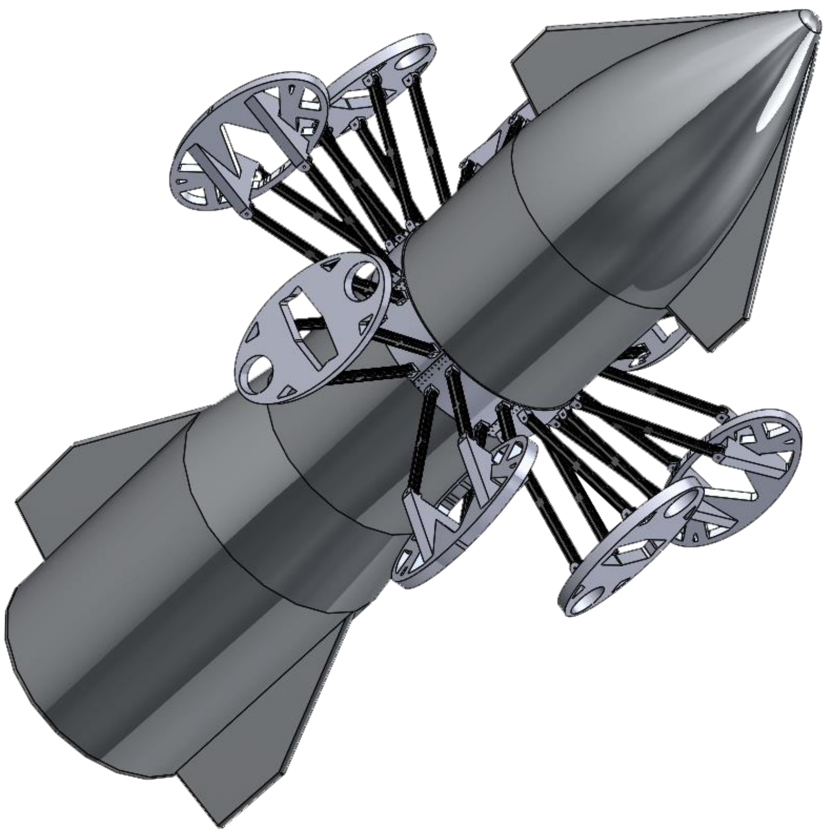
CREW·HaT Supporting Structures

Supporting an Active Magnetic Shielding Array for Deep Space Travel



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Executive Summary

This report presents an ongoing initiative aimed at designing a radiation shield for long-distance space missions. Leveraging superconducting coils arranged in a Halbach array configuration, the active shield generates a protective magnetic shield for astronauts. Building upon the foundation laid by a previous design group, the team is dedicated to refining the structural aspects of the CREW·HaT system, focusing on internal coil supports and beam structures.

The unique design of the Halbach array, with alternating magnets oriented radially outward and tangential to the spacecraft, presents complex Lorentz force dynamics. Compressive forces of 17 Meganewtons are experienced by the radial electromagnets, while the tangential electromagnets endure a saddle-like force distribution, resulting in a resultant tensile force of 11 Meganewtons. To address these challenges, the project uses advanced topology optimization techniques and structural simulations through finite element analysis.

Now through two semesters, the team has made significant progress in developing these support structures, as iterating through designs has resulted in improved structural performance. The team's final internal structure design has a maximum strain of 0.37% and an average of around 0.001%, falling well within the superconducting cable's limit of 0.45%. For the beam structures, the maximum stress observed was 40 Megapascals, also well within aluminum's yield strength of 275 Megapascals.

The team remained committed to refining the model's accuracy by comparing results from multiple software platforms. This effort confirmed results but took time away from fully optimizing the overall weight of the system. With results well below the stress and strain limits set by the client and manufacturers, there is plenty of room for further weight reduction. Let this model serve as proof-of-concept of a pioneering solution in advancing the frontiers of human exploration.

Table of Contents

Introduction

As humanity continues to push the boundaries of space exploration, new discoveries beckon, from potentially habitable exoplanets to the enigmatic red planet, Mars. Beyond the allure of these distant worlds, however, a formidable challenge lies: the journey itself. The prolonged travel time demands vast resources and poses significant risks, including the invisible threat of ionizing radiation. Earth's magnetosphere deflects this deadly radiation, but in space, astronauts are much more exposed to the elements. To reduce the long-term risk of cancer as well as shorter-term illnesses that could impact a mission, a solution must be found before crewed missions to Mars.

The answer lies within a magnetic phenomenon called the Halbach array - a particular arrangement of magnets that produces a strong magnetic field around the exterior of the array, and a diminished field on the interior. The concept behind using the array in this particular application is relatively simple: a strong enough magnetic field can deflect enough radiation that would otherwise be harmful to astronauts. In practice, however, things get quite complex. To produce such a radiation shield, extremely high current must run through superconducting coils, making electromagnets, which are then ultimately configured into a Halbach array. This array would attach to and surround a spacecraft's hull, providing shielding for those within.

Today, current solutions employ passive shielding systems, which leverage the inherent absorption of radiation that some compounds have, such as water and hydrogen. Having the walls of the spacecraft lined with such materials, however, proves to be too heavy for aerospace applications. Additionally, if humans will ultimately be exiting the spacecraft for surface missions or habitation, a method of shielding will also be necessary. Active magnetic shielding is thus called upon to either replace or supplement current shielding solutions.

The focus of this report is on the supporting structures of such an array, namely, the internal coil supports and external mounting beams, which undergo high Lorentz forces induced by the strong magnetic field. This team is challenged with designing a deployable system that not only mounts the array to the spacecraft, but can also withstand Meganewton-scale Lorentz forces, all while being lightweight enough to be launched into space. This report confronts these challenges with innovative structural analysis techniques, enabling safer and more ambitious voyages into the cosmos.

Background

The groundwork for our project has been laid out by a preceding senior design team within the Engineering Mathematics and Aerospace department. The team developed Cosmic Radiation Extended Warding using the Halbach Torus (CREW·HaT), during which they meticulously examined the forces that result from a Halbach configuration of electromagnets. To establish these intricate relationships, numerous software and computational methods were employed, most notably a collection of MATLAB scripts that paved the way for our structural analyses. Their exceptional efforts prioritized developing a comprehensive system, but given the time constraints of a single semester, it is natural that certain aspects could not receive exhaustive attention. Additionally, the project's scope expanded significantly from its originally envisioned application for NASA's Lunar Gateway Mission to accommodating SpaceX's Starship. Addressing this gap forms our team's senior design work, and before revealing our promising model, more background regarding our client, space radiation, operating principles and design constraints will be given.

Our Client

Our research is conducted in collaboration with NASA Innovative Advanced Concepts (NIAC), a federal program that funds research on innovative solutions to long-term issues that future NASA space missions face. The University of Wisconsin-Madison has been working with NIAC in Phase I to investigate the efficacy of an electromagnetic radiation shield. The primary contact within the team's interdisciplinary group of advisors is Astronomy Professor Elena D'Onghia, who serves as our client. Through NIAC's funding and the ongoing contributions from dedicated teams and advisors, a solid foundation for addressing a critical question has been made: the extent of the threat posed by space radiation.

Space Radiation Sources and Dosages

Spacecraft navigating outer space encounter formidable threats in the form of solar particle events (SPE) and galactic cosmic radiation (GCR). SPEs, also known as coronal mass ejections or solar flares, pose localized and intense radiation hazards. GCR, on the other hand, emanates from supernovae and other large-scale galactic events, blanketing the entirety of space. The magnetic field from the sun shields the inner solar system from low-energy GCR, but there is still a constant stream of high-energy particles that subjects astronauts to a dangerous dose of radiation [1].

Experts debate the allowable radiation dosage over an astronaut's career, but the current NASA allowance is 600 mSv. Table 1 shows how this compares to other radiation-exposing events, and Table 2 shows the health detriments from exposure.

Table 1. Radiation dosage from various radiation-exposing events [1].

Description	Exposure (mSv)
Single chest X-ray	0.06
Single CAT scan of body	1.1
One year of Earth radiation (approximate)	3.0
8 days on the Space Shuttle	5.59
9 days on the Moon	11.4
6 months on International Space Station	160
Lowest dose recieved during 1945 Hiroshima bomb	200
Estimated 6-month mission in lunar orbit [1]	520
Estimated dose for 3-year round trip to Mars	1200

Table 2. Health effects of sudden radiation exposure [1].

Radiation dosage (mSv)	Health Effects	Time to onset
<100	No health effects	none
Above 100	Cell and DNA damage	hours
Above 1,000	Nausea, vomiting, diarrhea	1-2 days
Above 1,500	Damage to blood-forming organs	$\approx$ 1 month
Above 10,000	Internal bleeding; death	days to 2 weeks

With this threshold as a benchmark, calculations were performed using the projected duration of space missions to determine the required magnetic field strength necessary to reduce the probability that GCR is transmitted to the crew and spacecraft's electronics. The CREW HaT folks determined that "an applied current of $1 \cdot 10^7$ amperes produces a transmission probability close to 50%...which was our Phase I initial requirement" [1]. In addition to this demanding requirement for the system, the effects of high currents interacting with electromagnets unveil critical design constraints for this project.

Active Magnetic Shielding

This project investigates the mechanical system needed to support a Halbach array for shielding spacecraft from radiation. The inspiration for this concept stems from Earth's magnetosphere, which diverts GCR particles back into space. To create an artificial magnetosphere on the scale of a spaceship, however, a few principles must first come together.

Electromagnets and Lorentz Forces

Electrical current and magnetic fields are closely related: current flowing through wires induces a magnetic field in the surrounding space, and magnetic fields induce current in wires. This can be visualized in Figure 1, where B represents the magnetic field induced by current, I, running through the loop of wire.

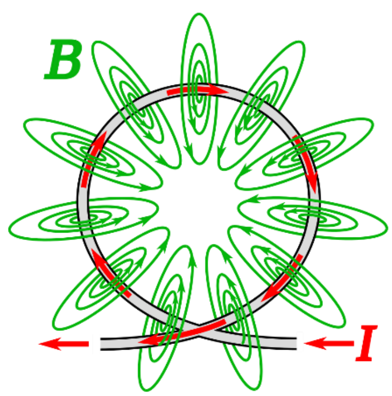

Figure 1. Induced magnetic field by flow of current through a wire.

This loop with magnetic polarity can be called an electromagnet. Now, if multiple electromagnets are near each other, the interaction of one magnet's magnetic field and another magnet's electrical current causes a Lorentz force. This relationship can be represented by the following equation.

$$\vec{F} = I\vec{L} \times \vec{B}$$

Where F is the force exerted on the conductor in newtons, I is the current in the wire in amperes, L is the length of the coil in meters, and B is the magnetic field in tesla. This simple relationship has complex manifestations throughout the system, with the observed induced forces serving as the project's primary design constraint.

Halbach Array

A Halbach array is a configuration of magnets that maximizes the magnetic field strength on one side of the array while minimizing it on the other, as demonstrated in Figure 2.

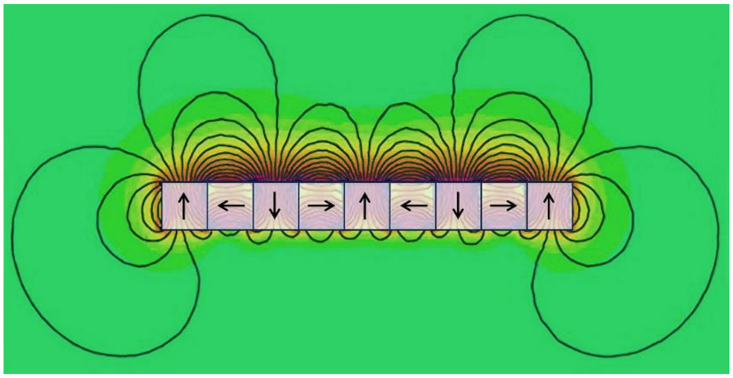

Figure 2. Magnetic field induced by a linear Halbach array [2].

The magnetic field lines are drawn in black, while the corresponding strength throughout the space is indicated by color gradient. Each individual block represents a magnet with polarity in the direction of its arrow. By alternating magnet orientation, magnetic field is maximized on one side of the array and minimized on the other. Variations of array geometry are possible that maintain this principle. The CREW HaT system includes eight electromagnets arranged in a circle around a spacecraft, with the previous design as shown in Figure 3.

Figure 3. CREW HaT system [1].

This Halbach array, featuring superconducting coils wrapped around an ellipse-shaped internal support structure, attaches to the Lunar Gateway craft's crew module via I-beams. This project's approach is effectively the same, with a few key differences stemming from the larger size of the SpaceX Starship. What remains, however, is the intriguing yet complex loading distributions that arise from the circular Halbach array configuration.

Induced Forces

There are two sets of forces induced by the current in the coils: self-induced forces and inter-coil forces. The self-induced forces are internal to the electromagnet and produce high hoop stresses in the material of the coil – they act to expand and unravel it. Since they are the result of the electromagnet's own interactions, they cancel out and do not induce any forces or moments on any of the other coils. Supporting these forces is an important part of the design of the system but is handled by a different team focusing on the superconducting technology.

The inter-coil forces are this project's focus, and manifest in two different loading cases that depend on the orientation of the electromagnet's polarity. A circular array of eight electromagnets would have four parallel to the hull of the spacecraft and the other four perpendicular, configured in an alternating pattern. The electromagnets perpendicular to the spacecraft (referred to as radial electromagnets) experience a net force towards the center of the array, and those parallel to the spacecraft (referred to as tangential electromagnets) experience a net force outward.

These net forces are the summation of individual vectors over the entire lengths of the coils, which upon further examination reveals a much more complex distribution for the tangential electromagnets. The magnet is forced into the shape of a hyperbolic paraboloid (or saddle), which closely resembles a Pringle chip, hence our naming them "pringle forces". The radial electromagnet's resultant force is made up of purely center-seeking vectors along the length of the coil, presenting a much simpler distribution. Both distributions were determined through MATLAB models, with the net forces shown in dark red in Figure 4.

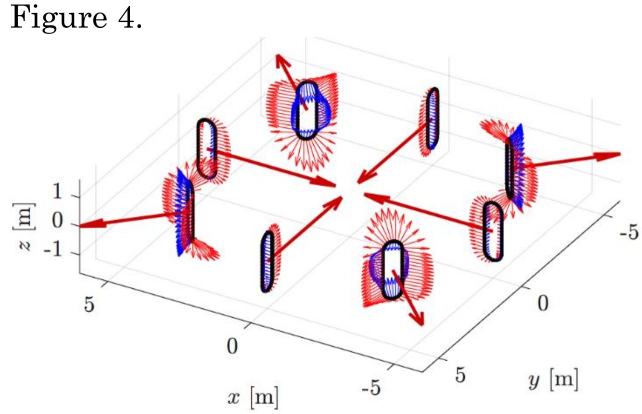

Figure 4. Inter-coil forces (light red), resultant force (dark red), and magnetic force on each coil (blue) in the Halbach array [1].

The resultant force calculated for the inward and outward variations are 17.6 MN and 11.1 MN, respectively. These resultant forces are imparted on the I-beams that attach the array to the spacecraft, revealing compressive and tensile loading cases. The individual components of these net forces affect the internal structure of the magnet, and zooming into Figure 4 helps visualize these in Figure 5.

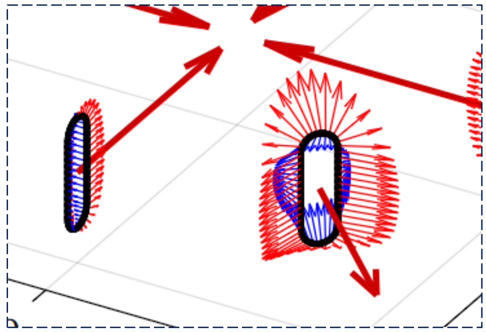

Figure 5. Locations of Pringle and Compressive forces on the Halbach array.

To convert these discrete vectors into a more user-friendly and accurate analytical expression for software analysis, the distribution was written in terms of an angle with respect to the center of the ellipse, θ, and a polynomial approximation was executed. The results of the equations in the x, y and z directions are shown below in figure 6.

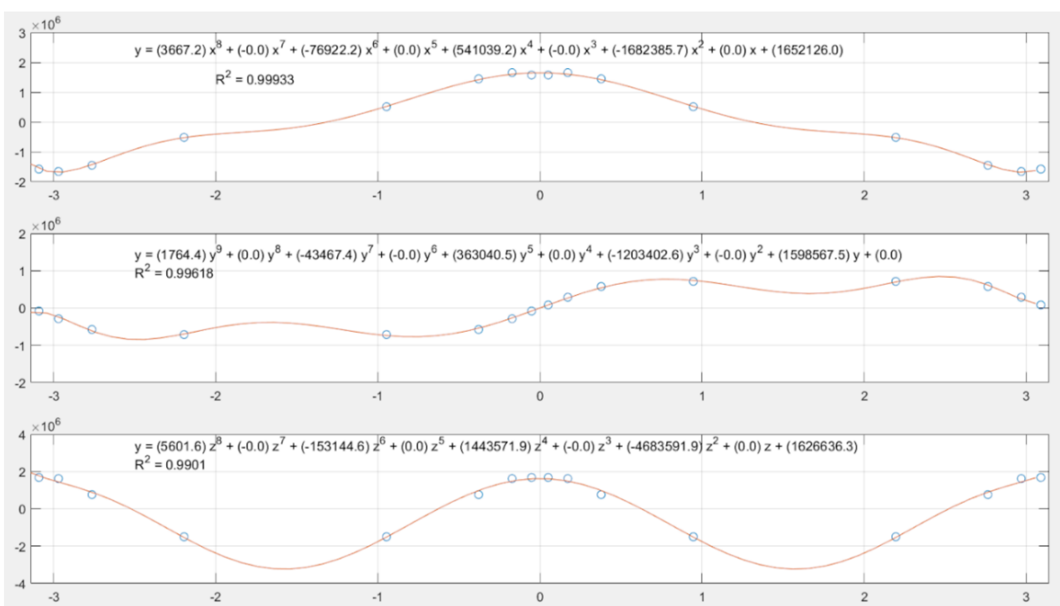

Figure 6. From top to bottom: Induced forces in x, y, and z directions as a function of the angle about the center of the ellipse.

Note that the equations in figure 6 are only valid for angles in radians between negative π and π. Also, the x direction is oriented along the minor axis of the ellipse, and the y direction is oriented along the major axis. The z direction is into the depth of the ellipse. This arduous task was not fruitful, as the resulting expressions could not be implemented into structural analyses with SolidWorks. It does, however, offer a different representation of the complex loading applied to the electromagnets, and we are confident that future research can further refine and utilize the analytical equations. Appendix C offers a more detailed outline for these calculations.

Design Specifications

Combining all the constraints imposed by the required current and induced forces, we are left with a better picture of what our design must withstand. The actual size of the coils and the strength of the superconducting materials that comprise the elliptical solenoid are still to be considered.

For sizing the coils, the superconductor team did a parametric study to compare coil shape geometries on magnetic field strength with circles, racetracks, and ellipses of varying sizes. The size and shape of each coil has been reduced to two options: an elliptical solenoid with a major and minor radius of four and two meters, respectively, and a circular solenoid with a radius of three meters (m). The elliptical shape was chosen to maximize the distance between the coils in the array, as when oriented like in Figure 3, the narrower radii provide more clearance. The length of the I-beams does impact the strength of the generated magnetic field, but with this parameter easily adjustable and given the scope of the project, the only constraint was that they do not allow the coils to physically interfere with each other.

This project's final design consideration is accommodating the strength of the superconducting wire that ultimately facilitates the array's shielding characteristics. The material the team plans to use is called Conductor on Round Core (CORC), which are composite cables and wires with high-temperature superconducting rare-earth barium copper oxide (REBCO) tapes. They are wound to form flexible layers and can carry extremely high currents, producing magnetic fields of up to 20 T. If the strain limit of 0.45% is reached, irreversible damage is done to the tapes and is considered, for our application, catastrophic failure. Therefore, our internal structure's deflection is constrained to this limit.

It is worth noting that the internal structural material chosen for this project is Aluminum 6061. While serving as a placeholder, Aluminum 6061 was chosen for its widespread availability in modeling software and comparable strength to other candidate alloys and composites. Relevant material standards were applied and assumed when evaluating the material (see Appendix A). All system parameters and design constraints are summarized in Table 3.

Table 3. Geometry and design constraints for the design project

Component	Internal Coil Support	External Coil Mounting
Description	*ellipse*: $\mathbf{R_{major} = 4m}$ $\mathbf{R_{minor} = 2m}$	*I-beam connects coil to vessel*
Tensile Case	*pringle forces*, $\boldsymbol{\epsilon_{max} = 0.45\%}$	*resultant* = 11 MN, $\boldsymbol{\sigma_{yield} = 275}$ **MPa**
Compressive Case	*compressive forces*, $\boldsymbol{\epsilon_{max} = 0.45\%}$	*resultant* = 17 MN, $\boldsymbol{\sigma_{yield} = 275}$ **MPa**

These parameters dictate the feasibility of any given structural design and guided us to our final product. For a full list and visualization of our client's design specifications and product architecture, refer to Appendix B.

Support Structure Analysis

The project was split into two main sections: designing the internal coil supports for the compressive and pringle loading distributions, and designing the beams that attach the coils to the spacecraft. Previously, the team also set out to investigate the specific mounting methods between the coils, beams, and spacecraft, but due to time constraints, this is left for future work.

Both the beams and internal supports were designed using finite element analysis (FEA) methods in SolidWorks and ParetoWorks. ParetoWorks is a finite element software that focuses on topology optimization and was provided courtesy of Professor Krishnan Suresh. SolidWorks has limited options when it comes to defining boundary conditions, constraints, and loading – all vital for successful and accurate FEA. ParetoWorks does these things best, and since it does not do modeling, the computing times are much faster. Ultimately, the team utilized ParetoWorks to confirm the results obtained through SolidWorks, which were strikingly similar.

Internal Coil Supports

A hexagonal design was initially considered for the internal coil support for both compressive and pringle loads, due to the popularity of honeycomb-inspired biomimetic designs seen in applications ranging from the SpaceX Starship's thermal coating to military vehicle tires [3]. These designs are shown in Figure 7.

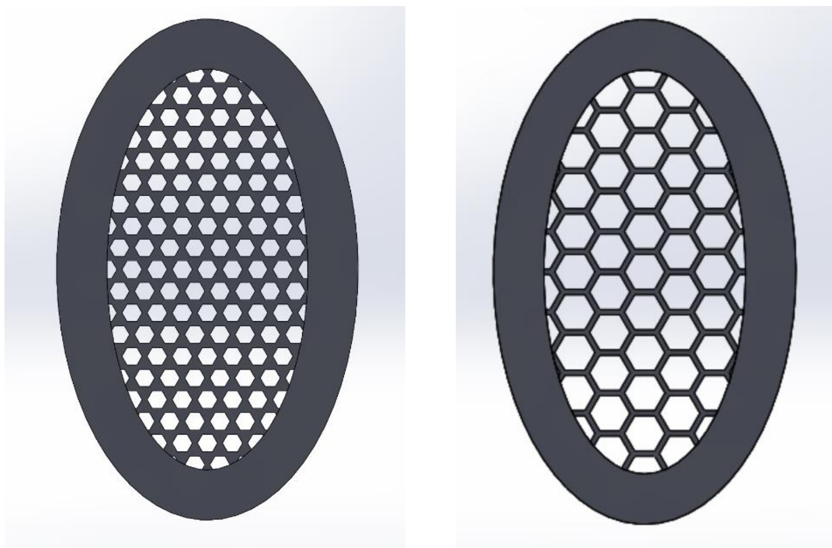

Figure 7. Hexagonal Coil Supports

The design on the left was the first, but the client recommended a lower surface area to minimize radiative heat transfer from the sun to the superconducting coils. The feedback was integrated into the design on the right, with larger hexagons halving the overall surface area from 13 m^2 to 6.4 m^2. However, both designs had overall displacements greater than what the client allotted, so alternate designs were considered.

The next step was to make a few designs based on intuition to get a better sense for the intensity of the forces and the support structures required. To this end, two designs were created, shown in Figure 8.

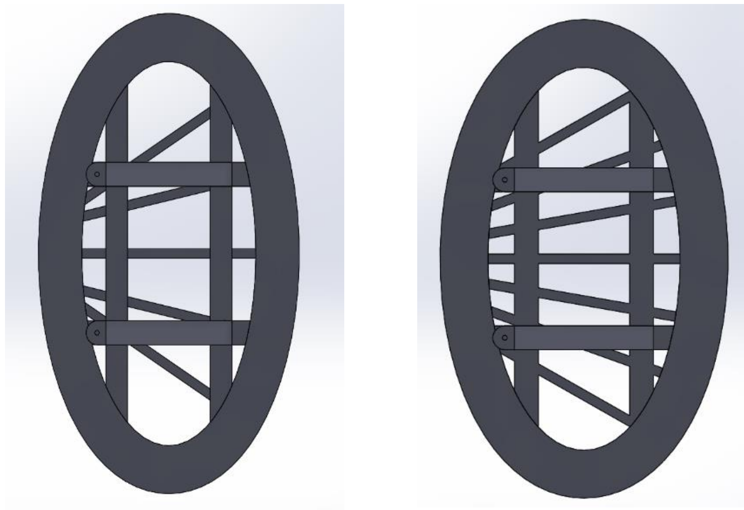

Figure 8. 5-bar design (left) and revised 7-bar design (right).

The idea was that each bar would absorb some of the compressive load, but after applying this load to the 5-bar design, the displacement results of 1.2 millimeters (mm) shown in Figure 9 were above the 0.02 mm limit set by our client (as strain became increasingly important, this limit would eventually be raised).

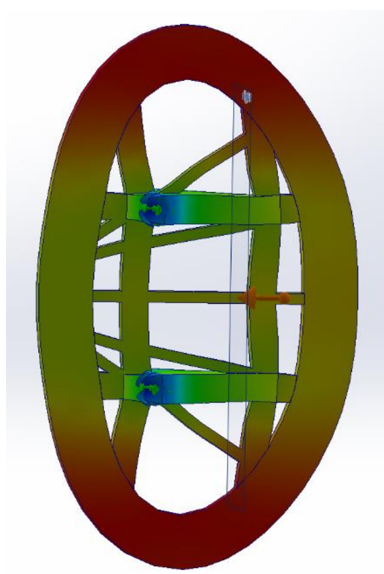

Figure 9. Compressive displacement visualization on 5-bar design.

Subsequent analyses on the 7-bar designs yielded marginally better results of 1.04 mm. This process resulted in useful design insights, however. First, the maximum stress and displacement occur at the major radii, and the stress in the center is relatively low. It also demonstrated just how large the forces involved are. At this point, the team decided a more robust method for determining a support design was required, so finite element methods were used.

The compressive coil was optimized first due to its simpler loading case. A constant load of 17.6 Meganewtons (MN) was applied to the outside of a solid aluminum ellipse. This solid part has dimensions to fit inside of the coil winding pack. A topology study was run in SolidWorks to reduce the mass by 70%. This study applies the desired load to the solid part and suggests which regions of the solid part may be taken away, with the goal of reducing mass while maintaining structural integrity. The results of the initial topology study are shown in Figure 10.

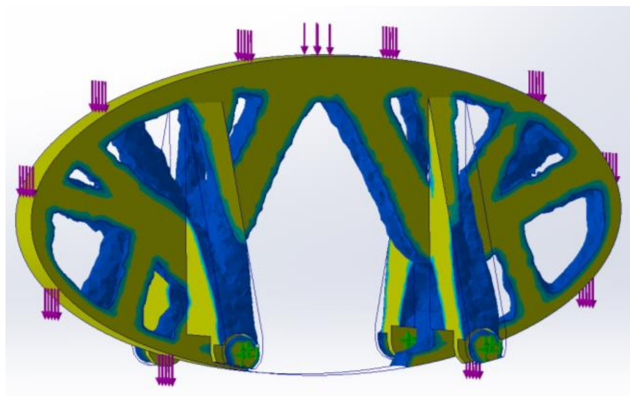

Figure 10. SolidWorks topology study results for compressive coil.

This design was promising, but SolidWorks' lack of comprehensive load and boundary condition options left the team uncertain about the results. To this end, the team consulted Professor Krishnan Suresh, a topology optimization specialist, who developed a software of his own: ParetoWorks. He generously provided ParetoWorks for the team to use, offering more accurate initial constraints and results. Figure 11 shows the results of the ParetoWorks topology optimization at about 70% mass reduction.

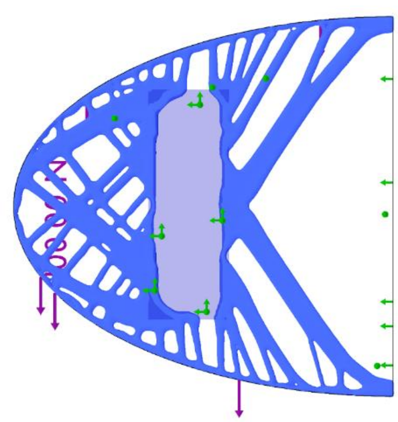

Figure 11. ParetoWorks topology study results for compressive coil (half symmetry).

Despite the difference in appearance between the two studies, both offer support in similar regions and have the same major support structures. This was taken as confirmation that the SolidWorks topology study was performed correctly, so the design was turned into the actual part shown in Figure 12.

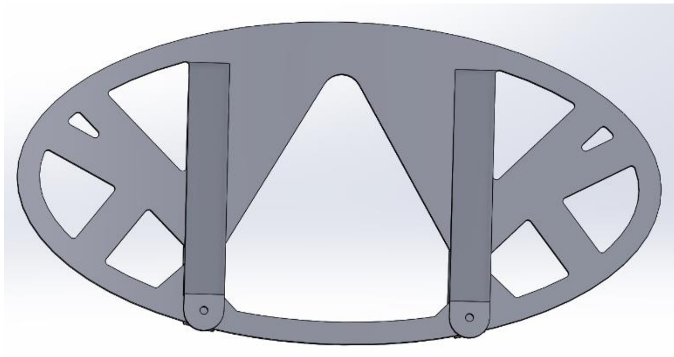

Figure 12. Compressive coil internal structure SolidWorks part.

A static structural study was performed to determine the strain imparted on this design. As shown in Figure 13, the strain peaks at 0.42%, but occurs at stress concentrations at the placeholder mounting points. Most of the outside radius of the ellipse, where the conducting wire would be, experiences a strain of around 0.04% - the CORC cable’s 0.45% strain limit was easily achieved. Note that the displacements in Figure 13 are greatly exaggerated by the software, as the actual displacements are impossible to distinguish at true scale.

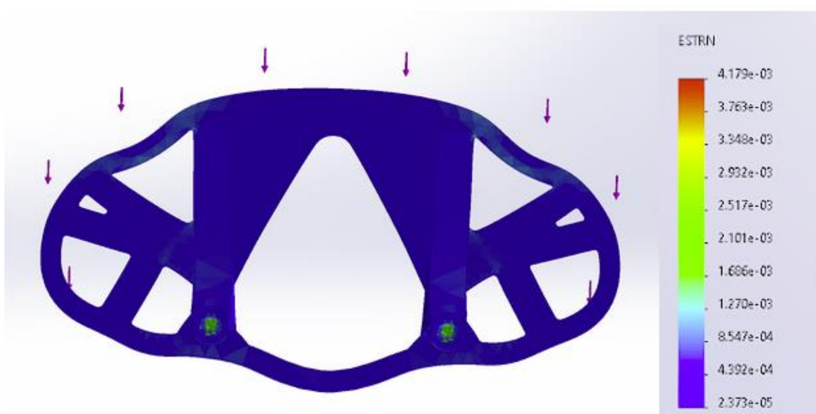

Figure 13. Compressive displacements from structural study with load of 17 MN applied.

A similar process was applied to designing the support for the pringle forces. Software limitations do not allow the complex force distribution to be applied as simply as the previous case Many different approaches were considered, but the team ultimately discretized and applied the individual loads to the exterior of the support structure (i.e. the load was translated from a separate body to the body of interest). The result of this SolidWorks topology study is shown in Figure 14.

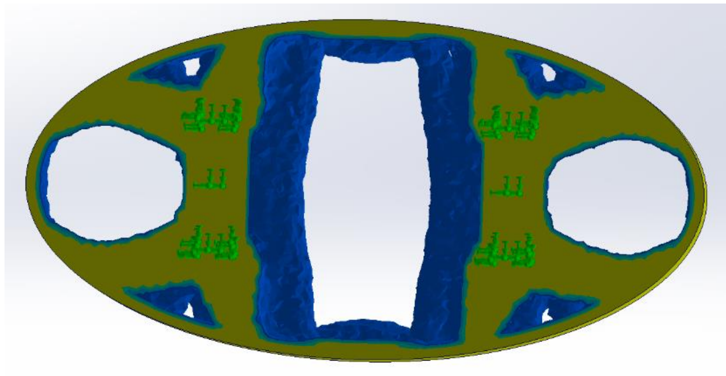

Figure 14. SolidWorks tensile coil topology results.

Again, ParetoWorks allowed for the full force distribution to be added to the structure, with the results shown in Figure 15.

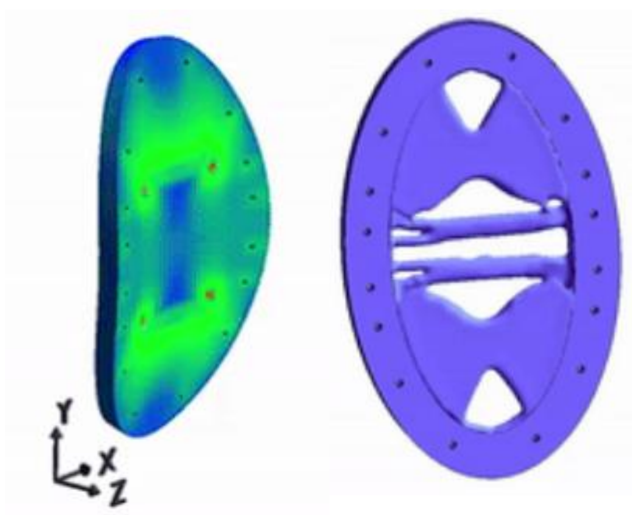

Figure 15. ParetoWorks structural pringle loading (left) and topology study results (right).

Due to the difficulty of converting the optimized ParetoWorks designs to real SolidWorks parts, this topology study was only used to verify the accuracy of the approximate loading used in the SolidWorks study. The designs created by SolidWorks and ParetoWorks were judged to be similar enough to proceed with the SolidWorks design. Figure 16 shows the final SolidWorks design for the tensile coils.

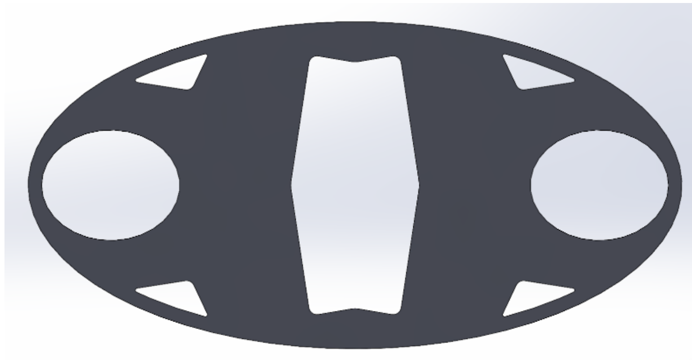

Figure 16. Pringle coil internal structure SolidWorks part.

Finally, a static structural study was performed on the design to confirm it can withstand the pringle loading. The results of the study are shown below in Figure 17.

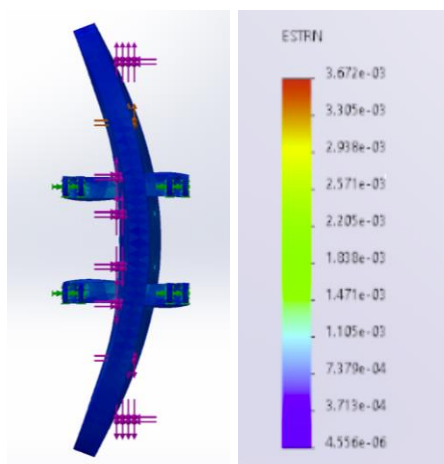

Figure 17. Pringle coil strain results, with applied loading visualized (left) and resulting strains (right), from low (blue) to high (red).

As shown, the strain of this design peaks at 0.367% at the placeholder mounting points. The critical area was the outside radius of the ellipse, which experienced a max strain of only 0.00046%. This indicates that there is significant room for refinement of the design, which unfortunately could not be done due to time constraints. The further mass reduction of both the tensile and compressive coils is left as future work.

Beam Supports

The design iteration for the radial coil supports began with the initial CREW·HaT design, which features beams pinned together that could actuate in a scissor-like motion. It was edited to create flat ends on either side and adjusted to the scale of the new parameters, as seen in Figure 18.

Figure 18. Edited scissor beam configuration from the CREW·HaT design.

Next, simulations were run to verify that the beams could undergo the maximum tensile and compressive forces. After discovering that the displacement was too large to continue, the focus shifted to individual beams, rather some configuration that would allow for actuation and deployment. In Figure 19, one I-beam was again scaled to fit the new ship.

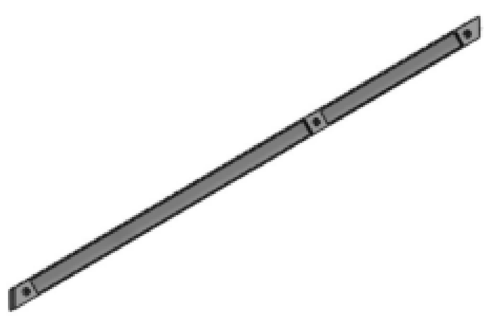

Figure 19. Individual I-Beam.

Then, after the mounting method's focus was shifted to simple and straight connections, the beam was changed again. This new beam shows rounded edges and a thinner profile, seen in Figure 20.

Figure 20. Edited I-Beam design.

Next, a topology study was run on SolidWorks with the goal of reducing the overall weight of the structure by 65 percent, to see which material was essential and which was extraneous. In Figure 21 below, the beam shape displays cuts through the flange section of the I-beam. The following studies focus solely on compressive loads, as the pringle forces were underdeveloped at this stage.

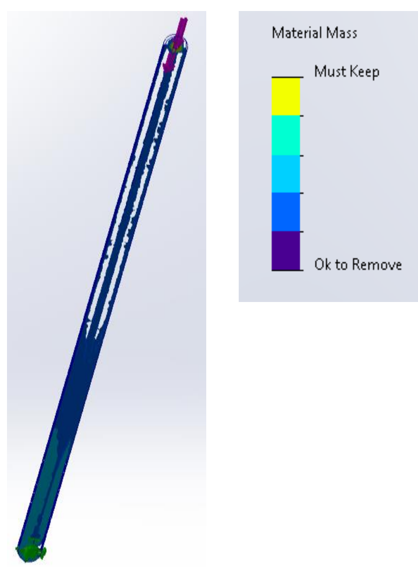

Figure 21. Beam after topology study removed 65% of total mass.

After the study was run, three different design were created, the first one was cut all the way down the sides, one was cut halfway, and the last was cut on either side of the midsection. In Figure 22, the three sequential designs are shown.

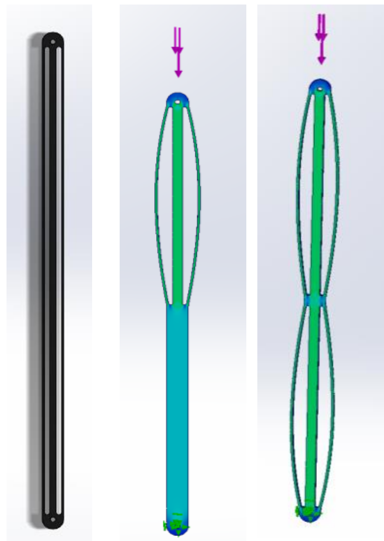

Figure 22. Three sequential beam designs created following topology study.

The previous beams displayed the following characteristics as shown in Table 4, as compared to the initial I-Beam design displayed in Figure 19. Note that the yield stress of aluminum is 275 MPa.

Table 4. Beam designs and associated stresses, strains, and weight percentages.

Design	Stress [MPa]	Strain [-]	Weight [%]
Original	220	2.4e-3	100
1	286	3.1e-3	69
2	261	2.9e-3	87
3	257	3.0e-3	74

As the designs reduce in weight, both the stress and strain increase. However, the third design displays a low maximum stress and strain, along with a 26 percent reduction in weight. Therefore, the third design was used for the array and added to the final assembly.

The culmination of our models is visualized in Figure 23, which displays the team's final prototype attached to SpaceX's Starship (same as cover image).

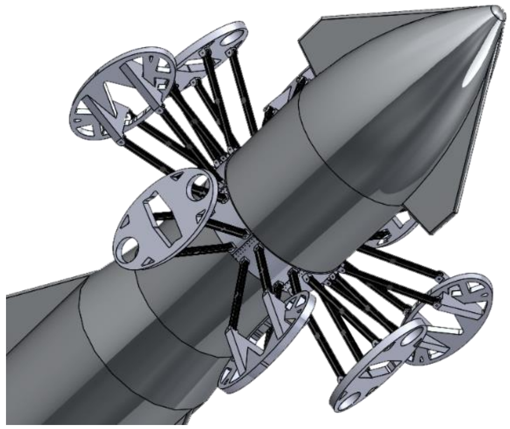

Figure 23. Revised CREW ·HaT on the Starship.

Though the team satisfied the client's needs and requirements, the job is not yet finished. Appendix D outlines future work for any group that picks up where we left off.

Conclusions

This interdisciplinary effort culminates in our software-based prototype, a dynamic model that engineers the support structures essential to an active magnetic shielding system and paves a way for spacecraft to explore beyond the protective confines of Earth's magnetosphere. The proposed CREW ·HaT uses superconductors to achieve the scale of electrical current needed to generate sufficient magnetic shielding. The high induced Lorentz forces require a sound internal structure to protect the coils from deflecting and external mounting structure to attach the array to the spacecraft, difficult tasks that our model accomplishes.

This report presents a modifiable SolidWorks model that utilizes MATLAB for calculating loading constraints, ParetoWorks and SolidWorks for topology optimization, and Ansys Workbench for structural analysis. Our model provides promising results for optimized support structures – all client design specifications were met regarding stress, strain, and dimensional limits. Although these results are for academic purposes only, they represent proof-of-concept in overcoming one of the greatest challenges in exploring the final frontier.

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Appendix A:

Relevant Standards

ASTM B85: Specification for aluminum-alloy die castings of all compositions

MIL-T-81556: Specification for aircraft quality titanium and titanium alloy extruded metal bar and shape products

AMS 4150: Specification for an aluminum alloy in the form of extruded bars, rods, wire, shapes, and tubing, flash welded rings fabricated from extruded stock, and stock for flash welded rings

AWS D1.2: Structural welding code for aluminum

ASTM B209-14: Specification for aluminum and aluminum-alloy sheet and plate

ASTM B308: Specification covers the standard structural profiles for 6061-T6 aluminum-alloy. The profiles are limited to I-beams, H-beams, channels, angles, tees, and zees

MIL-DTL-83488: Specification for high purity aluminum coatings

Appendix B:

Full Client Design Specifications and

At the beginning of the year, our client, NIAC, gave us the design specifications as shown in Table B-1.

Table B-1. NIAC design specifications.

Number	Category	Demand/ Want	Requirement	Method of Assessment
1	Feature	Demand	Ellipse major radius = 4m, minor radius = 2m	Measure inner and outer radii
2	Performance	Want	Allowable Strain = 0.45%	Run FEA and compare maximum deflection
3	Feature	Want	Rigid beam supports	Run FEA on beam design
4	Simulation	Demand	Simulate pringle and compressive forces	Run FEA in SolidWorks and Ansys
5	Weight	Want	Reduce weight to a feasible amount for space flight	Quantify system's weight in SolidWorks
6	Feature	Demand	Secure mounting attachments	FEA on coils, analyze stress at mounting points

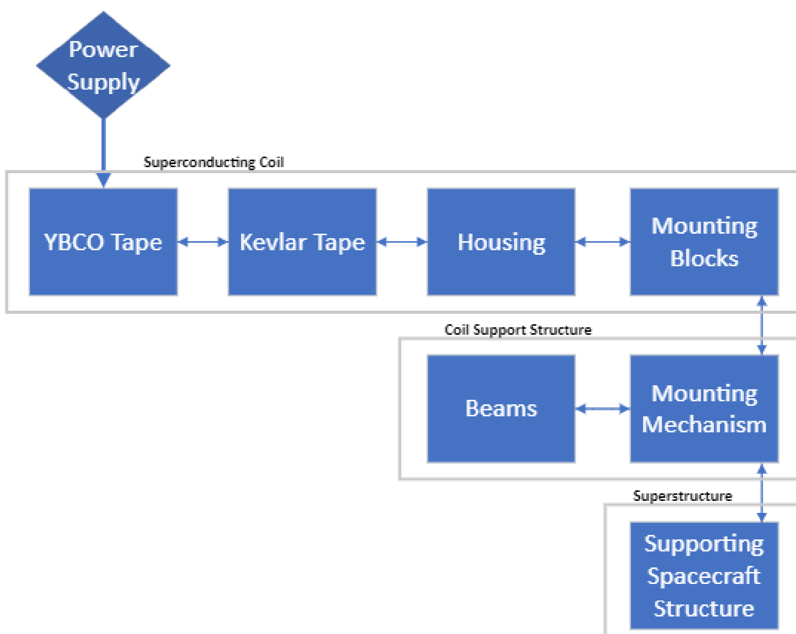

Figure B-1. Modular block diagram of product architecture.

Appendix C:

Software Calculations

MATLAB:

Developed by Kirby Heck and Matt Tuman and modified by the authors.

General: Approximately 30 scripts containing equations and code necessary for force distribution calculations. All scripts must reside in the same working directory for individual execution. Each script is extensively commented for clarity.

Key Scripts:
- force_visualization_2.m
- coil_geom.m
- analyze_forces.m

Workflow:
1. Open force_visualization_2.m.
2. Input operating parameters: coil_geom, current I, num_turns, etc.
3. Press solve. Output includes plots and tables.
4. In the "rotated_forces90" table, find Lorentz force vectors (x, y, z).
5. Corresponding vector locations are in the "translated_points" table (x, y, z).
6. Refer to Figure C-1 for an example.

rotated_forces90

16x3 double

	1	2	3	4	5	6	7
1	-1.5770e+06	-8.0795e+04	1.6812e+06				
2	-1.6569e+06	-2.8741e+05	1.6216e+06				
3	-1.4495e+06	-5.7573e+05	7.6229e+05				
4	-5.1405e+05	-7.1315e+05	-1.4986e+06				
5	5.1405e+05	-7.1315e+05	-1.4986e+06				
6	1.4495e+06	-5.7573e+05	7.6229e+05				
7	1.6569e+06	-2.8741e+05	1.6216e+06				
8	1.5770e+06	-8.0795e+04	1.6812e+06				

translated_points | coil_2_mp | coil_2_panel_forces | panel_forces

16x3 double

	1	2	3	4	5	6	7
1	-1.9792	-0.4056	0				
2	-1.8736	-1.3000	0				
3	-1.5324	-2.4346	0				
4	-0.6380	-3.5402	0				
5	0.6380	-3.5402	0				
6	1.5324	-2.4346	0				
7	1.8736	-1.3000	0				
8	1.9792	-0.4056	0				

Figure C-1. Force vectors and their corresponding x, y, and z coordinates.

Summary:
- The number of force vectors (16) was chosen due to coil symmetry and computational efficiency.
- Resultant forces alternate between compressive and tensile due to the Halbach configuration.
- Positive force values indicate tensile forces (tangential coils), while negative values indicate compressive forces (radial coils).
- Engineers primarily focus on overall force distribution (on coil structure) and resultant forces (on attaching beams).
- The force_visualization.m script is key for obtaining numerical data, while other scripts aid in troubleshooting and understanding the problem's mathematical aspects.

ParetoWorks:

This software belongs to Professor Krishnan Suresh, UW-Madison Dept. of Mechanical Engineering. Obtaining a license through him is necessary.

This software enables users to import an .STL file from SolidWorks, create a mesh, apply all possible boundary conditions and loading constraints, and run both static structural and topology optimization studies.

A benefit of using ParetoWorks is that the mass may be reduced to 1% of the original, with each step of the way saved and easily accessible. The user is then able to go back to a previous mass reduction percentage with the press of a button, without having to redefine the entire study and rerun it, like on SolidWorks, which saved the team lots of time.

Appendix D:

Future Work

With years of research on this topic coming to an end, the authors feel as though the end is in sight (at least for this portion of the project). Lack of medical physics data and general time limitations were the primary inhibitors to this project's progress. However, the team is extremely proud of successfully implementing advanced finite element techniques in determining structurally sound geometries. Coupling this with an additional optimization scheme, the team sees potential for further advancement.

Considerations must be made for a dual system – one that incorporates both active and passive shielding technologies. The current estimates for the overall weight suggest a balance of both, but the medical physics team has not yet developed an optimization scheme to determine shielding amounts from varying layer thicknesses and radiation doses. Nevertheless, the team is confident that another optimization scheme can be applied to both active and passive iterations to achieve the perfect amounts of both. The design of the support structure is directly influenced by the amount of current needed to generate enough magnetic field to deflect radiation. Incorporating passive shielding also alters this requirement.

The scope of this project extends beyond the limitations of a two-semester undergraduate course. While innovative methodologies were applied to determine optimal structure designs using advanced topology optimization techniques, the results of this report remain purely academic. The purpose of this section is to guide future research on the CREW HaT magnetic shield design. Drawing from years of combined research experience, the authors propose a plan of action, recognizing that this portion of the project is nearing completion.

Launch considerations and deployment methods (engineering): Due to the weight of the system, the array will likely need to be assembled in space, hence this project's focus on static beams rather than the previously suggested scissor deployment mechanism.

Further mass reduction strategies (engineering): The design in this report still has room for improvement. The stress and strain requirements can still be met with further reductions in weight.

Particle physics and medical physics investigations (physics and astronomy): The particle and medical physics can be more accurately modelled to determine the effectiveness of different passive shielding materials and thicknesses. This then can be compared to active shielding.

Research on superconductors and cryocoolers (engineering): It is superconducting technology that makes this project possible. Though the current concept leverages the cold temperatures of outer space, further cooling is needed, and cryocoolers will need to be used and aboard the system.