SANDIA REPORT
SAND2019-15248
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Magnetic Shielding with Soft Magnetic Alloys

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ABSTRACT

Abnormal electrical environments receive a lot of attention from nuclear safety engineers, but less attention has been paid to the magnetic effects that accompany such environments. Engineers with backgrounds outside of physics or electrical engineering may not be as familiar with this topic; this report serves as a brief summary of the phenomena and proposes experiments to support practical engineering solutions. Lightning strikes, in particular, create an environment hazardous to electronics, especially to components that rely on magnetic coupling for normal function. The most direct method of mitigating unwanted magnetic effects caused by lightning is to shield the component of interest; several materials and configuration options are explained here. An experimental approach is recommended to validate numerical modeling.

ACKNOWLEDGEMENTS

Kim Merewether, Ashish Jindal, Ian Sturdevant, and Jeff Dohner, for explanations of EMI and technical review

Ephraim Arquitola, for guidance and feedback during the project

Katie Mabey, for technical guidance regarding proprietary systems

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ABS	Acrylonitrile Butadiene Styrene

1. THEORY AND PRACTICAL CONCERNS

1.1. Introduction

Lightning strikes pose a significant hazard to electronics, particularly within aircraft. This report characterizes the effects of lightning on magnetic circuit elements and the mechanisms by which these effects occur and offers information on mitigation efforts that might be undertaken through magnetic shielding.

This report presents a brief summary of the concepts behind magnetic induction and the characteristics of lightning strikes followed by an overview of magnetic shielding best practices. Several options for shielding a space or individual component are presented, as well as information regarding simulations for magnetic effects. Finally, a series of experiments is proposed to measure the shielding effectiveness of two materials, and to determine to what extent a particular magnetic shield configuration can reduce magnetic coupling in a transformer.

1.2. Electricity and Magnetic Fields

Electricity and magnetism are inextricably linked; the following is a brief overview of the mathematical relationships between the two that will be used to inform subsequent sections.

1.2.1. Magnetic Fields and Current

Current moving through a conductor generates a magnetic field around the conductor (Figure 1-1).

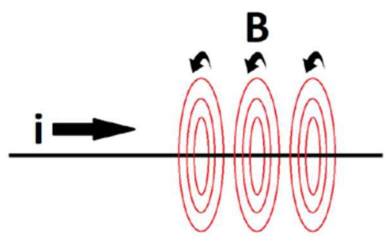

Figure 1-1. Magnetic field induced by current

The magnitude of the magnetic field is described by the following equation:

$$\left[\boldsymbol{B} = \frac{\mu_0 i}{2\pi r}\right] \qquad \text{Equation 1}$$

where: μ_0 = permeability of free space ($4\pi \times 10^{-7}$ H/m)
i = current through the conductor

r = radial distance from the conductor

From this equation it is clear that: $B \propto i$

$$B \propto \frac{1}{r}$$

B is in Teslas; 1 Tesla = 10,000 Gauss

1.2.2. *Magnetic Induction*

Current moving through a conductor generates a magnetic field as shown above, and the reverse is also true; a magnetic field moving through or changing magnitude in an area enclosed by a conductor loop will generate a current through the conductor.

A magnetic field may be imagined at any given point as a series of parallel lines radiating from a current source. The amount of magnetic field lines passing through a given area is equal to the dot product of the magnetic field vector and the differential area- a quantity known as the magnetic flux, denoted here as φ_B. In other words, the magnetic flux is the amount of magnetic field passing through the projection of an area onto a plane orthogonal to the incident magnetic field lines.

Mathematically:

$$[\boldsymbol{\varphi_B} = \int \boldsymbol{B} \bullet \boldsymbol{da}] \qquad \text{Equation 2}$$

from which it is clear that the orientation of the current channel generating a magnetic field with respect to the area in question is considerably important (Figure 1-2).

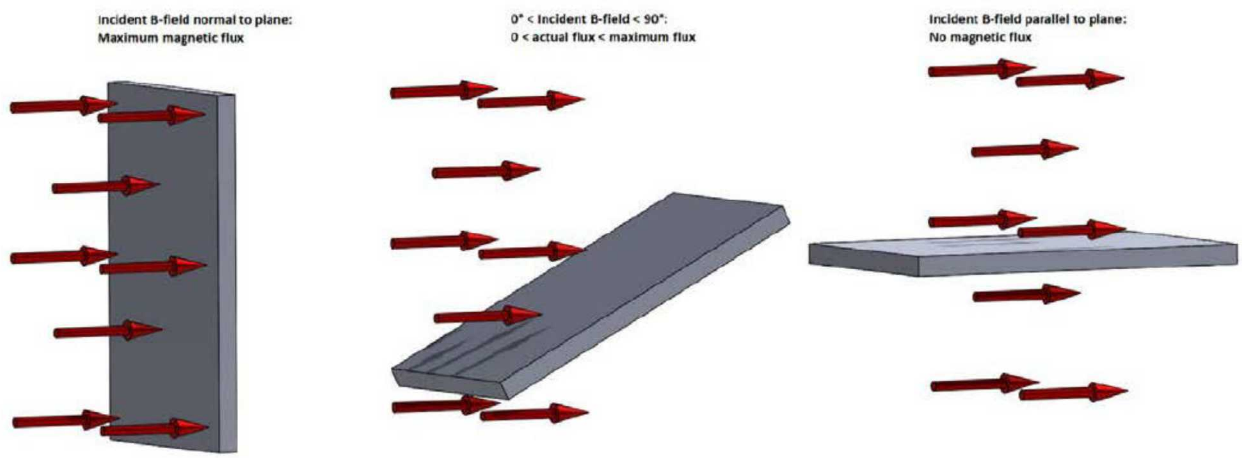

Figure 1-2 Magnetic flux through a plane

If the area of interest is known, the magnetic flux φ_B can be expressed as:

$$[\boldsymbol{\varphi_B} = \boldsymbol{BAcos\theta}] \qquad \text{Equation 3}$$

where: A = area of interest

θ = angle between normal vector and incident magnetic field

A voltage will be induced in a conductor loop if the area enclosed by the loop is present in a *changing* magnetic field–that is, if the magnitude changes or the magnetic field moves relative to the loop–a relationship described by the following:

$$[\boldsymbol{V} = \boldsymbol{\varphi_B}\, \boldsymbol{dt}] \;\therefore\; \left[\boldsymbol{V} = \int_0^{dt} \boldsymbol{B} \bullet \boldsymbol{ds}\right] \qquad \text{Equation 4}$$

1.2.3. *Lightning and Skin Depth*

The *skin depth* of a current channel, which is a measure of how far into the surface of a material current will flow, is defined as follows:

$$\left[\delta = \sqrt{\frac{\rho}{\omega\mu}}\right] \therefore \left[\delta = \sqrt{\frac{\rho}{\pi f \mu}}\right] \qquad \text{Equation 5}$$

where: μ = relative magnetic permeability of the conductor

ϱ = resistivity of conductor material

This is important when considering higher-frequency signals, which is treated further below.

1.3. Lightning Strikes

Lightning is a broad-frequency, high-current pulse of electricity. The electromagnetic frequency range of lightning is about 1 Hz to 300 MHz, with a peak in the area between 5 kHz - 10 kHz, and the current can be as high as 200 kA. This generates an extremely strong, changing magnetic field, which could induce a magnetomotive force (voltage) in electrical components and cause unwanted events to occur in critical circuitry.

Aircraft fuselages are constructed from aluminum, which has a high electrical conductivity that almost guarantees a lightning current channel will run along the surface of the fuselage and not penetrate through the aircraft's skin [**Equation 5**]. Industry is researching composite materials as a replacement for aluminum structural components like the fuselage, but the composites developed so far offer no such protection. Lightning normally attaches to an aircraft near the nose, passes along the fuselage in a narrow channel, and discharges out the aft end, and any electronics located close to the skin could be affected. If current were to penetrate through a composite fuselage, the high current itself would become a significant threat in addition to magnetic effects, and provisions would have to be made to shield electrical components within the aircraft so that a penetrating current channel would behave in the same way as if it struck an aluminum fuselage- for example, a streamlined aluminum capsule within the aircraft that contains critical circuitry. The typical forward-to-aft current channel is very similar to the situation illustrated in Figure 1, which will thus be used as the model for a lightning strike in this report.

Although lightning has a broad range of constituent frequencies, most of the higher frequencies are attenuated in the aluminum surface of an aircraft via eddy currents [**Equation 5**] like radio-frequency signals, while the lower frequencies penetrate deeper and pose a greater risk of magnetic coupling. Lightning is also a very short-duration event; the threat can therefore be simplified for modeling and experiment by treating it as a single cycle of a large-amplitude direct current square wave with a rapid rise time.

1.3.1. Mitigation Options

There are several parameters that affect the amount of voltage a magnetic field may induce in a circuit, per the previous expressions. Referring to **[Equation 1**], the distance between a current source and electronics should be maximized to reduce magnetic flux density; the magnetic field strength drops as the square of the distance from the current channel. Depending on the size, location, and configuration of a component or system, physical constraints could severely limit the extent to which this principle may be exploited.

Reducing the area through which magnetic fields may travel is another method of reducing magnetic coupling, and could be accomplished in two ways:

1. Orienting all circuit loops such that they are parallel to the incoming magnetic field
2. Minimizing the cross-sectional area of circuit loops

Option 1 is not a practicable means of mitigation, as it is not possible to plan for the orientation of a current channel due to a lightning strike; however, the orientation of magnetic circuit devices could be adjusted to minimize coupling based on the most likely configuration of the current channel-forward to aft in an aircraft.

Option 2 is already a standard practice in circuit design when it comes to the placement of traces on a circuit board; a loop on a printed circuit board functions as an antenna, and circuit designers must ensure that individual conductor loops do not interfere with one another (crosstalk) or have enough area for considerable current to be induced. However, of greater concern are magnetic circuit components like inductors or solenoids, as the function of these components relies on magnetic induction; the extent to which the loop area can be minimized while retaining component function is limited.

In short, it is inevitable that magnetic fields of some magnitude will be present within an aircraft during a lightning strike. Because the exact orientation of circuit components relative to these magnetic fields is unknowable, and certain components rely on magnetic coupling for their normal function, the most effective option to mitigate the effects of unwanted magnetic coupling is the use of a magnetic shield tailored specifically for this purpose.

1.3.2. Magnetic "Shielding"

In the interests of both brevity and clarity, a mathematical representation of magnetic shielding will be eschewed here in favor of a graphical explanation. Magnetic shielding expressions comprise several layers of mathematical operations–rigorous treatments fill entire chapters or books and draw upon dozens of concepts from physics, an effort that will not be repeated here–but some simple guidelines may be derived from them. Furthermore, magnetic shield design benefits from decades of industry experience that support these guidelines, and a reputable vendor could assist with shield design given a few parameters. A brief summary of magnetic shielding principles follows, as well as a list of best practices when designing a magnetic shield. For a more detailed explanation, the reader is encouraged to consult Rikitake and Celozzi [1], [2]. Magnetic shields do not actually *block* magnetic fields–nothing will stop the field lines from completing a loop – but rather provide a "path of least resistance" through which the fields can travel. The material property that quantifies this tendency is a material's relative permeability (μ), which is a ratio of a material's permeability relative to the permeability of free space (μ0). The higher this ratio, the more a magnetic field will be diverted through the material of a magnetic shield. This effect can be likened to electrical conductivity; as more current will flow through a material with higher conductivity than one with lower conductivity, more magnetic field will flow through an area with higher permittivity. In a cylindrical ferromagnetic shield with high relative permeability, the lines of flux are drawn into the material almost perpendicular to the shield surface and then shunted along the shield almost parallel to the surface, as shown in Figure 1-3. Some magnetic field penetrates, but the flux is lower than outside the shield.

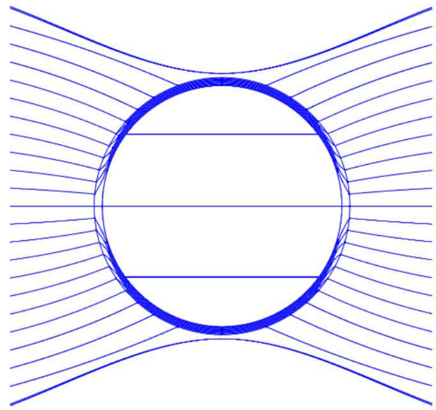

Figure 1-3: Magnetic field distribution for cylindrical ferromagnetic shield in a uniform field

Saturation induction is a measure of how much flux a material can shunt along its surface in this way; once a material is magnetically saturated, it cannot shunt any more flux, and any flux above the saturation point of the material will simply pass through. The relationship between the magnetic field strength and the flux through a material is described by the material's B-H curve. High-saturation materials are good for shielding strong magnetic fields, but generally have lower permeability, while high-permeability materials generally have a lower saturation point. High-saturation materials are best used as the outer layer in a multi-layer shield design; the outer shield drastically reduces the magnitude of the magnetic field by attenuation, and the inner, high-permeability shield(s) can effectively shunt what penetrates through the outer shield. At the edges of a planar shield or the ends of a cylindrical shield, unpredictable "edge effects" occur; this is similar to what would happen at these points if the shield were stationary in a moving fluid. Accordingly, a shield should extend beyond the component of interest to such a degree that edge effects are inconsequential. A quick heuristic for cylindrical shields is that the shield should extend beyond the shielded component a distance equal to the shield diameter on either side.

There are several factors that influence the effectiveness of a shield in decreasing magnetic flux:

- Material (intrinsic properties such as μ and σ)
- Shape
- Wall thickness, layers, and spacing

1.3.3. Materials

Several materials are commonly used for magnetic shielding. For high frequency shielding, materials with high electrical conductivity (σ) such as aluminum or copper are appropriate, as eddy currents induced by the oscillations effectively cancel one another out. For lower-frequency signals and transient events like lightning, iron-nickel or iron-cobalt alloys are the most common.

Among iron-nickel alloys, a higher percentage of iron corresponds to a higher saturation point and lower permeability at a given field strength compared to an alloy with lower iron content; 99.99% Fe is available and offers good shielding characteristics at high field strengths due to its high saturation point. On the opposite end of this spectrum, permalloy, MuMetal® HyMu 80®, and other alloys referred to colloquially as "mu-metals" are usually about 80% nickel, 20% iron with small amounts of molybdenum and traces of other elements; they offer higher permeability at a given field strength vs. high-purity iron, but with a correspondingly low saturation point.

Iron-Cobalt alloys such as Hiperco® 50 offer even higher saturation points than high-purity iron (about 10% greater), as well as higher initial and maximum permeability–but these benefits come at a significantly higher cost; Hiperco® 50 is 48.75% cobalt, 1.9% vanadium, and 0.05% niobium, all of which are rare and expensive elements. Hiperco® alloys are most commonly used in motors and generators that require a high field strength-to-weight ratio (airplane auxiliary generators and motors), but their relatively high permeability at high field strengths could make them a good candidate for shielding material where spatial considerations preclude multi-layer shields.

1.3.3.1. Shape

For an in-depth explanation of how shield geometry affects shielding effectiveness, see T. Rikitake, chapter 2[1]. Simply put, a spherical shield is ideal because it almost eliminates edge effects; a cylindrical shield is the next-best option, and rectangular shields with flat shielding surfaces are the least effective. In any event, predicting shield effectiveness for a given configuration requires simulation software designed to solve such a problem, vast computing resources, and a considerable amount of time.

1.3.3.2. Wall Thickness, Layers, Spacing

For oscillating signals, shielding is affected by the cancellation effect of eddy currents. Skin depth is inversely proportional to frequency **[Equation 5**]; in a shield the same thickness as the skin depth of an incident signal (thin for a high-frequency signal), the signal will flow uniformly through the material, making the shield ineffective. However, if the thickness of the shield is much greater than the skin depth of a signal, eddy currents induced in the shield cancel out much of the signal and thereby offer good shielding effectiveness. With low-frequency signals, however, the shielding mechanism is flux shunting. This is the deflection of flux flowing through the material of a shield and is most pronounced on the inner surface of the shield; although a thinner shield will have less mass and therefore reach its saturation point faster, the flux will also be deflected sooner than would be the case with a thick shield. This means that with a given radius, several thin concentric shields are more effective than a single thick shield, especially if space is left between them. For both spherical and cylindrical shields, Rikitake [1] notes a drastic increase in shielding effectiveness by simply using two physically separated thin shields in place of a single thick shield. This approach offers the added benefit of reducing the requisite mass of shielding material, thereby reducing cost and weight.

1.3.3.3. Mechanical Attributes of Magnetic Shielding Materials

High-purity iron is ductile and has a Young's modulus of 211 GPa. It is machinable but requires that certain provisions be taken due to its ductility. Whether it is hardenable and via what methods is unknown, nor is information regarding the corrosion susceptibility of pure iron or its weldability. These would be fertile areas for experimentation–particularly tests examining galvanic corrosion with a range of dissimilar materials, intergranular corrosion after welding, weldability, and hardenability via heat treatment and cold working.

μ-metal is ductile and has a Young's modulus of 217 GPa. It is similar to 300-series stainless steels in several respects: it offers good corrosion resistance due to its high nickel content, and is challenging to machine for the same reason, tending to be "gummy." μ-metal is readily welded with traditional processes. It is hardenable through cold working, but not through heat treatment- and in fact must undergo a specialized annealing process in a dry hydrogen atmosphere to maximize its permeability following any forming or machining process. This latter requirement may make μ-metal undesirable for structural components.

1.3.3.4. Shield Configurations

1.3.3.4.1. Planar Shield

Advantages:

- Small footprint and low height for surface-mount applications
- Easy to manufacture (hydroforming, pressing)
- Pre-made shields available; custom work relatively inexpensive due to manufacturing process

Disadvantages:

- Commercial-off-the-shelf products generally small, thin, limited materials available, shield from only one direction
- Generally offer inferior shielding performance vs. cylindrical, spherical shields

1.3.3.4.2. Cylindrical Shield

Advantages:

- Better performance than planar shield
- Easy to manufacture (deep drawing/pressing/hydroforming)

Disadvantages:

- Larger footprint and height; more wasted space for surface component
- Transverse mounting options for surface-mount components not commercially available
- Novel attachment method required for transverse surface mount application

1.3.3.4.3. Spherical Shield

Advantages:

- Best possible shielding performance; offers same shielding effectiveness from all directions
- Thin shield could be inexpensively custom-made

Disadvantages:

- Manufacture of thicker shields could be expensive, requiring machining
- Novel attachment method required for surface-mount components
- Much more wasted space for surface-mount components

1.3.3.5. Shield Sourcing Options

1.3.3.5.1. Magnetic Shield Corporation

Located in Bensenville, Illinois, Magnetic Shield Corporation offers custom shield design, hydrogen annealing, and a multitude of forming, cutting, welding, and finishing processes. Three materials in multiple thicknesses and pre-formed shapes are available. This company has been in operation for

75 years and provides the most comprehensive range of services available for the manufacture of magnetic shielding solutions. Price quotes are available upon request.

1.3.3.5.2. MuShield

MuShield, located in Manchester, New Hampshire offers custom shield design, laser welding, and hydrogen annealing. Two materials in multiple thicknesses are available. Price quote for notional parts are in Table 1-1; all shields are single-layer, 0.040" thick, with custom-formed hemispherical end caps- one laser-welded on, one slip-on. Price includes hydrogen annealing. Batch deliveries could begin six weeks after order receipt.

Table 1- 1 :MuShield Notional Price Range

	Cost/unit, delivered	
Shape	80% Ni, 20% Fe	49% Ni, 51% Fe
12" OD X 8" Cylinder	$475	$375
5" OD X 8" Cylinder	$160	$125
1" OD X 1.5" Cylinder	$35	$32
0.5" OD X 1.5" Cylinder	$33	$32

1.3.3.5.3. Ad-Vance Magnetics, Inc.

Ad-Vance Magnetics, Inc., located in Rochester, Indiana, offers custom shield design and hydrogen annealing. Three materials in multiple thicknesses are available. Price quote for notional parts are in Table 1-2; all shields are single-layer, 0.040" thick, with custom-formed hemispherical end caps, both slip-on. Price includes hydrogen annealing. Lead time for such an order would be approximately eight weeks.

Table 1- 2 : Ad-Vance Magnetics Price Range

		Cost/unit, delivered	
Shape	80% Ni, 20% Fe	48% Ni, 52% Fe	High-purity Fe
12" OD X 8" Cylinder	$440	$340	$125
5" OD X 8" Cylinder	$154	$120	$64
1" OD X 1.5" Cylinder	$32	$31	$33
0.5" OD X 1.5" Cylinder	$23	$22	$24

1.3.3.5.4. Amuneal

Amuneal, located in Philadelphia, Pennsylvania, offers custom shield design, laser welding, and hydrogen annealing. One material is available in multiple thicknesses. Price quote for notional parts are in Table 1-3; all shields are single-layer, 0.040" thick Amumetal (80% nickel, 20% iron), custom-formed hemispherical end caps-one end laser-welded on, one slip-on. Price includes hydrogen annealing. Such an order would have an approximate five-week lead time.

Table 1- 3 : Amuneal Price Range

Shape	Cost/unit, delivered
12" OD X 8" Cylinder	$1,410
5" OD X 8" Cylinder	$705
1" OD X 1.5" Cylinder	$470
0.5" OD X 1.5" Cylinder	$460

2. NOTIONAL SHIELDING EXPERIMENTS

2.1. Planar Shield

A planar shield similar to the setup in Figure 2-1 offers the least expensive option for validating a simulation, assuming, 1) the experiment is conducted in an anechoic chamber or the fixture is placed upon material that attenuates electromagnetic radiation so as to reduce coupling from fields wrapping around the outside of the shield and 2) the simulation is set up to accurately reflect the physical phenomena.

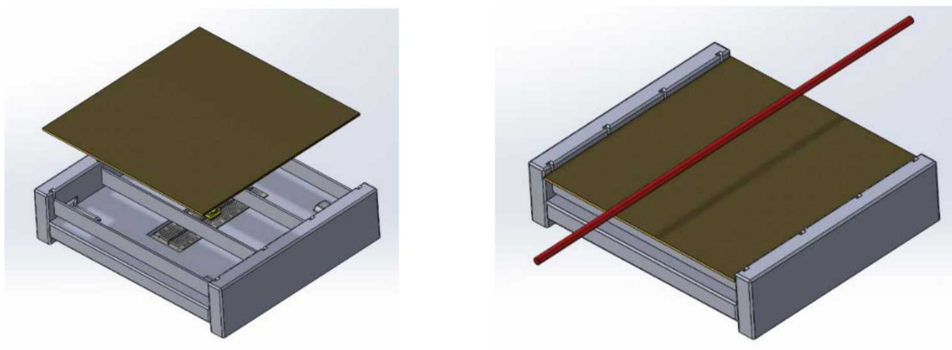

Figure 2-1: Planar shield experiment setup

2.2. Cylindrical Shield

A cylindrical shield offers better protection than a flat shield, as one need only be concerned about magnetic edge effects at the ends of the cylinder. A three-layer, cylindrical μ-metal shield is shown in Figure 2-2; several sizes of these shields are available commercially in an annealed condition to maximize magnetic permeability. Three layers of 0.025"-thick μ-metal shields are separated by acrylonitrile butadiene styrene (ABS) spacers; one end of each shield is welded on while and the other end has a slip-on cap, and the slip-on ends have small penetrations for leads.

Figure 2-2: Cylindrical shield experiment setup

2.3. Spherical Shield

A spherical shield offers the best shielding effects, particularly if the shield comprised several layers; Figure 2-3 shows a possible experiment setup. The base is additively-manufactured from ABS plastic and holds the lower half of a two-piece outer sphere of either high-purity magnetic iron or Hiperco50® iron-cobalt alloy with a diameter of about 2.5 inches. An ABS sphere with a thickness of about 0.25 inches rests within the outer sphere and acts as a spacer between the two magnetic shields; an inner sphere of μ-metal (~80% nickel, 20% iron) rests within this spacer. A small, surface-mount transformer is mounted on a piece of perforated circuit board that is cut to fit snugly inside the inner sphere. Leads to and from the transformer pins exit the central sphere via round holes that are aligned with cutouts in the perf-board. Cutouts in the ABS spacer sphere leave room for the leads to exit through holes in the outer sphere, which are offset by 90° with respect to the holes in the inner sphere to minimize edge effects around the penetrations. An alternative to using a single, thick μ-metal inner shield, an assembly of several thin shield layers and spacers with the same inner and outer dimensions could be used to see if an increase in shielding effectiveness could be realized.

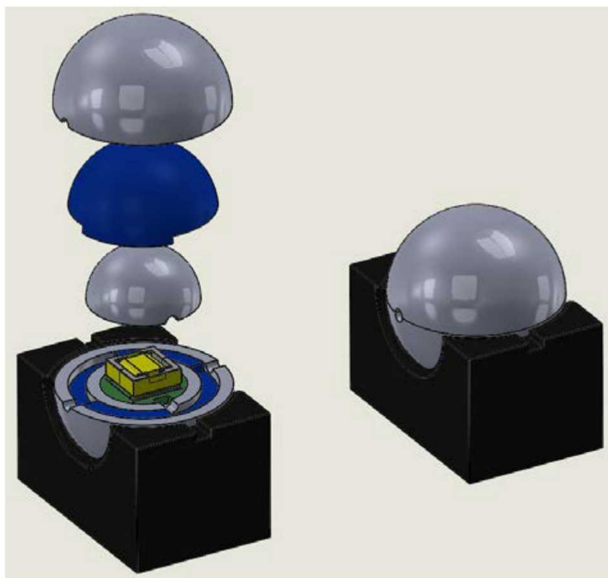

Figure 2-3: Spherical shield experiment setup

This type of shield has some significant disadvantages in terms of practical use and production. It would be expensive to manufacture, particularly if the shields are thick, and it would occupy much more space within an enclosure relative to the size of the component it is protecting. Regarding the inner shield, thin μ-metal sheets could easily be hydroformed or drawn into a hemisphere- but a thicker shell would have to be machined from bar stock. High-nickel alloys tend to be "gummy" and easily gall and machining a hollow hemisphere to a certain tolerance is a lengthy, expensive process. After machining, a μ-metal shield would have to undergo a special annealing process to maximize permeability. In addition to the time spent machining the inner shield, machining from bar stock would involve a great deal of material waste. The outer shield would also have to be machined above a certain thickness; magnetic iron machines reasonably well, but Hiperco50® is a gummy like μ-metal and very expensive, owing to its cobalt content.

3. NUMERICAL MODELING

It is reasonable to expect that computer simulation would be appropriate for such mathematically complex problems as magnetic shielding, and that may in fact be the case; unfortunately, the learning curve for the software was steep enough that this report's author chose to pursue an experimental route, due to time constraints. Furthermore, Celozzi [2] warns that due to the complexity of the computations, using commercial numerical modeling software for such an application may result in inaccurate results unless the software was specifically designed for this purpose; this particular problem may require purpose-built numerical modeling in both the frequency and time domains (see Celozzi[2], Ch. 5 and pages 286-287).

Simulations of this general type have been conducted in ANSYS Maxwell 2D and COMSOL by experienced users in the Weapon Analysis Department, but unexplained effects and technical difficulties have arisen. (As an aside, Dassault Systèmes' computer simulation technology (CST) suite has been used elsewhere for lightning simulations and may prove useful – available at https://www.3ds.com/products-services/simulia/products/cst-studio-suite/) Even when additional parallel computing resources were applied to these problems, a single solution could take up to 7 hours–and still be inconsistent with reasonable expectations and empirical results, requiring more troubleshooting. An effort toward conducting numerical modeling of this problem would benefit from the involvement of a specialist in numerical modeling.

4. CONCLUSION

Electromagnetic shielding is a complicated topic, but shielding solutions can be devised using some simple design rules: keep the component to be shielded as far away from the anticipated current channel as possible; maximize shield thickness and number of shield layers to the extent practicable given the shielding need and space constraints; use appropriate materials for the anticipated magnetic field strength; spherical shields are best, followed by cylindrical and then planar; ensure sufficient shield coverage to minimize edge effects; minimize the number and size of shield penetrations.

Several competent vendors in the U.S. supply custom and off-the-shelf shielding products and services, and shield design can benefit from their extensive experience. Computer simulations of magnetic shielding arrangements to protect from lightning-induced magnetic fields may be useful if tailored to this purpose by an expert in numerical methods; commercially-available software isn't generally designed to solve this sort of problem. Due to the complexity of calculation required for simulation, and the commensurately high number of opportunities for error to be introduced, a simulated approach requires experimental validation.

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