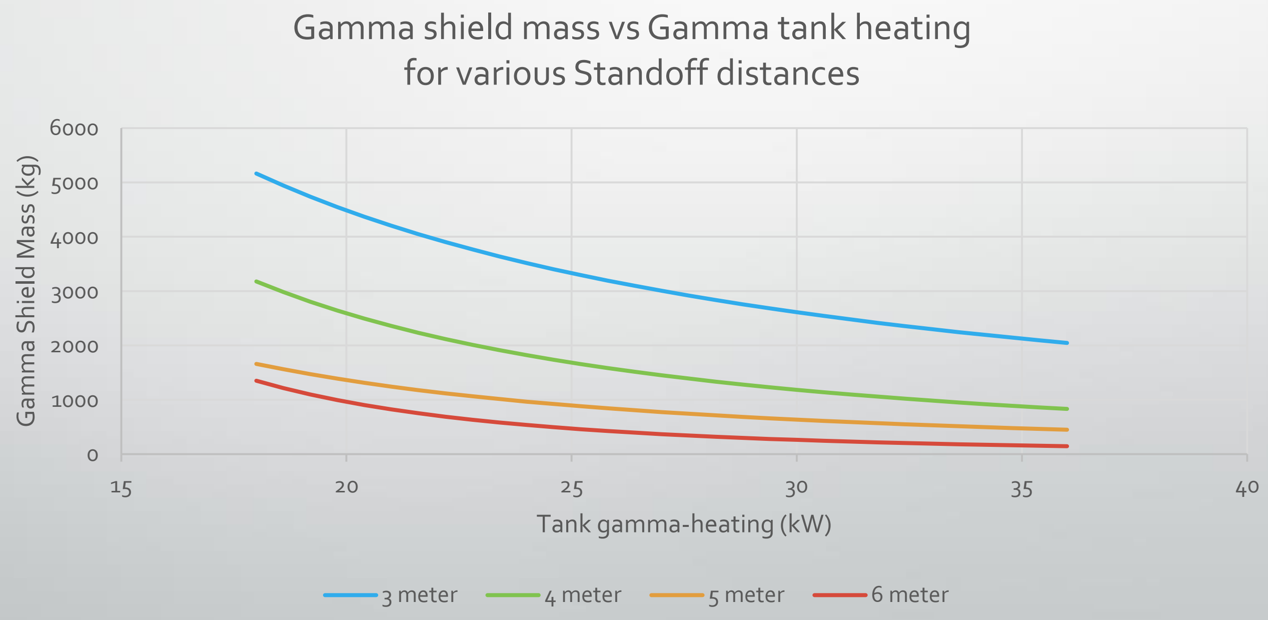
Truss 3
$y = 5.7335x^2 + 27.879x + 65.725$
$R^2 = 0.9978$

Truss 4
$y = 4.2028x^2 + 51.532x - 47.895$
$R^2 = 1$

Truss 5
$y = 2.8037x^2 + 37.039x - 20.388$
$R^2 = 0.9996$

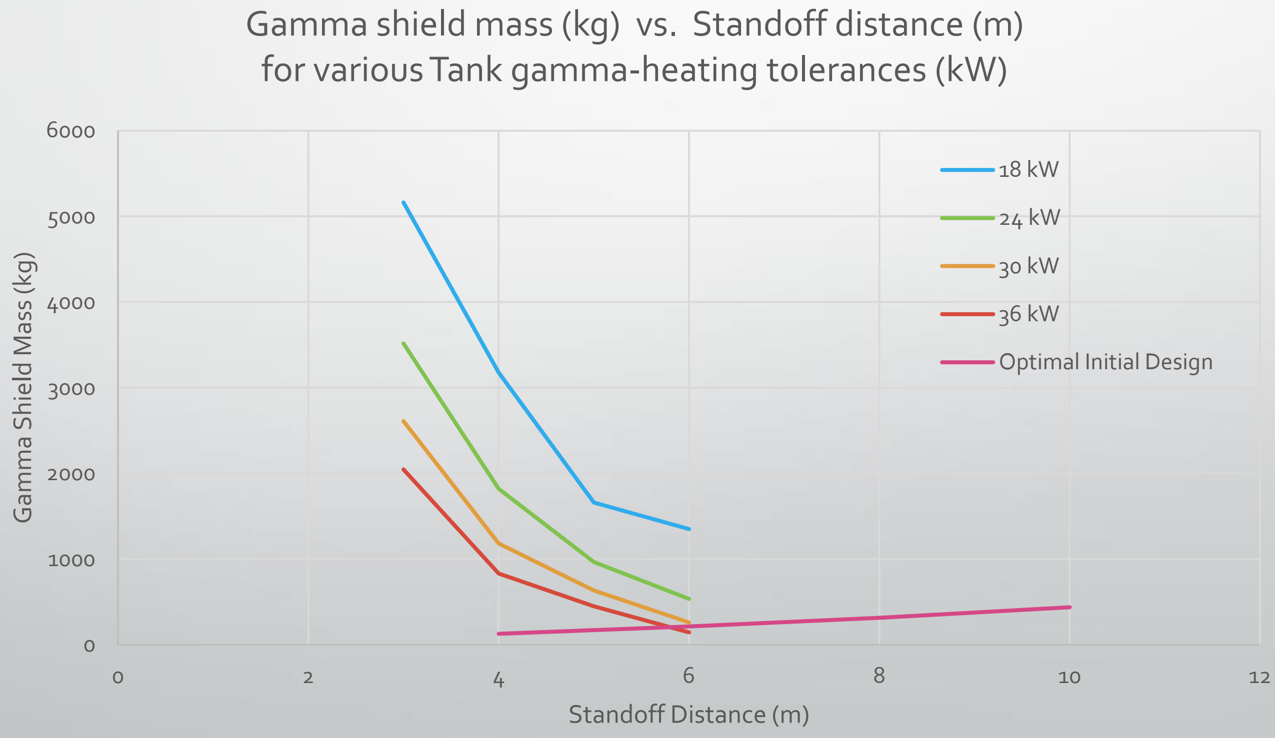
Determining Mass Shielding

Difficulty in predicting maximum allowable thermal load in cryogenic propellant lends itself to consideration of various cases of heating tolerance levels and their corresponding shielding requirements. The neutron contribution was excluded in this optimization analysis, although gammas account for the vast majority of heat and thus mass in this system. The tolerable range was varied between 18 and 36 kW, and exhibits a dramatic reduction in heating vs length for all distances within the heating range.



Initial Truss Mass Vs. Shielding Mass

It is immediately apparent that distancing the engine from the tank at any heating level is optimal for reducing the mass of the spacecraft up to approximately 6 meters in distance. Past this the heating tolerance level will determine the optimal length up until the ~9 meter limit imposed by the launch capability.

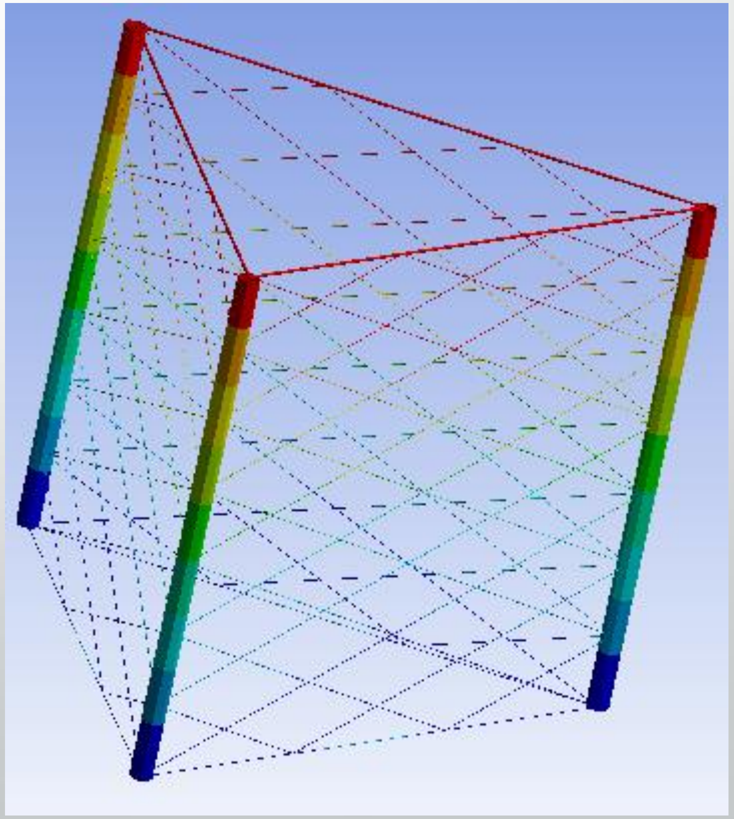


Conclusion

At 3 meters of separation the mass of the shielding can very between 2050 and 5162 Kg for 18 and 36 kW of heat resistance respectively. At 6 meters these values have dropped to 145 and 1350 Kg each. Relatively even the basic optimized truss design saw only an increase of 109 Kg between 3 and 6 meters. It is apparent that there is a significant overall savings in mass (anywhere between 1796 and 3703 Kg) up to six meters, however beyond that the mass savings may begin to decrease depending the tank’s gamma-heating tolerance.

Future Work

- Determine gamma-heating resistance.
- Develop specifically optimized truss for rocket engine.
- Expand mass prediction to include piping and mounting equipment.
- Evaluate dynamic impact of truss on spacecraft structure.
- Evaluate feasibility of telescoping truss design to increase volumetric savings.



Questions?

Thank you