Electromagnetic Radiation Shield for Spacecraft

Oseas Hudy-Velasco
Western Michigan University, ohudyvelasco@gmail.com

Follow this and additional works at: https://scholarworks.wmich.edu/honors_theses

Part of the Space Vehicles Commons

Recommended Citation
https://scholarworks.wmich.edu/honors_theses/3001
SUPERCONDUCTING ELECTROMAGNETIC RADIATION SHIELD FOR ASTRONAUT PROTECTION

Developed by Group #26:
Robert Hallenbeck
Oseas Benjamin Hudy-Velasco

Advisors:
Dr. Kristina Lemmer
Dr. Asghar Kayani

Dr. Bade Shrestha
Department of Mechanical and Aerospace Engineering
College of Engineering and Applied Sciences
Western Michigan University
1903 Western Michigan Avenue
Kalamazoo, MI 49008
DISCLAIMER
This project report was written by students at Western Michigan University to fulfill an engineering curriculum requirement. Western Michigan University makes no representation that the material contained in this report is error-free or complete in all respects. Persons or organizations that choose to use this material do so at their own risk.

ACKNOWLEDGEMENTS
We would like to thank:

Dr. Kristina Lemmer for advising us on this project. You were very supportive as we navigated the intricacies of high-energy particle physics and trying to go to NASA. Sorry that it did not work out.

Dr. Asghar Kayani for advising us on this project and allowing us to use his equipment for testing, as well as serving as our contact for AMSC and helping us acquiring material.

Professor Joseph Kelemen (ret.) for the electrical engineering perspective and access to copper wire to practice winding magnet coils.

Martin Rupich, American Superconductor, for suppling the materials to build the scale model. We thank you profusely for your generosity with this advanced material.

Matthew Baird for your help with Comsol and use of your computer. We would still be modeling magnetic fields without you.
## CONTENTS

Tables of Figures and Tables........................................................................................................ v
Abstract........................................................................................................................................ vi
Introduction ...................................................................................................................................... 1
  Background ................................................................................................................................. 1
    Underlying Physical Phenomena .............................................................................................. 1
    On the Shielding of Spacecraft............................................................................................... 2
Proposal .......................................................................................................................................... 3
Objective ......................................................................................................................................... 3
Design Constraints ...................................................................................................................... 3
Specifications and Requirements ................................................................................................. 4
Project Timeline ........................................................................................................................... 5
Magnet Design ............................................................................................................................... 6
Alternate Solutions ..................................................................................................................... 6
Final Geometry ............................................................................................................................. 8
Simulation ....................................................................................................................................... 10
Parameters ...................................................................................................................................... 11
  Scale Model ............................................................................................................................... 11
  Full-Size System ...................................................................................................................... 12
  Parametric Sweep ................................................................................................................... 12
  Small Scale for Testing ............................................................................................................ 13
Simulation Results ....................................................................................................................... 13
  Scale Model ............................................................................................................................... 13
  Full-Size System ...................................................................................................................... 15
  Parametric Sweep ................................................................................................................... 16
  Small Scale for Testing ............................................................................................................ 18
Experimentation ............................................................................................................................ 18
  Procedure ................................................................................................................................. 18
  Results ...................................................................................................................................... 19
Analysis ......................................................................................................................................... 21
Conclusion ...................................................................................................................................... 23
Suggestions for Further Research

References

Appendix 1: ABET Forms
Form 1: Assessment of Student Outcome #C (ME 4800)
Form 2: Assessment of Student Outcome #J (ME 4800)
Form 3: Assessment of Student Outcome #H (ME 4800)
Form 4: Assessment of Student Outcome #I (ME 4800)—1
Form 4: Assessment of Student Outcome #I (ME 4800)—2

Appendix 2: Resumes
Robert Hallebeck
Oseas Benjamin Hudy-Velasco

Error! Bookmark not defined.
TABLES OF FIGURES AND TABLES

FIGURE 1. GALACTIC COSMIC RAY AND SOLAR ELEMENTAL COMPOSITIONS ......................................................... 2
FIGURE 2. NASA ASTRONAUT RADIATION LIMITS ........................................................................................................ 4
TABLE 1. GANTT CHART FOR PROJECT CHECKPOINT.S ............................................................................................. 5
TABLE 2. DECISION MATRIX TO DETERMINE TYPE OF ACTIVE SHIELDING ............................................................... 6
FIGURE 3. THE DIFFERENT MAGNET GEOMETRIES .................................................................................................. 7
TABLE 3. DECISION MATRIX FOR DETERMINING MAGNET GEOMETRY ................................................................. 8
FIGURE 4. ORION CAPSULE, FIGURE AND DIMENSIONS .......................................................................................... 8
FIGURE 5. SCALE MODEL MAGNET GEOMETRY ........................................................................................................ 9
FIGURE 6. SYSTEM CONFIGURATION: SOLENOID-TYPE MAGNETS SURROUNDING THE SPACECRAFT .................. 9
TABLE 4. PARAMETERS FOR SCALE MODEL SIMULATION ....................................................................................... 11
TABLE 5. PARAMETERS FOR FULL-SCALE SYSTEM SIMULATION ............................................................................... 12
FIGURE 7. SCALE MODEL MAGNETIC FIELD, ISOMETRIC VIEW ............................................................................... 13
FIGURE 8. 0.932 keV PARTICLE TRAJECTORIES, ISOMETRIC AND TOP VIEWS FOR SCALE MODEL ..................... 14
FIGURE 9. 27.7 keV PARTICLE TRAJECTORIES, ISOMETRIC AND TOP VIEWS ....................................................... 14
FIGURE 10. SCALE MAGNETIC FIELD, TOP AND SIDE VIEWS .................................................................................. 14
FIGURE 11. FULL-SIZE MAGNETIC FIELD, TOP AND SIDE VIEWS ........................................................................ 15
FIGURE 12. FULL-SIZE MAGNETIC FIELD, ISOMETRIC VIEW .................................................................................. 15
FIGURE 13. PARTICLE TRAJECTORIES, 27.7 MeV PARTICLES, FULL-SIZE MAGNETIC FIELD ..................................... 16
FIGURE 14. PARTICLE TRAJECTORIES, 300 MeV PARTICLES, FULL-SIZE MAGNETIC FIELD ...................................... 16
FIGURE 15. PARTICLE TRAJECTORIES AT VARIOUS ENERGY LEVELS ...................................................................... 17
FIGURE 16. REAL-WORLD SCALE MAGNETIC FIELD, ISOMETRIC VIEW ............................................................... 18
FIGURE 17. REAL-WORLD MAGNETIC FIELD, TOP AND SIDE VIEW .................................................................... 18
FIGURE 18. EXPERIMENTAL SETUP FOR TESTING MAGNETIC FIELD ................................................................. 19
FIGURE 19.REWOUND COIL FOR PARTICLE ACCELERATOR TESTING .................................................................... 19
FIGURE 20. COOLED MAGNET SETUP FOR PARTICLE ACCELERATOR TESTING ..................................................... 20
FIGURE 21. TESTING THE REAL-WORLD MAGNET ................................................................................................. 21
ABSTRACT

To protect astronauts from high-energy radiation during long-duration missions, an electromagnetic radiation shield was designed and sized for the Orion spacecraft with physical dimensions at a 1:100 scale and magnetic fields and particle energies at a $\sim 1:10833.3$ scale. The electromagnetic radiation shield was simulated in the multi-physics software Comsol using the Magnetic Fields and Particle Tracing modules. The scale model used a DC amperage of 60 A with a 9-turn solenoid wound in three layers and the full-size system used a DC amperage of 6500 A and a 5-layer solenoid of 390 turns per layer. These models generated magnetic fields of $0.047 \, \text{T}$ and $5.4 \, \text{T}$, respectively and were exposed to particle energies of 0.932 keV and 27.7 keV for the small scale and 10 MeV and 300 MeV for the full-size. A parametric sweep of the particles’ energy from 10 MeV to 300 MeV was conducted on the full-size model. The results from these simulations indicated that the magnetic fields generated by the magnet were sufficient to deflect incoming particles away from the simulated capsule at low energies, up to 50 MeV, but only provided a reduction at higher energies (above 100 MeV), roughly halving the experienced radiation. A physical model was then built out of yttrium barium copper oxide (YBCO) superconducting tape and tested by using a gaussmeter and particles in WMU’s particle accelerator to validate the magnetic flux density and particle trajectories seen in the Comsol simulations.
INTRODUCTION
Current space missions have length limitations due, in part, to the amount of ambient radiation experienced by astronauts. In order for extended missions, such as those proposed to Mars, to be possible, better shielding methods must be developed in order to provide adequate protection to astronauts and equipment. As much of space radiation is charged ions, they would be deflected by an electric or magnetic field. If such a field were to be generated around a spacecraft, incoming radiation would be redirected away and thus protect astronauts and equipment within the shielded area.

BACKGROUND
Underlying Physical Phenomena
The Earth’s magnetic field protects the Earth from much of the radiation from the Sun by deflecting incoming charged particles towards the poles. The electromagnetic radiation shield operates on the same principle: when charged particles enter a combined electric and magnetic field, they experience a force from the fields with the force given by the Lorentz Force Law:

\[ \mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \]

Here \( q \) is the particle’s charge, \( \mathbf{v} \) is its velocity, and \( \mathbf{E} \) and \( \mathbf{B} \) are the directions of the electric and magnetic fields [1]. The resulting force is perpendicular to both the particle’s initial velocity and the direction of the magnetic field and results in the particle describing a curved trajectory along a plane parallel to the force. Notably, the particle’s velocity parallel to the direction of the magnetic field is unchanged. This is the principle upon which our shielding device is based.

Radiation comes from two major sources: the Sun and distant cosmic sources. While radiation from the Sun is more prevalent, galactic cosmic radiation (GCR), comprising a mix of electromagnetic radiation and particles, is still a significant radiation source due to its high energy—up to \( 10^{19} \text{ eV} \) [2]. Most GCR particles have energies between 0.1-14 GeV, specifically 0.3 GeV; the most energetic solar radiation, by contrast, has an energy content of merely 10 MeV, with the average being much lower [3, 2]. This disparity in energy content means that a shield that can effectively protect against GCR particles will by nature protect against even the most energetic solar events. Consequently, throughout the project, only GCR particles were considered. In either case, the radiation is principally comprised of various ions, from hydrogen to iron and beyond, with the lighter elements comprising a majority and all traveling at relativistic speeds. For GCRs, the approximate species distribution is 87% protons (hydrogen nuclei), 12% alpha particles (helium nuclei), 1% high-energy high-atomic number (HZE) particles, and 3% electrons [2]. The relative abundance of these particles can be seen below in Figure 1 (from Ref. [4]):
What makes GCR particles such an important consideration with regards to radiation shielding is that they possess sufficient energy to react with nuclei when these particles collide with matter. This is especially true of the HZE particles, due to their larger size; when such a particle collides with the nucleus of another atom, protons, neutrons, gamma rays, and pi mesons can result, producing a cascade of radiation that has as much or more of an effect than the single initial particle [5]. This is secondary radiation and is as important a consideration as the primary particles when dealing with radiation shielding.

On the Shielding of Spacecraft
For the Earth, radiation hits the magnetic field and travels to the Earth’s poles or is gradually attenuated by the atmosphere. For spacecraft, lacking a thick atmosphere or strong magnetic field, there are several ways of reducing the exposure of astronauts within the craft to the harmful radiation of space.

In passive shielding, materials are placed between radiation sources and the protected areas so that the physical mass of the materials is sufficient for the incoming radiation to collide with the shielding’s atoms and disperse its energy harmlessly. For greatest effectiveness against low-energy protons and electrons, the materials must necessarily be dense to maximize the collisions between radiation and atoms. To prevent secondary radiation and block higher energy particles, the shielding should be of a material with few nucleons (protons or neutrons) [2]. In both cases, incoming radiation possesses a lot of kinetic energy—a fact which presents a conundrum to spacecraft designers, who must incorporate sufficient shielding to reduce radiation to manageable levels while not creating a craft that is too massive to be launched into orbit. Aluminum is the typical compromise between weight and density, though recent forays have been made into using high-density polyethylene as a shielding material [6].

Active shielding focuses instead on the generation of an electric or magnetic field, possibly including the use of plasma, to repel radiation particles through the Lorentz force. These
systems are called active because they require a constant power source to operate. To date, no such system has flown in space, though they have been theorized since the 1960s. There are three main types: electrostatic, electromagnetic, and plasma [7].

The appeal of active shielding is primarily that it could drastically reduce the mass required for a long-term mission. With passive shielding, the shielding effectiveness is strictly dependent on the mass of the shielding material—to decrease the radiation to which astronauts are exposed requires more shielding mass. For a long-duration mission dealing with high-energy cosmic radiation, the mass required would be prohibitive, especially on a mission that is already mass intensive due to its length. Furthermore, the very act of using nuclei to stop incoming radiation results in secondary radiation from nuclear interactions that can be as or more dangerous than the radiation itself. Active shielding, by contrast, has a single system that could protect against many radiation levels without its mass increasing significantly, merely requiring increasing current to deal with higher radiation levels. Secondary radiation would also be less of an issue, as many of the particles resulting from those nuclear collisions are still charged and would thus also be deflected. For these reasons, active shielding is seen as a technology that could enable manned missions far from Earth’s protective environment.

**PROPOSAL**

**Objective**
The objective of this project is to build and model a method of active radiation shielding to determine its effectiveness at reducing the radiation exposure of astronauts. The goal is to reduce the radiation that traverses the shield that would affect the astronauts to an acceptable level as defined in current National Air and Space Administration (NASA) radiation standards.

In scope, this project will select a type of active radiation shielding and develop an appropriate setup to model a simulated spacecraft subjected to space radiation. Both computer simulation models and physical experiments will be carried out and the results compared to estimate the effectiveness of a full-size, real-life version of the device.

**Design Constraints**
For this radiation shield to be considered a viable alternative to current passive shielding and be used in space, the device must be comparatively light. Large currents will be required to power a magnet sufficiently strong to protect the spacecraft, so superconducting wire must be used to reduce the material needed and avoid resistive heating. However, using superconducting materials brings along with it the need to provide cooling sufficient to lower the conductor to its superconducting temperature, as there are no room-temperature superconductors. Another consideration is that the magnet geometry must be selected such that there is no magnetic
field traversing the occupied areas of the spacecraft, as the field could interfere with equipment and have unforeseen health effects.

**SPECIFICATIONS AND REQUIREMENTS**

The magnet will be designed to protect NASA’s Orion capsule in a configuration for a mission to Mars. The scale model must be designed such that it can be built with the amount of YBCO tape material available. In order for the project to be considered a success, the radiation blocked by the electromagnet must keep the radiation received by the astronauts for a standard trip to Mars under NASA’s safety threshold of 0.005 sieverts per year. NASA’s current guidelines are set to ensure that the radiation experienced by astronauts over their career leads to a less than 3% increase in the risk of death from cancer [8]. These limits are collected in the following tables, seen in Figure 2 (Ref. [9]):

**TABLE 1. ORGAN SPECIFIC EXPOSURE LIMITS**

<table>
<thead>
<tr>
<th>EXPOSURE INTERVAL</th>
<th>DEPTH (5 CM)</th>
<th>EYE (0.3 CM)</th>
<th>SKIN (0.01 CM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 DAYS</td>
<td>25 REM</td>
<td>100 REM</td>
<td>150 REM</td>
</tr>
<tr>
<td>ANNUAL</td>
<td>30 REM</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>CAREER</td>
<td>100 TO 400</td>
<td>400</td>
<td>600</td>
</tr>
</tbody>
</table>

**TABLE 2. CURRENT CAREER EXPOSURE LIMITS BY AGE AND SEX**

<table>
<thead>
<tr>
<th>SEX</th>
<th>AGE</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>35</td>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>MALE</td>
<td>150 REM</td>
<td>250 REM</td>
<td>325 REM</td>
<td>400 REM</td>
</tr>
<tr>
<td>FEMALE</td>
<td>100</td>
<td>175</td>
<td>250</td>
<td>300</td>
</tr>
</tbody>
</table>

* The career depth equivalent dose limit is based upon a maximum 3% lifetime excess risk of cancer mortality. The total equivalent dose yielding this risk depends on sex and age at the start of exposure. The career equivalent dose limit is approximately equal to:

\[
200 + 7.5 (\text{age} - 30) \text{ rem for males up to } 400 \text{ rem maximum}
\]

\[
200 + 7.5 (\text{age} - 38) \text{ rem for females up to } 400 \text{ rem maximum}.
\]

**FIGURE 2. NASA ASTRONAUT RADIATION LIMITS.**
**PROJECT TIMELINE**

Table 1 displays the Gantt chart detailing the timeline for achieving various project checkpoints:

**TABLE 1. GANTT CHART FOR PROJECT CHECKPOINTS**

Electromagnetic Shielding for Spacecraft

<table>
<thead>
<tr>
<th>Period Highlight:</th>
<th>03/29 - 04/12</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>PERIODS</th>
<th>ACTIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/5 - 9/19</td>
<td>Choose Topic</td>
</tr>
<tr>
<td>9/20 - 9/26</td>
<td>Find Faculty Advisor</td>
</tr>
<tr>
<td>10/5 - 10/29</td>
<td>Background Research</td>
</tr>
<tr>
<td>10/20 - 11/03</td>
<td>Preliminary Calculations</td>
</tr>
<tr>
<td>11/04 - 11/28</td>
<td>Select Magnet Geometry</td>
</tr>
<tr>
<td>11/29 - 12/13</td>
<td>Purchase Materials</td>
</tr>
<tr>
<td>12/20 - 12/28</td>
<td>Design Experiments</td>
</tr>
<tr>
<td>12/29 - 01/12</td>
<td>Computer Simulations</td>
</tr>
<tr>
<td>01/03 - 01/27</td>
<td>Build Model</td>
</tr>
<tr>
<td>01/13 - 01/27</td>
<td>Data Collection</td>
</tr>
<tr>
<td>02/12 - 02/26</td>
<td>Write Report</td>
</tr>
<tr>
<td>02/27 - 03/13</td>
<td></td>
</tr>
<tr>
<td>03/14 - 03/28</td>
<td></td>
</tr>
<tr>
<td>03/29 - 04/12</td>
<td></td>
</tr>
</tbody>
</table>
MAGNET DESIGN
ALTERNATE SOLUTIONS

There are several types of active shielding, but only one will be analyzed in this project. As stated previously, there are three prevalent methods: electromagnetic, electrostatic, and plasma shielding. Table 2 shows the decision matrix used to determine which one of these three systems was to be studied:

TABLE 2. DECISION MATRIX TO DETERMINE TYPE OF ACTIVE SHIELDING.

<table>
<thead>
<tr>
<th></th>
<th>Manufacturability</th>
<th>Shielding Effectiveness</th>
<th>Presence in Literature</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Plasma Shield</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>7</td>
</tr>
</tbody>
</table>

Combined with its low presence in literature, the manufacturing of a plasma shield would require expensive equipment, would be dangerous due to its high temperature, and would involve unproven physics regarding the enlargement of a magnetic field within a plasma [7]. Electrostatic shields are more practical; however, they require dangerously high voltage to produce a shield strong enough to deflect particles. When compared to each other, the most practical shielding method to use for this project was an electromagnetic system due to its ease of manufacturing, relatively low cost, and higher effectiveness as a shield than the other two methods.

Having chosen to use an electromagnetic field to deflect the radiation, there are several possible electromagnet geometry configurations that could be used. Three main geometries were found in the literature:

- **“Pumpkin” Structure**- this is a design developed by the European Space Radiation Superconducting Shield working along with CERN. It is an unconfined magnetic field and would be able to envelope the spacecraft in a magnetic field without surrounding it in solenoid-type electromagnets [10]. This geometry has the advantage of producing a field outside of the confining material, meaning the generation of secondary particles is significantly reduced; however, it is a complicated design and would require more superconducting tape to construct compared to other designs.

- **Counter-wound Spool**- like the pumpkin structure, this is an unconfined magnetic field. The counter-wound spools of superconducting wire are angled to produce a magnetic dipole that would surround the spacecraft [11]. Like the pumpkin structure, this geometry greatly diminishes the generation of secondary particles. Though it uses less
tape than the pumpkin structure, the two integral coils increase its complexity compared to the solenoid-type and require a greater current to generate a similar strength magnetic field as the angled spools cancel out a portion of said field.

- **Solenoid-Type** - this is the type that has the most representation in the literature. The magnetic field at the interior of a solenoid is many times stronger than the magnetic field outside the solenoid; as such, this concept depends on surrounding the spacecraft with solenoids to ensure that a particle must pass through a solenoid to be deflected. This is a *confined magnetic field* (as it is enclosed within a body) (Refs. [5], [7], [12]). As with the counter-wound design, several coils must be used. The largest drawback to this design is that the incident particles must necessarily penetrate the magnet’s composing material in order to encounter the magnetic field, resulting in secondary particle emission and an increase in the radiation that must be blocked.

Visuals of the three designs considered can be seen in Figure 3 below:

![Pumpkin Structure](image1)

![Counter-wound](image2)

![Solenoid-type](image3)

**FIGURE 3. THE DIFFERENT MAGNET GEOMETRIES.**

Again, a decision matrix (Table 3) was used to select among these designs:
TABLE 3. DECISION MATRIX FOR DETERMINING MAGNET GEOMETRY.

<table>
<thead>
<tr>
<th></th>
<th>Manufacturability</th>
<th>Shielding Effectiveness</th>
<th>Ease of Simulation</th>
<th>Presence in Literature</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumpkin</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Counter-wound</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>Solenoid</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>18</td>
</tr>
</tbody>
</table>

Based on this matrix, the solenoid geometry was chosen for this project for the following reasons: firstly, more information was available for the solenoid magnet geometry than the other designs; and secondly, the solenoid design is much simpler to wind, so a higher quality magnet can be produced. While the pumpkin and counter-wound geometries produce a better shield that gives off little secondary radiation, the solenoid is still an effective radiation shield and is much easier to manufacture.

**Final Geometry**

The final geometry of the solenoid was determined from the superconductor geometry and the geometry of the Orion command module (Figure 4), with the magnet coils running the length of the combined crew and service modules.
The height of the magnet was set to the height of Orion—5 m—at 1:100 scale and the number of turns was the height of the coil divided by the width of the YBCO tape. For the shield to be effective, the diameter of the coil must be sufficiently large so that the radiation particles avoid contact with Orion: in a full-scale design, a 3 m magnet diameter has been often cited in the literature [12], [13]. Using a 1:100 scale, this means that the model magnet will have a diameter of 3 cm and a height of 5 cm. This scale model of the solenoid magnet, shown in Figure 5, was modelled as a single unit, with no capsule to protect (the shape on the left is the surface from which the particles were emitted):

![Figure 5. Scale Model Magnet Geometry.](image)

For the full-size model, the capsule was surrounded by six solenoid cylinders, each 3 m in diameter and 5 m tall. This geometry can be seen in Figure 6:

![Figure 6. System Configuration: Solenoid-Type Magnets Surrounding the Spacecraft.](image)
SIMULATION

Two sizes of simulations were created: one of the scale model magnet and the other of the full-size system. The full-size system included an aluminum cylinder to represent the Orion capsule nestled between six surrounding solenoids. In both cases, a stationary (time-independent) study was performed to determine the magnetic field generated by the coils and then a time-dependent study was performed over 1 µs (1 × 10^{-6}s) to track the particles’ trajectories through the magnets and the magnetic fields.

In both simulations, the magnet material was simulated as copper instead of YBCO tape. This is an acceptable substitution, as the magnetic field is dependent only upon the magnet’s geometry and the current passed through the tape; as heating effects are ignored in this simulation, there is no breakdown in the material. Furthermore, the electric field generated by the tape is not of interest and so no accounting need be done for non-linearities peculiar to superconductors. To simulate the vacuum conditions of space and the superconducting tape cooled to below its critical temperature, the Physics modules in Comsol were evaluated at 77K and 1e-12 Pa.

The number of turns for each magnet was determined by dividing the height of the solenoid, 5 cm, by the width of the superconducting tape, 12.8 mm [14], and rounding down to the closest integer.

Given current and practical material properties and power generation, a full-size magnet is expected to have a magnetic field of approximately 5T and a diameter of 3m, as described previously ([13], [15]). This field strength and diameter result in a bending power of 15 Tesla-meters (Tm), whereas the scale model has a bending power of 0.00141 Tm. Bending power is the product of magnetic field strength and field length (in this case, the solenoid’s diameter). Between the full-size and scale models, this is a ∼1:10833.3 scale. The radiation to which the scale model was exposed was scaled down using this scale: the peak energy of GCRs is 300 MeV; therefore, the ions shot at the scale model magnet had an energy of 27.7 keV.

The particles in the simulation were modelled as Co^{2+}, as these would be easily generated in WMU’s particle accelerator and are similar in weight to iron. Iron is the most common heavy particle found in the GCR and is important because its large mass produces many secondary particles when its ions collide with matter. However, cobalt is easier to ionize in the particle accelerator at WMU and is only slightly heavier than iron; hence, cobalt was used in the simulations.

The kinetic energy was simulated at two energy levels: 300 MeV to represent the peak of GCR and 10 MeV to represent the most energetic solar radiation; for the scale model, the energy levels were 27.7 keV and 0.92 keV, respectively. The ions’ velocity was calculated from the particles’ kinetic energy:
\[ E_k = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}} - mc^2 \Rightarrow v = \sqrt{c^2 \left(1 - \frac{mc^2}{E_k + mc^2}\right)^2} \]

where \( E_k \) is the kinetic energy of the particles, \( m \) is their mass, \( v \) their velocity, and \( c \) is the speed of light.

One additional simulation was conducted: the scale model dimensions with 5 loops of wire, 5 A of current, and ambient atmospheric conditions. These limited dimensions were used due to receiving less material than expected and time constraints preventing the acquisition of liquid nitrogen with which to cool the magnet.

**PARAMETERS**

*Scale Model*

The following parameters, shown in Table 4, define the scale model so it could be simulated in Comsol. 60 A was chosen as the current because that is the largest current supply to which access could be procured. Three layers were used to approach 10 total loops; this was the maximum number of loops that could be constructed using the sample superconducting tape from American Superconductors, Inc.

**TABLE 4. PARAMETERS FOR SCALE MODEL SIMULATION.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ipeak</td>
<td>60[A]</td>
<td>60 A</td>
<td>Peak Current</td>
</tr>
<tr>
<td>Nturns</td>
<td>floor(Hcoil/12.8e-3[m])</td>
<td>3</td>
<td>Number of Turns per Layer</td>
</tr>
<tr>
<td>Twire</td>
<td>0.2[mm]</td>
<td>2E-4 m</td>
<td>Thickness of the Tape</td>
</tr>
<tr>
<td>Rint</td>
<td>1.5[cm]</td>
<td>0.015 m</td>
<td>Inner Radius of Magnet</td>
</tr>
<tr>
<td>Rext</td>
<td>Rint + Twire</td>
<td>0.0152 m</td>
<td>Outer Radius of Magnet</td>
</tr>
<tr>
<td>Hcoil</td>
<td>5[cm]</td>
<td>0.05 m</td>
<td>Height of Magnet</td>
</tr>
<tr>
<td>E0</td>
<td>27.7[keV]</td>
<td>4.438E-15 J</td>
<td>Initial Particle Kinetic Energy</td>
</tr>
<tr>
<td>mass</td>
<td>0.053893[g]/6.02e23</td>
<td>9.789E-29 kg</td>
<td>Mass of Particle</td>
</tr>
</tbody>
</table>
\[ V_0 = \sqrt{c_{\text{const}}^2 \left(1 - \left(\frac{\text{mass} \cdot c_{\text{const}}^2}{E_0 + \text{mass} \cdot c_{\text{const}}^2}\right)^2\right)} \]

9.5187E6 m/s

Initial Ion Velocity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ipeak</td>
<td>6500[A]</td>
<td>6500 A</td>
<td>Peak Current</td>
</tr>
<tr>
<td>Nturns</td>
<td>(\text{floor}(H_{\text{coil}}/12.8e-3[m]))</td>
<td>390</td>
<td>Number of Turns</td>
</tr>
<tr>
<td>Twire</td>
<td>0.2[mm]*100</td>
<td>.02 m</td>
<td>Thickness of the Tape</td>
</tr>
<tr>
<td>Rint</td>
<td>1.5[m]</td>
<td>1.5 m</td>
<td>Inner Radius of Magnet</td>
</tr>
<tr>
<td>Rext</td>
<td>(R_{\text{int}} + \text{Twire})</td>
<td>1.52 m</td>
<td>Outer Radius of Magnet</td>
</tr>
<tr>
<td>H_{\text{coil}}</td>
<td>5[m]</td>
<td>5 m</td>
<td>Height of Magnet</td>
</tr>
<tr>
<td>E0</td>
<td>300[MeV]</td>
<td>4.8065E-11 J</td>
<td>Initial Particle Energy</td>
</tr>
<tr>
<td>mass</td>
<td>((0.05893[g]/6.02e23))</td>
<td>9.7892E-26 kg</td>
<td>Mass of Particle</td>
</tr>
<tr>
<td>V0</td>
<td>\sqrt{c_{\text{const}}^2 \left(1 - \left(\frac{\text{mass} \cdot c_{\text{const}}^2}{E_0 + \text{mass} \cdot c_{\text{const}}^2}\right)^2\right)})</td>
<td>3.1209E7 m/s</td>
<td>Initial Ion Velocity</td>
</tr>
<tr>
<td>Nlayers</td>
<td>5</td>
<td>5</td>
<td>Number of Layers</td>
</tr>
</tbody>
</table>

**Full-Size System**

The following parameters, shown in Table 5, define the full-size system so it could be simulated in Comsol. The current magnitude was chosen to generate a magnetic field close to 5 T given the other field-determining parameters (number of loops and layers). 5 layers was chosen because this number of layers would give the coil a stable structure.

**TABLE 5. PARAMETERS FOR FULL-SCALE SYSTEM SIMULATION.**

**Parametric Sweep**

A parametric sweep was conducted with the full-size system to determine the range of energies for which the magnet provides protection. The kinetic energy of the particles was parametrized
and run at values of 10, 25, 50, 100, 150, 200, 250, and 300 MeV. The setup was the same as for the full-size simulation: 6 solenoids made of 5 layers of 390 loops in a cylinder with 6500 A of DC current producing a magnetic field of 5 T.

**Small Scale for Testing**

While the original plan was to build a 3 layer 9 turn coil, the YBCO tape sample received from AMSC was not as long as expected. With the materials that were received, the largest magnet that could be constructed was a 2-layer, 5-turn coil with an aluminum/air core. At the time of testing, the particle accelerator and 60 A current source were unavailable. In their stead, a 5 A current source was used at standard room temperature conditions.

**Simulation Results**

**Scale Model**

Figures 7 and 8 show the resulting magnetic field from a 1-layer, 9-turn/layer solenoid with 60 amps of DC current passing through it. The simulations showed a magnetic flux density of 4.7 mT at the center of the coil.

![FIGURE 7. SCALE MODEL MAGNETIC FIELD, ISOMETRIC VIEW.](image-url)
25 particles were emitted by a cylindrical inlet with a release current intensity of 1 nA on a vector directed towards the centerline of the solenoid using the Particle Tracing module of Comsol. This emitter was chosen for simplicity. Figures 9 and 10 show results of the simulation for particles with initial energies of 0.932 keV and 27.7 keV, respectively.
**Full-Size System**

Figures 11 and 12 are images of the resulting magnetic field from a 5-layer, 390-turn/layer solenoid-type magnet with 6500 amps of DC current passing through it, along with accompanying top and side views. The full-scale magnet simulations show a peak magnetic flux density of 5.4 T at the center of each solenoid.

![Multislice: Magnetic flux density norm (T)](image)

FIGURE 12. FULL-SIZE MAGNETIC FIELD, ISOMETRIC VIEW.

![Multislice: Magnetic flux density norm (T)](image)

FIGURE 11. FULL-SIZE MAGNETIC FIELD, TOP AND SIDE VIEWS.

25 particles entered through a quarter-circle inlet with a release current intensity of 1 nA. The quarter circle inlet was chosen to provide a range of particle entry vectors into the magnets, more closely matching real-world conditions. This simulation was performed with Comsol’s
Particle Tracing module, and the results are shown in Figure 13 for 10 MeV particles and in Figure 14 for 300 MeV particles.

**FIGURE 13. PARTICLE TRAJECTORIES, 27.7 MEV PARTICLES, FULL-SIZE MAGNETIC FIELD.**

**FIGURE 14. PARTICLE TRAJECTORIES, 300 MEV PARTICLES, FULL-SIZE MAGNETIC FIELD.**

*Parametric Sweep*

Figure 15 shows the results of the parametric sweep of incident particle energies. As may be seen, the trajectories for the 10 MeV and 300 MeV are the same as those presented previously.
FIGURE 15. PARTICLE TRAJECTORIES AT VARIOUS ENERGY LEVELS.
Small Scale for Testing

Figures 16 and 17 show the resultant magnetic field from this test peaks at a magnetic flux density of 1.166 mT. This model has a bending power of $3.498 \times 10^{-5}$ Tm.

EXPERIMENTATION

PROCEDURE

As mentioned in the Small Scale for Testing subsection of the Parameters section, the YBCO tape sample received from AMSC was not as long as expected and so the original scale model
could not be constructed. Instead, 2-layer, 5-turn coil was built with the material available, with an aluminum/air core (the aluminum was used to keep the coil in a wound configuration. The current source used was 5 A at standard room temperature conditions. The magnetic flux density was measured with an axial magnetic probe connected to gaussmeter; the probe was moved around the interior of the magnet to measure the field at various points to determine the highest magnitude. The tape, spool, and assembled magnet are shown in Figure 18.

For the testing in the particle accelerator, the coil was rewound. Electrical tape was used to insulate the spool and the coils from each other to ensure the coil length was correct and no short circuits were present. This rewound coil is seen in Figure 19 below:
This magnet was then connected to a current source providing up to 30 A and brought close to a stainless steel pipe containing a particle beam composed of protons in the accelerator. Due to time and logistics constraints, a setup allowing the placement of the magnet within the pipe was not able to be devised and so the magnet remained on the exterior of the pipe. The effect of the magnet was seen in a change in the beam intensity as measured by a 1-in Faraday cup placed further down the course of the particle accelerator. This was done with the magnet cooled by liquid nitrogen to ~70 K (see Figure 20).

**RESULTS**

With 5 A of current, this 5-turn magnet produced a magnetic field with an intensity of 6.44 gauss (0.644 mT). Figure 21 (on the next page) shows the experimental setup.

Comparing these experimental values with those obtained from simulation, the real-world magnetic field was about half of the magnitude of that seen in simulation. This discrepancy in magnetic flux density prompted us to deconstruct the magnet to determine what could be the cause. It was found that a few of the coils were in contact with each other as well as with the aluminum spool, and as these components are themselves conductive, this resulted in a shorter
coil length and consequently a weaker magnetic field. The bending power of this real-world setup is $1.932 \times 10^{-5} \, Tm$.

From the particle accelerator testing, even though the particles were affected only by the weak magnetic field found outside of the magnet, the beam was deflected enough for the Faraday cup to register a decrease in the beam’s intensity. Unimpeded by any magnetic field, the beam had an intensity of $-115.55 \, mA$; upon the magnetic field deflecting the particles, the beam intensity decreased to $-116.23 \, mA$. This decrease in the beam’s intensity means that the magnetic field altered the trajectory of the particles by an angle such that the particles were not captured by the Faraday cup. This effect was stronger when liquid nitrogen was used to cool the coil.

**ANALYSIS**

As stated in the Simulation section, cobalt was the particle used in the simulations. Though not the only particle found in space radiation and not the most prevalent, these results are applicable to the other particles composing space radiation because cobalt is a heavy element and so lighter particles will be more affected by the magnetic fields.

In all cases, impinging radiative particles were deflected by the magnetic field generated by the solenoids, demonstrating that a magnetic field can in theory protect a spaceship from space radiation. For the scale model, the magnetic field did deflect particle trajectories: the $27.7 \, keV$ particles were deflected by an angle of $24^\circ$ from the line of origin, while the $0.923 \, keV$ particles were deflected at angles ranging from $85^\circ$ to $180^\circ$. However, only the $0.923 \, keV$ particles did
not fully penetrate the magnet. For the full-size system, no particles followed a straight path: the 10 MeV particles did not reach the spacecraft and the 300 MeV particles were deflected in curved paths. This deflecting effect persisted even when the weak magnetic field outside of the magnet was used, as seen in the test results from the particle accelerator testing.

However, the results are not an unquestionable success: the more energetic 27.7 keV and 300 MeV particles were able to penetrate the shielding magnets and reach the interior of the spacecraft. Despite the magnetic fields reaching 5 mT and 5.4 T respectively, the particles were not deflected enough to stop them from penetrating the spacecraft. In some cases, the angle and location of entry combined with the Lorentz force of the magnetic field pushed the particle out of the field and into the spacecraft.

For the tests of the magnet, the peak strength of the electromagnet was approximately half of what the simulations predicted. This could be due to several factors. The likely main factor was winding errors with the tape. While the magnet in the simulations was modeled as perfect, the actual scale model required gaps between the individual coils and the layers. These layers were necessary in order to prevent the shorting of the coils, but these gaps cause a larger magnet height and a larger outer diameter causing a reduction in peak magnetic flux density. Another possible cause for error is the coils shifting during testing. If coils were to shift and touch one another or the inner aluminum spool, it would cause them to short and reduce the number of coils causing a weaker magnet.

In the case of the full-size system, this penetration was due in part to particles entering the coils at oblique angles, on the edges of the field, or between coils. These are weak points in the magnetic shielding; oblique entries pass through less of the field and encounter a weaker magnetic field, and entries between coils see little or no field. Adding a second ring of solenoids around the first ring would help address this issue by reducing the number of these weak points at the cost of requiring more power and superconducting tape.

According to the data from the parametric study, the shield can effectively stop up to 50 MeV particles. While cosmic radiation can reach up to 300 MeV and beyond, the majority of particles encountered are below this threshold. These results show that, for the majority of space radiation, the solenoid is an effective shield for primary radiation.

It is important to note that this shield is effective only against charged particles; high-energy photons such as x-rays or gamma rays are unaffected as they have no charge and would have to be stopped through more conventional means (solid, passive shielding).

In addition to the incident particles that traverse the magnetic fields, the problem of secondary particles remains. Unfortunately, this feature of the Comsol Particle Tracing module was not able to be implemented in the model; however, based on the inability of the magnetic fields to deflect the primary particles, it is doubtful that the fields would be able to prevent secondary
particles from reaching the interior of the shielded volume, despite these particles’ much lower energy. Given that secondary particles are almost as dangerous biologically as primary particles due to their heavier masses, this is a severe failing of a radiation protection system.

Besides particles reaching the spacecraft at the interior of a supposedly shielded volume, this model has several other issues. In both the scale model and full-size simulations, the magnetic field is not completely contained within the solenoid structure: a weak magnetic field permeates the entire surrounding area, particularly in the full-size case, and is still sufficiently strong as to affect particle trajectories. This magnetic field, though much weaker than the field within the solenoids, could affect electronic equipment with the spacecraft, particularly sensitive scientific instruments.

One other consideration that was not fully within the scope of this project is the logistical factors involved in the construction of a system such as the one investigated. Each of the six solenoids surrounding the spacecraft is wrapped in five layers of 390 turns, giving an overall length of 1862.34 meters of tape per coil. The density of the wire is 0.217 kg per meter, which results in an overall mass of 2424.8 kg for the tape. A high estimate for the cost of the tape is 1040.00 $/m. This means that the entire system has a cost of $11,621,001.60, just for the superconducting tape for all of the coils.

Other considerations are the mechanical supports required to support a system of this mass and the cooling system necessary to maintain the superconducting tape below its critical temperature. Cooling, in particular, would be a non-trivial issue: when conducting the testing in the particle accelerator with a cooled magnet, the device quickly returned to room temperature when not submerged in the liquid nitrogen—a problem which would be present in space even without the presence of an atmosphere to convect heat. While these factors were not included in the overall analysis of the shield, if a full-sized system were to be built, these would also account for a significant portion of the budget.

**CONCLUSION**

Despite failings discussed in the Analysis section, the magnetic fields do provide sufficient shielding against solar radiation, even the most energetic of these particles such as those during a coronal mass ejection or solar proton event. While not all high-energy radiation will be stopped by the shield, the shield is effective in stopping the most common radiation in space. The caveat to this statement is that secondary radiation was not accounted for; even though the magnet is able to protect from the majority of primary radiation in space, the secondary radiation produced by particles passing through the magnet could be more dangerous than even the primary radiation. However, at the more common lower energy levels, secondary radiation is not being generated because the particles do not penetrate the magnets.
Superconducting electromagnetic radiation shields can effectively alter the trajectories of charged particles to avoid a specified shielded volume. For lower-energy particles up to about 50 MeV, such as those emitted by the Sun and the more common GCR particles, a single layer of magnets with a bending strength of 5 T is sufficient to block almost all primary particles from reaching the spacecraft. Above energies of 100 MeV, the more dangerous heavy particles can penetrate the magnetic shield, producing secondary radiation along the way. Stronger magnets or more magnets could be used to increase the energy cutoff for effective shielding and if unconfined magnetic fields were used, secondary radiation becomes a non-issue.

**SUGGESTIONS FOR FURTHER RESEARCH**

The results from this study show that, while not perfect, an electromagnetic radiation shield is a promising method of radiation protection to replace current methods as long as the issues associated with secondary radiation can be addressed. Because of its potential for biological damage, now that the basic principle has been validated, more attention needs to be placed on secondary radiation created by the irradiation of the electromagnet. In this respect, the suggestion of this project is to focus research on designs that produce unconfined magnetic fields such as the pumpkin design.

If further research is done on this project, the feasibility of the electromagnet system as a whole must also be evaluated. For a system that has as one of its main selling points a decrease in weight, a calculation must be carried out to determine if this active shielding system—that is, magnet, cooling system, power supply, and mechanical supports—is actually lighter than an amount of aluminum able to provide equivalent shielding. As was mentioned in the Analysis section, cost could also be a factor to investigate. Though the largest NASA missions may cost upwards of a billion dollars [16], $11 million dollars for radiation protection is still a significant amount that could influence the viability of this system.
REFERENCES


