

ABSTRACT

FRAHM, MATTHEW RYAN. Electromagnetic Interference Shielding Effectiveness of Composite Materials. (Under the direction of Dr. Eric Klang).

North Carolina State University is one of several schools participating in the 2011-2014 Advanced Vehicle Technology Competition. This competition is called EcoCAR2: Plugging In to the Future. The NCSU team's goals are to make a vehicle that maintains performance but has less of an impact on the environment, such as greenhouse gas emissions. This means that the team's car will be a hybrid. The team is using seven A123 Systems lithium ion battery modules to help power the 2013 Chevy Malibu.

While the lithium ion batteries help to provide power and reduce the amount of greenhouse gases emitted, it does come with its problems. Lithium ion batteries like many electronic devices emit Electromagnetic Interference (EMI). These EMI emissions are a problem as they will disrupt electronic equipment and can cause malfunctions. To counter this problem shielding is used. Typically shielding is metal; however due to potential weight savings, this thesis is looking into composites as they can be lighter which will save fuel consumption and help reduce the carbon footprint of the vehicle.

In this thesis carbon fiber samples were researched to see if they could provide enough shielding to replace the aluminum material that would be used to shield the lithium ion batteries. The carbon fiber samples were tested with just carbon fiber as well as carbon fiber with silver paint adhesive, aluminum powder, and aluminum mesh. The samples were tested in a frequency range from 50 Hz to 25 MHz. The results achieved from the testing suggest that all of the carbon fiber samples could provide sufficient shielding to replace the aluminum, as the shielding achieved by the carbon samples was from 45 dB to 55 dB.

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Electromagnetic Interference Shielding Effectiveness
of Composite Materials

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Aerospace Engineering

Raleigh, North Carolina

2013

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DEDICATION

I would like to dedicate this thesis to my parents, Mark and Sandra Frahm. They have been an instrumental part of my life and education. They have always pushed me to do what interested me and encouraged me to do the best that I could. Upon receiving grades that I did not deem good enough, they would still be proud and say that I did my best and that is all anyone can ask for.

BIOGRAPHY

The author, Matthew Frahm has always had an interest in building things. This interest in building things started out with woodworking and building small objects. However, a little later in his life he helped his father build a fort in their back yard. It was not until later on that he would truly take an interest in engineering. His first passion of what to become started the same as other children. He wanted to grow up and be like his dad, which in this case was working with electronics and electronic testing.

Matthew Frahm was born February 13th, 1988 in La Crosse, Wisconsin. He is the only child of Mark and Sandra Frahm. He grew up in the country very close to where his father grew up. Matthew attended the same high school as his parents, Arcadia High School. As a child he spent a lot of time outside either playing baseball, playing with friends, or riding his four-wheeler. He would later on begin to play golf as well while in high school. It was not until high school where he decided to become an engineer. This occurred through the interest of airplanes and NASA. Through speaking with some of his teachers and having one of his high school teachers working with NASA in the summer, he grew very interested in Aerospace Engineering.

After graduating high school, he decided to pursue an engineering degree in composite materials at Winona State University. He decided to pursue this degree instead of an aerospace degree as when he toured the campus the department had told him several students that graduated from there worked in the aerospace field even without that degree. This worked out great for Matthew as it satisfied his desire to work in the Aerospace industry and satisfied his desire to build/construct things. After graduating from Winona State University in 2010 he decided he wanted to pursue his Master's degree. He decided he would apply to Aerospace schools to get his Master's in Aerospace Engineering. This led Matthew to North Carolina State University.

With Matthew's background in composite materials, he desired to work with composite materials and structures. This led him to Dr. Eric Klang and the EcoCAR2. While the work was not directly dealing with aerospace applications, he was told there was some overlap between the automotive and the aerospace field as far as structures. It was decided that the project Matthew would do for his Master's Thesis was to deal with Electromagnetic Interference and composite materials.

Upon graduating from North Carolina State University with his Master's degree, Matthew will pursue a job in the Aerospace industry wherever that may take him. Matthew's ideal job will be in the Aerospace industry dealing with composite materials which he believes will be the future.

ACKNOWLEDGMENTS

There are many people that I would like to acknowledge for their help and support in writing this thesis and making the experiment possible.

The first person I would like to acknowledge is Dr. Eric Klang for his role as my advisor and his help in picking a project for me. Without his help I would not have had a project idea after the first project idea did not work out.

Secondly I would like to acknowledge Dr. Ewan Pritchard and the NCSU FREEDM Systems Center. Without their financial and equipment support the project would not have been possible. The FREEDM Systems Center is responsible for the materials required to make the testing apparatus for this thesis project. In addition to the raw materials that were bought through them, they were generous enough to provide me with a place to work and do this project as well as the equipment needed to do testing. I was grateful for the opportunity to work with the staff at the NCSU FREEDM Systems Center.

Thirdly I would like to thank Steve Cameron from the NCSU's Mechanical and Aerospace Engineering department for his incredible machine work done. Without Steve's help and great work there would not have been any testing apparatus. The amount of work that Steve put into the testing apparatus was greatly appreciated and his skills provided a working testing apparatus on the first try. I am greatly appreciative to have had the opportunity to work with Steve.

Finally I would like to acknowledge my parents for their support and help throughout my educational career and this thesis project. I would like to give a special

thanks to my dad who has made several trips from our Wisconsin home to come to North Carolina. Without his aid in the electronics side of this thesis, I may still have been a little lost, but through his determination and help explaining some of the electronics portion I was able to finish this project.

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1. INTRODUCTION

1.1 EcoCAR2

The research being done in this thesis is for making a better battery case for the EcoCAR2 program at NCSU. What is this EcoCAR2 program? EcoCAR2: Plugging In to the Future is an engineering program established by General Motors (GM) and the Department of Energy (DOE). In this program participating schools are to modify cars and compete against each other to see whose car is the best. There are guidelines and regulations that have to be met all along the way, but there are some technical goals to this competition. The technical goals of the EcoCAR2 program are to: reduce fuel consumption, reduce well-to-wheel greenhouse gas emissions, reduce criteria tailpipe emissions, and maintain consumer acceptability in the areas of performance, utility, and safety [1]. The EcoCAR2 challenge is for 15 Universities and they are challenged to reduce the environmental impact of the 2013 Chevy Malibu. This competition is a three year competition, but this is not the first competition created by GM and the DOE. These competitions are referred to as Advanced Vehicle Technology Competitions, AVTCs. The AVTCs are sponsored by the U.S. Department of Energy in partnership with Natural Resources Canada and the North American Auto Industry [1]. Shown below in figure 1 is a timeline of the AVTCs. As can be seen this year is the 25th year that the AVTCs have been occurring.

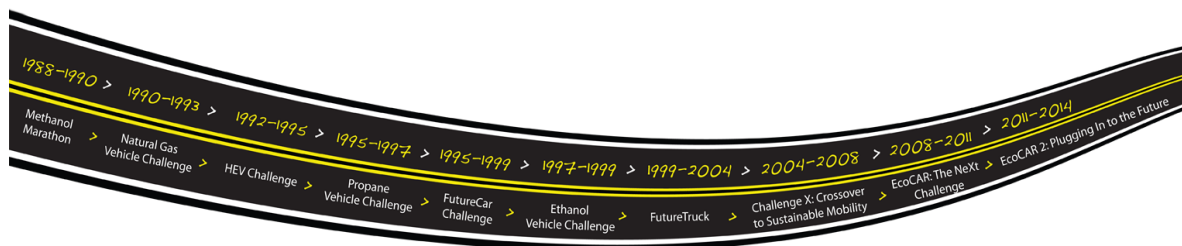


Figure 1: AVTC Competition Timeline [1]

In review of the timeline it appears as if the main objective of the AVTCs is to change the auto industry to help reduce the impact of greenhouse gases on the environment. So anything that can help reduce those greenhouse gas emissions would qualify as a modification worthy of the challenge. In this thesis the modification of the battery case could save weight which would allow better fuel mileage and in turn allowing fewer emissions.

1.2 Problem Statement

The NCSU EcoCAR2 team, like many other teams, is using a Lithium Ion Battery Pack to help reduce the emissions that are polluting our environment. The problem with Lithium Ion batteries like other electrical equipment is that it emits radiation. This radiation is referred to as electromagnetic interference or EMI. The NCSU EcoCAR2 team's plan to reduce the EMI emissions of the lithium ion batteries is to make a battery case from an aluminum shell bolted to a steel frame. The most common form of protection against EMI is metal shielding. The shielding of electronics uses mainly metals due to their potential of eliminating all emissions through absorption of the wave and thus terminating it through grounding. However there is research ongoing into whether or not composite materials can be sufficient as a replacement for metals. The reasoning behind this research has to deal with metals being heavier in nature. The lighter the material for shielding the better the fuel mileage the vehicle can get, which in turn will be better for the environment as fewer greenhouse gases will be emitted.

1.3 Definition of Terms

There are several terms that will be used throughout this thesis that may not be of common knowledge. The first and most used term that is electromagnetic interference or EMI. EMI is the focus of this thesis, thus making it the most important term to understand. So, what is EMI? "Electromagnetic interference, EMI, is any undesirable electromagnetic

emission or any electrical or electronic disturbance, man-made or natural, which causes an undesirable response, malfunctioning or degradation in the performance of electrical equipment” [2]. EMI is thus protected against by something called a shield or shielding. As stated above this shield is most commonly metals but other materials can be used. In this thesis the EMI is being looked at from the lithium ion batteries via charging and discharging.

So what is a lithium ion battery? “A type of rechargeable battery in which lithium ions move from the negative electrode to the positive electrode during discharge, and reversely when charged” [3]. This type of battery can be used for a variety of applications. The lithium ion battery can be used for electric vehicle (EV), hybrid electric vehicle (HEV), or a plug-in hybrid electric vehicle (PHEV) [3]. Depending on its application it could provide up to 400 volts. In order to do this the battery pack would have to consist of several modules which contain lithium ion cells. Through set-up of series, parallel, or series-parallel the desired voltage can be achieved. For the NCSU EcoCAR2 team, there are 7 modules that make up the lithium ion battery pack. For the NCSU car a voltage range is in 263 volts to 378 volts. Shown below in figure 2 is the NCSU EcoCAR2 team’s battery set-up.



Figure 2: NCSU EcoCAR2 A123 battery pack

1.4 Significance of Study

Composites are being looked into as a suitable replacement for shielding electronic devices. This has to deal with the several desired properties that composites can offer. Composites are typically light weight, fairly cheap, and have tailorable properties. It is for these reasons that many different studies are being conducted. These studies vary from carbon nanotubes (CNTs) to regular carbon fiber. Plenty of research is being done on composites. The purpose of this specific study is to analyze composites for use as a shield of a lithium ion battery pack.

In this thesis carbon fiber is studied to see how/if it could be used as a potential replacement for the aluminum shell. This is important because if carbon fiber can be used; it typically is lighter and stronger. For the EcoCAR2 program that would mean an increase in performance and a reduction in greenhouse gases.

1.5 Scope and Limitations

Research in this area of composites has been done before. However, with EMI testing there is a vast frequency range that EMI can occur at. This range is from Hertz (Hz) to Giga Hertz (GHz). Most testing of composites for EMI shielding has been done in the mega hertz (MHz) to the GHz range. In this application the lithium ion batteries current is in the form of direct current (DC) instead of alternating current (AC). What this means is that the emissions from the lithium ion batteries will occur at a much lower frequency range than that of which has been tested. For this testing to be done a testing apparatus was needed. Since EMI is not something commonly tested by non-professionals the making of the testing apparatus was necessary. It was decided that following the ASTM Standard D4935 was the optimal choice. In this standard the testing apparatus was made from a brass material.

The brass material required to make the apparatus was quite expensive and the NCSU ECOCar2 team did not have the financial capability of buying it. However, the team was working with the NCSU FREEDM Systems Center. It was through the NCSU FREEDM Systems Center that the brass and other materials were able to be bought and supplied to make the EMI testing apparatus described in the ASTM Standard D4935.

The brass was then machined out at the NCSU MAE department. Since the objective of the EcoCAR2 program is to reduce carbon footprint or greenhouse gases, the brass that was machined off to create the parts was saved and recycled. Shown below in figure 3 are the brass shavings being recycled.



Figure 3: Brass shavings being recycled

With the testing apparatus made the composite samples were fabricated, cut, and tested according to the ASTM Standard D4935. The results were also recorded and calculated according to the ASTM standard. This form of testing was valid for the application it would be used for. However, if the battery pack casing were to be mass produced a more professional form of EMI testing should be conducted. At the professional level, there are more accurate ways to measure and calculate the EMI shielding effectiveness. This has to deal with different methods of testing, higher end equipment and a special enclosed environment for testing. The testing done in this thesis was sufficient, but due to the lack of capable equipment the full spectrum of frequency ranges could not be tested to see if the composite would have any other potential applications. In addition to the lack of equipment there was no enclosed environment to test in. While it is not

necessary to test in an enclosed environment, it would provide a more accurate reading as the oscilloscope would not be able to pick up other signals from any other electrical devices.

As was stated earlier there is a vast amount of research being done on composite materials in the area of EMI shielding. The next portion of this thesis is to look at some of the research being conducted.

2. LITERATURE REVIEW

2.1 Introduction

Today's society is one that relies heavily upon technology. It could be said that today's society is living in an information age. Living in this information or technology age means that there is an ever increasing use of advanced technology on a daily basis for personal as well as professional use. This not only means computer technology and smart phones, but even some of the appliances used to prepare food. The increasing use of advancing technology can create problems. One big problem is called Electromagnetic Interference or EMI.

The most common form of protection against EMI is metal shielding. The shielding of electronics uses mainly metals due to their potential of eliminating all emissions through absorption of the wave and thus terminating it through grounding. However there is research ongoing into whether or not composite materials can be sufficient as a replacement to metals. The reasoning behind this research has to deal with the cost of the metals being rather expensive and heavier in nature. According to the ASM Handbook Volume 21 a composite material is classified as "a macroscopic combination of two or more distinct materials, having a recognizable interface between them" [4]. Composite materials have been around as early as World War II [4]. Since composites have been around for some time, composites have had many improvements along the way in terms of cost, weight, and desirable properties. Composites also have greater moldability than metals do, which allows them to be used in a more versatile manner than metals can be used. These are some of the reasons composites are being looked into as a suitable replacement for metals in EMI shielding applications.

EMI is a huge problem for technological devices. This phenomenon can cause disruptions in service of applications such as televisions. In noticing that the television set has become blurry via lines on the screen is an indication of EMI and is shown below in

Figure 4. EMI can temporarily disable a piece of technology or if exposed long enough to it without protection could potentially cause permanent damage. So in knowing this there is a great need to ensure all electronic devices are properly shielded against this problem. The EMI phenomenon occurs in the frequency ranges from Hertz (Hz) to Giga Hertz (GHz).



Figure 4: Electromagnetic Interference on an Analog TV [5]

The literature that is being reviewed in this thesis will show what has been done in the field of EMI with composite materials. There are three main different areas in the literature that will be reviewed in this thesis. The first area under review is that of carbon nanotubes.

2.2 EMI shielding with carbon nanotubes

Carbon nanotubes are a rather new form of composite that has been gaining ever increasing interest. Carbon nanotubes or CNTs are exactly what they sound like, carbon tubes at the nano-scale. CNTs are being investigated for uses in many different applications. One such application is EMI shielding. This is due to the fact that CNTs have been said to offer better electrical and mechanical properties than conventional composite fillers (Singh, Gupta, Mishra, Govind, Chandra, Mathur, Dhawan) [6]. There are two different types of CNTs. There are Single-walled carbon nanotubes (SWCNTs) and Multi-walled carbon nanotubes (MWCNTs). According to Li, Huang, Du, He, Lin, Gao, Ma, Li, Chen, and Eklund, "The small diameter, high aspect ratio, high conductivity, and mechanical strength of carbon nanotubes (CNTs), including SWNTs and MWNTs, make them an excellent option for creating conductive composites for high-performance EMI shielding materials at low filling" [7]. In this thesis only a few of the many papers dealing with CNTs and EMI shielding will be discussed in further detail. Three different papers were chosen which investigate CNTs. Studies on the CNTs dealt with SWCNTs, MWCNTs, and MWCNTs in layers. Each of these three studies has its merits and its problems, and they will be explored further starting with the SWCNTs.

One main issue dealing with CNTs is obtaining uniform distribution and dispersion in the matrix. The SWCNTs were created through annealing in a furnace tube and then were mixed with an epoxy resin. This matrix material is the same material that will be used for creating the samples in this thesis. Thus there is a comparison that can be made here as to how varying the filler type affects the EMI shielding effectiveness of the composite. As was stated earlier CNTs have problems with dispersion and distribution. In reviewing the paper on SWCNTs, it was found that there was no confirmation done on the samples created to ensure that the distribution and dispersion was adequate. There was microscopy work done in a previous work to show the distribution and dispersion of the materials, but it was

not done with the current samples (Li et al.) [7]. This is important as it is very difficult to achieve full replication of composites in most cases.

The testing done on the SWCNTs was similar to what will be done later in this thesis. The testing done on the SWCNTs was conducted through the use of a Keithley SCS 4200 [7]. The problem here is there is nothing stated about what that specific machine is. Based off of knowledge in the subject area of EMI, it could be thought to be a spectrum analyzer. The spectrum analyzer is what is used to measure the amount of voltage, frequency, conductivity, etc. In addition to this, they did not actually explain their test setup or whether or not they are using an ASTM standard. This is important to note so others can replicate the study and is also important for validating the data as it allows a proper comparison to current research already available. The samples were tested in a frequency range from 10 MHz to 1.5 GHz (Li et al.) [7]. The authors have decided to test their samples in the middle of the EMI frequency spectrum. The data suggests the material can be used for EMI shielding, but the authors did not state what applications the frequency ranges tested would qualify for.

In reviewing the MWCNTs paper it was observed that there was more done than in that of the SWCNTs paper. In the MWCNTs paper the authors reported dispersion and distribution of the samples that were created and tested for EMI shielding. This is very important as it proves their samples did in fact have adequate dispersion/distribution and can be used as a viable material for EMI. However, like the SWCNTs review, there is a lack of test setup discussion, a lack of any ASTM standard mentioned and finally no specifics mentioned about applications the material will be used for. It can be inferred that the material will be used for electronic devices along the lines of computers, TVs and cell phones from the introduction, but no actual statement of what it would be used for is made (Singh et al.) [6]. The matrix material used was Portland cement. It seems rather odd that cement would be used in an electronic device as cement is usually heavy. The testing was

done through a spectrum analyzer and it was concluded that the material is sufficient for EMI Shielding in the frequency ranges of 8.2 GHz to 12.4 GHz (Singh et al.) [6].

Finally in review of the multi-layered MWCNT samples it was observed to be similar to the SWCNTs paper in terms of what was lacking. There was no mention of ASTM standard, testing method, no mention of how adequate dispersion/distribution was achieved and no mention of what the material would be used for. It can be inferred from the introduction that this material is used for stealth technology such as that of the B2 bomber (Song, Liu, Leng) [8]. The frequency range tested in this paper was a very high frequency range of 3.22-40 GHz (Song et al.) [8]. However, like the previous paper reviews it cannot be said for certain what actual use this material can be used for.

In conclusion, there are some similarities to the testing that will be conducted later in this thesis. The data from these studies is beneficial to see how varying the matrix and reinforcement material can change the EMI shielding effectiveness. The SWCNTs paper will have the best comparison to the research being done in this thesis. The testing range that will be explored in this thesis is from 50 Hz to 25 MHz. So from the ranges of 10 -25 MHz, there could be a comparison made to determine how much better the CNTs are over that of traditional carbon fiber.

2.3 EMI Shielding with non-traditional Composites

Several different types of fillers can be used in composites. The fillers can be continuous, discontinuous, and natural occurring. Most of the traditionally used composites deal with fibers, flakes, and particles. However this is not all composites are limited to as was shown earlier with carbon nanotubes. In this section of the review, organic materials and graphene materials will be looked into and discussed as potential uses for EMI shielding.

Graphene sheets are not naturally occurring. Graphene is in fact the base material of CNTs. It is made in the same way CNTs are made, however the graphene sheet is not rolled

up into a tube, but left in the form of a sheet to be used as reinforcement. In leaving the graphene as a sheet you are able to attain some of the benefits to the CNTs and removing some of the negatives of CNTs. An example of the downfalls to CNTs that would be avoided may be the lack of impurities and a reduced cost from that of CNTs. The graphene sheet would however be larger than that of the CNTs.

In this portion of the review different matrix materials will also be looked at. The most common matrix material for composite materials is epoxy. Epoxy is generally used due to its good balance of properties. However, this does not mean epoxy is the only resin used. Other resin systems may be used based on the requirements of the applications. As the title of this section of the review states, a discussion of non-traditional materials is conducted. Two of the three papers that will be discussed use different matrix materials, one of them being an organic material. This is relevant as composites are harder to recycle than metals. This means we are increasing the pollution of the earth, which could lead to ever increasing greenhouse gases causing more global warming. With that said organic materials are being looked into to help reduce the carbon footprint of composites. The first paper that will be discussed in this section of the review will be dealing with EMI shielding of graphene sheets.

In review of the graphene/epoxy composites paper it was noticed that microscopy of the samples was done. This information is great to have as it shows how well the samples are bonding as well as dispersion of the sheets in the matrix material. The testing was done in the frequency range of 8.2GHz to 12.4 GHz (Liang, Wang, Huang, Ma, Liu, Cai, Zhang, Gao, Chen) [9]. While the testing here is higher than the testing that will be done in this thesis, it gives a good indication of how shielding efficiency changes at the higher frequencies as well as show how graphene reinforcement changes the shielding efficiency from that of traditional materials. The testing method is not discussed in detail however, which leads to questions of how the samples were analyzed for EMI Shielding. Was it done in a closed exposure, an open exposure, what equipment was used and was an ASTM standard

followed in some way, shape, or form? All of these questions help to validate the data provided by this research, but there are no answers to them in the paper. The detailing of the making of the samples is great. Similar to the papers already reviewed, there is no statement of use for this material. Is it to be used in small electronic devices such as phones or to be used in computers, or is it to be used in aircraft? While the materials are different from what will be used later in this thesis, there is still some usefulness to this paper in review as the material can be compared to traditional materials used in this thesis as the matrix material remains the same, epoxy. The authors lay claim that the graphene composites can be used in commercial applications (Liang et al.) [9].

Moving on to other non-traditional composites for EMI shielding, the review will now look into a paper dealing with a different matrix, polyphenylene sulphide. This specific matrix material is a high performance polymer that exhibits fire retardant properties (Goyal and Kadam) [10]. For this reason the testing of this material is very valuable for applications that have a potential of catching on fire. While the data retrieved in this test is valuable there is no mention of how many decibels (dB) can be shielded by this material. This paper mentions several different machines used to test for EMI shielding, but does not give a detailed setup of how the testing was done or where it was done, an open or closed enclosure. The details are very important as it will allow the reader to know if/how any signal loss was taken into effect. Similar to all of the papers reviewed thus far there is no mention of specific uses for the material, but a claim that the material may be the future for antistatic/EMI shielding applications (Goyal and Kadam) [10]. The testing done for this material was within a similar frequency range that will be done and discussed later in this thesis, 100 KHz to 15 MHz. Unfortunately as was stated before there is no direct comparison that can be made as there were no recorded values in shielding decibels.

The final paper in this section of the review is similar in some sense to the previous paper reviewed in the aspect that it is non-traditional. The material used for the matrix was an organic material, salmon sperm-based DNA (Zang and Grote) [11]. The interest of using

DNA comes from the fact it is renewable, can be broken down and exhibits some electrical properties. The study conducted in this paper deals with several different types of fillers or reinforcement to allow the composite to shield EMI emissions. The most common material used is metal. In this paper Zang and Grote look into metals, graphite, and graphene for fillers to provide the shielding needed. The materials used as fillers are very similar to what will be used later on in this thesis. Unlike the previously reviewed papers this paper gives a very descriptive detailing of how the EMI testing was done and the equipment used to test for EMI shielding. This is an indication that the Zang and Grote are very confident in their findings and others are given the opportunity to replicate the test by getting the same equipment and setup used. However, there is no indication why they used this specific setup for measuring EMI shielding. There are several different ways to measure EMI shielding effectiveness and many ASTM standards that offer ways to test. The testing done for these samples was over a wide frequency range from 10 KHz to 18 GHz (Zang and Grote) [11]. This shows that the authors are trying to create a material that can be used for a wide variety of applications and not just a few specific applications over a certain frequency range. This paper will provide a fairly good comparison to some of the testing that is done later on in this thesis as similar filler materials were used and will allow a comparison of Epoxy matrix to DNA based matrix material. The authors state this material may be used for electronic devices and circuit boards (Zang and Grote) [11].

2.4 EMI Shielding with Traditional Composites

Composite materials are usually made from a matrix material and reinforcement material. The reinforcement material can either be a continuous or a discontinuous material. However, in traditional composites they are not usually at the nano-scale level. This does not mean that the particles can't be that small, but typically are not at the nano-scale but rather the micro-scale or larger. According to Chung, "Carbon materials for EMI shielding are mainly carbon fiber composites, colloidal graphite and flexible graphite" [12].

Traditional composites for EMI shielding are not limited to carbon based fillers; there is also the use of metal particles and metal meshes used for the filler or reinforcement of the composite to increase electrical conductivity of the composite.

The traditional composite most closely resembles the research that has been done in this thesis. The use of a polymer matrix and carbon reinforcement with the addition of meshes, metal particles, or metal paint would be classified as a traditional composite material for EMI shielding. The last three papers to be reviewed fit this description/type of composite. The first paper that will be discussed in this portion of the review has to deal with carbon reinforcements and differing matrix materials.

The authors of this paper decided that they were going to comprehensively research the use of composite materials in an attempt to replace the metal materials. This is important as metal materials are typically very heavy; if a lighter material can be used, typically it is for the better. The materials used for the matrix were Natural Rubber (NR) and Ethylene-vinyl acetate co-polymer (EVA) and the reinforcements were conductive Vulcan XC-72 black and short carbon fibers (SCF) (Das, Khastgir, Chaki, Chakraborty) [13]. There is some importance in the materials chosen as the natural rubber would be more of an organic material and should allow for easier recycling. However, there is no reference of the data obtained to any of the current material used for EMI shielding.

In reviewing the paper for testing details it was shown that the authors give good detail as to how the testing was done. In order to measure the EMI SE, there would need to be a way of calculating these values. This is done with the use of a basic scalar co-axial system using a Sweep Oscillator, Network Analyzer, detectors, and some cables to comprise the testing equipment (Das et al.) [13]. Testing was done over frequency ranges from 200 MHz to 2 GHz and 8 GHz to 12 GHz (Das et al.) [13]. With these frequency ranges the authors are looking at applications in the medium to high frequency ranges. The authors do not state any applications that the specific composite may be used for; however, in the introduction of the paper they do indicate that polymer housing is used for the casings of

smaller electrical devices, with reference that they do not have good EMI SE properties. Similar to the previously reviewed papers there was no mention of any use of an ASTM Standard. The use of an ASTM Standard allows proper comparisons to be made to other research in the field of study.

The next paper to review has to deal with varying the matrix materials as well. In this paper the authors are using carbon matrix and epoxy matrix (Luo and Chung) [14]. The use of the epoxy matrix gives some similarities to what will be done later on in this thesis, and allows for a comparison. The authors also varied the fillers, between fibers and filaments. The testing done was presented with some amount of detail but more detail could have been to better understand the setup. The testing was done over a frequency range of 300 KHz to 1.5 GHz (Luo and Chung) [14]. Some of the testing range will be similar to what is going to be done in this thesis and will allow a comparison to the epoxy matrix material being tested here. However, while the data may be of similar, there is a question of how the authors chose this test method. Did they follow any ASTM standard? There is no mention of this, so while a comparison can be made, it may not be absolutely correct as there may be differing testing specifications that could cause a difference in decibels of shielding.

In review of the final paper of this literature review we arrive at the paper that closely resembles the research done later on in this thesis. This paper is testing unidirectional carbon fiber, woven carbon fiber, and stitched carbon fiber for the reinforcement (Klemperer and Maharaj) [15]. The authors decided to test the three different composite reinforcements with differing concentrations of metal powders mixed into the resin. This is similar to the testing that will be conducted later on in this thesis as it was woven carbon fiber material that was used as the reinforcement material and aluminum powder was used to increase shielding efficiency.

The authors of this paper followed an ASTM standard. This is the only paper in this review that followed an ASTM standard; though it was not completely followed as the

ASTM standard was used as more of a guideline. This should allow the best comparison to what will be done later on in this thesis. The authors tested over a frequency range of 800 MHz to 5 GHz. This range is much higher than the range that will be tested later. However, the frequency range difference has to deal more with the applications that the composites will be used for. The data the authors collected will help to give an indication of how the EMI shielding effectiveness changes as frequency is increased.

2.5 Conclusion

All of the articles reviewed have their importance the Electromagnetic Interference shielding community using composite materials. In an ideal world the testing done in this thesis would be able to relate to each paper that has been reviewed. However, due to financial, testing and processing capabilities that is not the case. Each article or paper reviewed has in some part a way to be compared to the research that was conducted in this thesis. In some of the papers reviewed comparisons can be made to the materials used and how increasing frequency range would affect the shielding effectiveness, while in other changing the reinforcement material will allow comparisons of shielding effectiveness.

3. **THEORY**

3.1 **Introduction**

As has been stated earlier in this thesis, an experiment is being conducted on composite materials and their shielding effectiveness of Electromagnetic Interference (EMI). This is important as society today is one that demands the ever increasing use of technology. Technology is used for just about everything a person may do in a day, varying from computer work to something as simple as cooking food. With this being said there is a need to try and solve the EMI problems that can potentially cause malfunction of electronic devices used day in and day out. However, before trying to solve these EMI problems or run tests some basic knowledge about what and how EMI works should be looked into. In this section of the thesis, knowledge of EMI will be further explored and explained in some detail.

3.2 **EMI Theory**

Electromagnetic Interference (EMI) theory can be broken down into two different subject areas. These areas consist of EMI and EMI Shielding. Before getting into the EMI shielding, which is the subject of this thesis, knowledge of EMI and how it works must first be understood.

So, what is EMI? “Electromagnetic interference, EMI, is any undesirable electromagnetic emission or any electrical or electronic disturbance, man-made or natural, which causes an undesirable response, malfunctioning or degradation in the performance of electrical equipment” [2]. EMI propagates through the air or any lines/wires connected from one piece of equipment to the other. So EMI can go from equipment that is connected to each other or simply through the air like radiation. EMI may also be referred to as radio frequency interference (RFI). EMI and RFI are very similar; the main difference

between the two is RFI occurs at lower frequencies (Hz-MHz), whereas EMI occurs at higher frequencies (MHz-GHz).

So, how do we prevent EMI? EMI can be prevented in two different ways. EMI can either be filtered or shielded and prevented. Some examples of filters would be inductors and capacitors. They act as a higher resistance to the frequency and as such reduce the waves that are propagating out/through the wires/lines. This method is common, but does not eliminate EMI emissions as a whole, it only reduces them to levels that should not disrupt or cause very minimal disruption to other electronic equipment. The other method is to provide a shield of some sort to shield the device that is emitting the EMI. In this method a shield is placed around the device and then grounded to prevent the emissions from escaping and disrupting other devices. To explain why the shield is grounded, the mechanisms of shielding must now be explained.

EMI Shielding effectiveness is determined by three different mechanisms, reflection, absorption, and multiple reflections (scattering) [11, 12, 16, and 17]. There is a hierarchy among the mechanisms with reflection being the primary and absorption being the secondary mechanism [12]. This hierarchy is not always the case, but it is usually the order of the hierarchy. "For reflection of the radiation by the shield, the shield must have mobile charge carriers (electrons or holes) which interact with the electromagnetic fields in the radiation. As a result, the shield tends to be electrically conducting, although a high conductivity is not required" [12]. Metals are the most common candidate of choice as they have free electrons and are conductive. However, as stated above having a high conductivity is not necessary, though it will aid in the shielding. This is due to the fact that conduction requires connectivity in the conduction path, but shielding does not require connectivity [12]. As stated earlier, reflection is the primary mechanism of shielding and is indicative of metals especially. Now with some background on reflection, the next mechanism to understand is that of absorption.

Absorption, as stated earlier, is a secondary mechanism for EMI shielding. Absorption is what it sounds like; the shield absorbs some of the electromagnetic radiation. This is where the grounding of the shield comes into play. If the shield is grounded to a metal it will allow the electromagnetic radiation absorbed to ground out. "For significant absorption of the radiation by the shield, the shield should have electric and/or magnetic dipoles which interact with the electromagnetic fields in the radiation" [12]. Different materials can be used for the shield to get a desired shielding mechanism to occur. For example metals such as gold, silver, copper, and aluminum are good choices of material for reflection, while nickel-iron magnetic alloys are good choices for absorption [12]. There is something that should be noted about the differences between absorption and reflection. "The reflection loss decreases with increasing frequency, whereas the absorption loss increases with increasing frequency"[12]. It is termed as loss as when shielding effectiveness is measured it is recorded as a negative value of decibels (db). So the mechanisms are measured in terms of how much of the original signal was lost or "loss". Now with some background on reflection and absorption, the final mechanism to look at is that of multiple reflections.

The final mechanism to look into is multiple reflections. This has to deal with reflections that occur within the shielding material. In order for multiple reflections to occur the shielding material needs to have a large surface or interface area [12]. Chung states, "An example of a shield with a large surface area is a porous or foam material. An example of a shield with a large interface area is a composite material containing a filler which has a large surface area" [12]. It is possible for this final mechanism to be neglected from the calculations. In order to neglect multiple reflections from the calculation, the distance between the reflecting surfaces must be greater than the thickness of the shield. As the frequency increases the electromagnetic radiation will only penetrate the initial portion of the shield, and this is referred to as the skin effect [12]. Figure 5 below shows an

image of the three mechanisms and an equation that is used to calculate EMI Shielding Effectiveness.

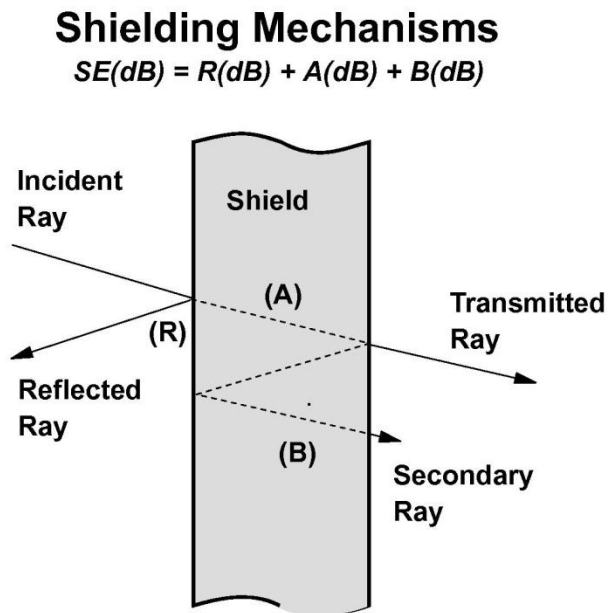


Figure 5: EMI Shielding mechanisms and equation for Shielding Effectiveness (SE) [18]

3.3 Why use Brass for the testing apparatus?

For this thesis an ASTM Standard was followed to ensure data would be able to be compared to other data already out in the field of study. The ASTM standard used was ASTM D4935-10. ASTM D4935-10 is the standard test method for measuring the electromagnetic shielding effectiveness of planar materials. The material suggested for the testing apparatus was brass for most of the parts and acrylic for one part [19]. The acrylic part was used to prevent movement of the center conductor inside the apparatus. The brass that is used in this thesis to make the testing apparatus was ordered from McMaster

Carr. The brass used was Ultra-Machinable Brass (Alloy 360) and was chosen for its machineability. The alloy compositions of Brass Alloy 360 are shown below in Table 1 while the properties of the brass are shown below in Table 2.

Table 1: Composition of Brass Alloy 360

Copper	Zinc	Lead	Iron	Silicon
60-63%	32.95-	2.5-3.7%	0-0.35% Iron	0-0.17%

Table 2: Properties of Brass Alloy 360

Nominal Density, lbs./ cu. In	Modulus of Elasticity, ksi	Melting Point or Range, °F	Thermal Conductivity, BTU/sq. ft./ft./hr/°F @ 68°F	Electrical Resistivity, ohms @ 68°F	Temper	Hardness, Rockwell (unless noted)	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, %
0.307	14,000	1630-1650	67	39.9	1/2 Hard	B25-B86	55-68	15-52	18-32

There are a few reasons that brass is used over copper. Copper is generally softer than brass, and would be more easily formable. For the testing apparatus it is designed in a specific way as to ensure proper testing will be done. So a material that can be machined is desired but not a material that is so soft that the final shape of the apparatus can be modified with some force. Copper is also much more expensive. This is very likely the main reason for not using copper. Copper has greater electrical properties than brass and would be expected to be used. However, as stated earlier due to the price difference and the hardness of copper, brass is used as the material for the testing apparatus instead.

3.4 What is the significance of that apparatus design?

The design of the testing apparatus may appear to be one of a random configuration. However, there is significance to the design. The significance of this design has to do with something called impedance. Impedance refers to the resistance of an alternating current (AC) circuit. It is similar to resistance but impedance refers to magnitude and the phase instead of just the magnitude [20]. The testing apparatus or specimen holder shape is designed in a way to retain an impedance of 50 ohms throughout the entire length [19]. The most common impedance used is 50 ohms. This has to deal with the equipment used for testing and the cables being at 50 ohm impedances as well. The goal of the impedance is to prevent any mismatching [21]. What this means is the impedance acts as a way to keep/ensure power is being distributed equally throughout and that there are no/or minor variances in the power going through the testing apparatus. "The source impedance of free space, or air, is approximately 377 ohms. When an RF wave hits a material the energy is reflected, transmitted, and absorbed. The percent of energy in each category is directly related to the complex impedance mismatch between the material and free space. What this means is that a material with impedance greater than 377 ohms allows more transmission than reflection. When the impedance is substantially lower than free space, more is reflected" [21]. As can be seen above electrical impedance is very

important. It can show what will happen with the material, whether that is transmission, reflection, or absorption. In addition it is needed to regulate the power that is being sent through the testing apparatus. With this information it would be expected that reflection will be the main source of shielding in this case as 377 ohms is much greater than 50 ohms of impedance and therefore should expect more reflection.

4. **EXPERIMENTAL SETUP**

4.1 **Introduction**

As has been stated earlier in this thesis, an experiment is being conducted on composite materials and their shielding effectiveness of Electromagnetic Interference (EMI). However, before any experimental data can be reviewed a detailed explanation of the experimental set-up must first be looked into. This thesis followed the ASTM D4935-10 standard. The testing equipment, procedure used, and the testing holder followed the ASTM standard. While the ASTM standard was followed, it was not followed directly, it was used more as a guideline and it will be explained in further detail in the next section.

4.2 **ASTM Standard Modifications**

As was previously stated the ASTM standard was followed as a guideline. Upon reviewing and consulting with the machinist about the testing apparatus it was discovered that the machinist would not be able to make the apparatus as it was in the ASTM Standard. The testing apparatus was to be made of fourteen different pieces total. The apparatus consisted of seven pieces per half portion of the apparatus. It was determined that at minimum three of the seven pieces per half would have to be changed or modified to allow the machinist to make the current apparatus. The parts are listed as parts A through G. The three parts that needed to be modified were parts A, E, and G. Shown below in figures 6 and 7 are the half assemblies of the testing apparatus. As can be seen below there is actually an additional part in the modified assembly. This additional part is an n-connector that was purchased and placed into the design.

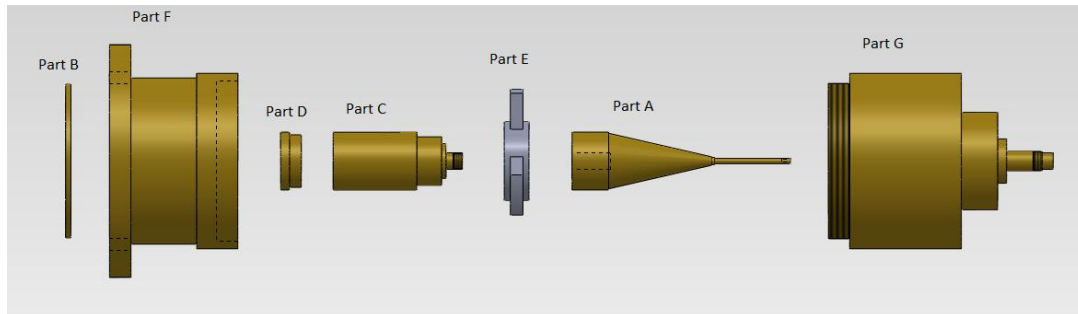


Figure 6: ASTM Half Assembly exploded view

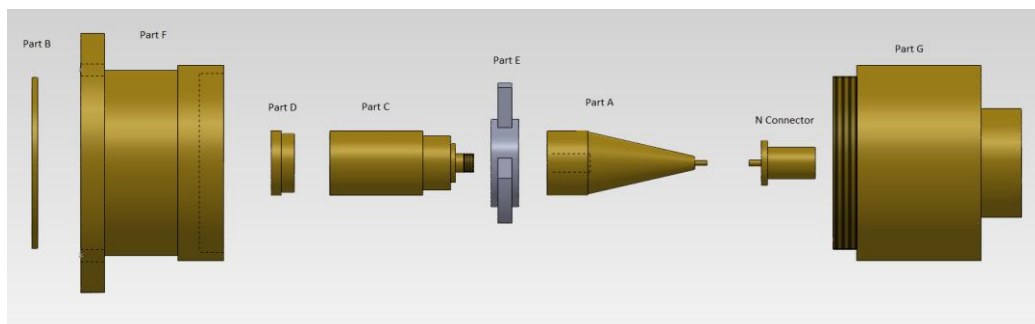


Figure 7: Modified Half Assembly exploded view

The first part to be modified was part A; it was shortened up to allow easier machining of the piece. Secondly part E had the edges of it brought to a straight edge again to allow easier machine ability. This was acceptable as part E's only purpose is to keep the center conductor (parts A, C, and D) from moving inside the apparatus. Part G, however had more complex changes than it may appear to have. The first thing done to part G was to make the hole that was to be bored out much larger as it would be quite difficult to machine something so small. Once the hole was made bigger there was no need for the external parts, so they were simply taken away. However, with boring a bigger hole, there needed to be a way to connect the testing apparatus to the measuring devices that will be discussed a little later on. To do this, a special connector was needed. The connector

needed was a type N-connector. This connector had to be press fit into part G. So part G was not only modified to allow for a larger bored hole, but also to allow a press fit of a type N connector. Shown below in figures 8-13 are the three original parts and the three modified parts. In addition to these parts being made and modified in SolidWorks the testing apparatus as a whole was also fabricated and the parts and assemblies are shown in Appendix 1.

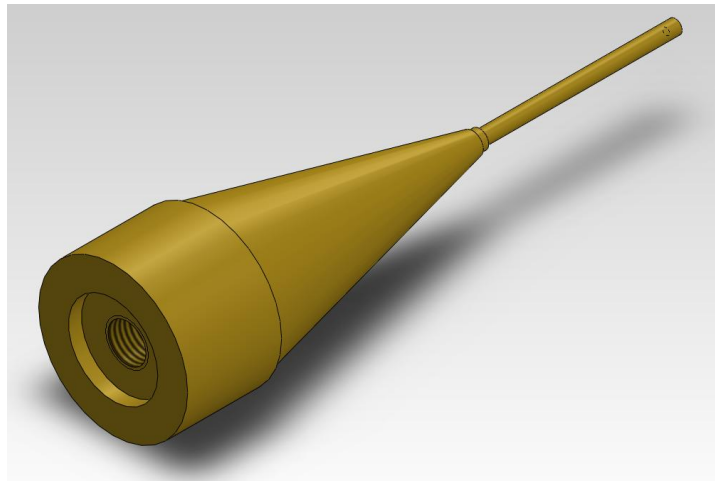


Figure 8: Part A made in SolidWorks

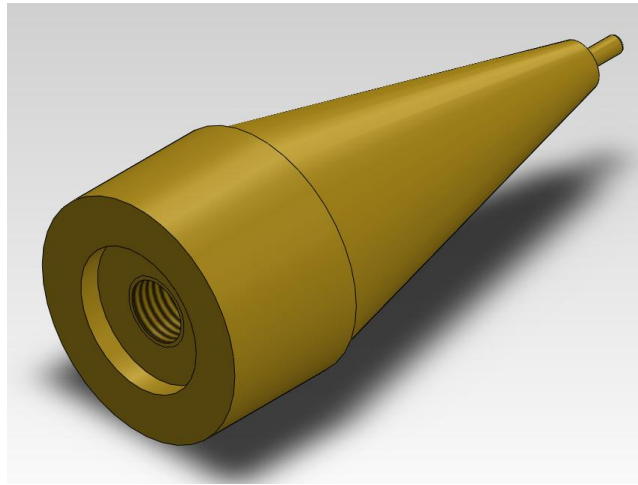


Figure 9: Part A modified in SolidWorks

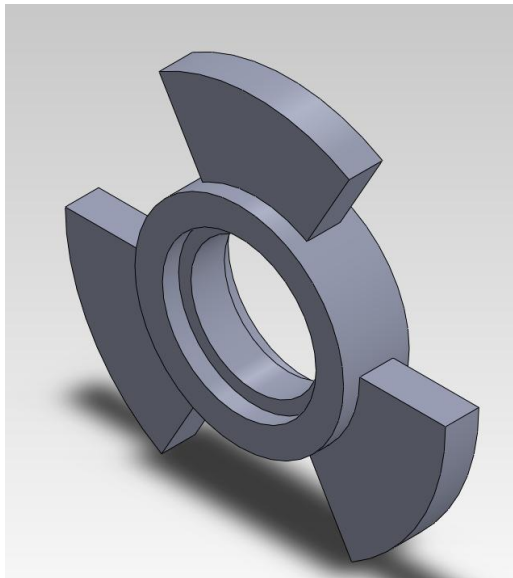


Figure 10: Part E made in SolidWorks

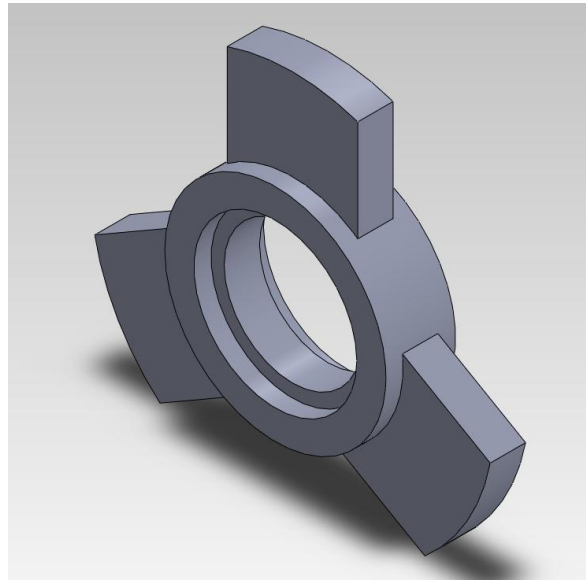


Figure 11: Part E modified in SolidWorks

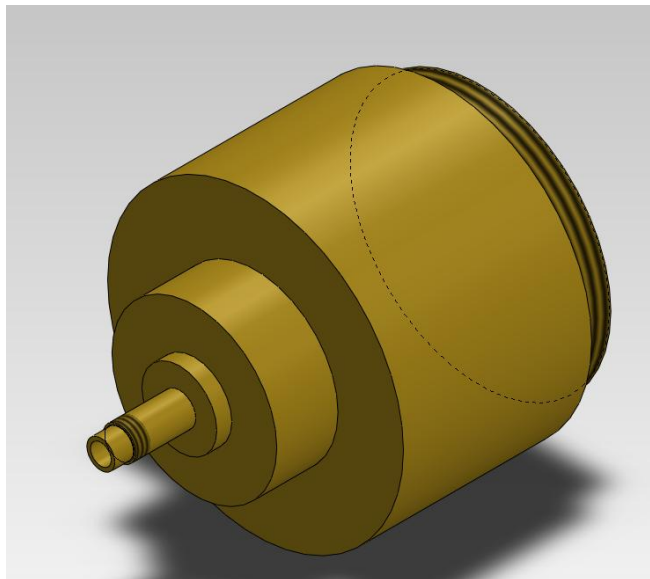


Figure 12: Part G made in SolidWorks

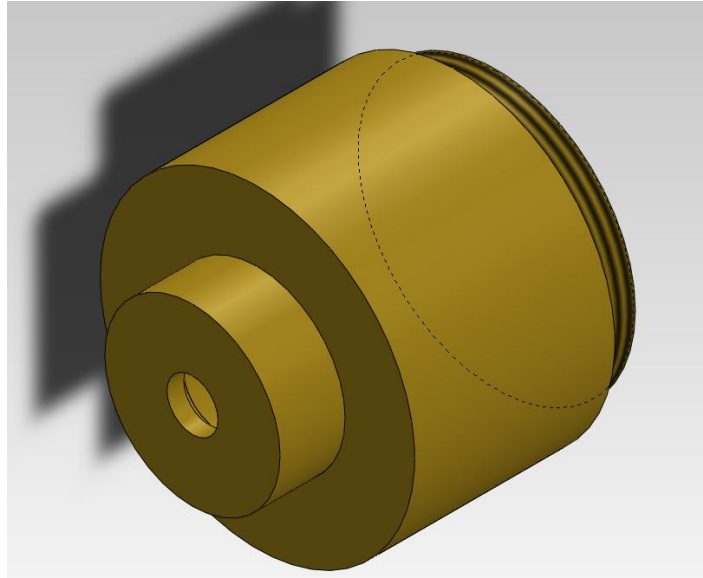


Figure 13: Part G modified in SolidWorks

In addition to the modified testing apparatus there has also been a modification made to the testing frequency range. The ASTM Standard suggests a testing range of 30 MHz to 1.5 GHz, however due to lack of equipment available to go that high, the testing range was modified from 50 Hz to 25 MHz. The intended range of testing was to extend from 50 Hz to 2 GHz.

Due to the modifications of some of the parts, some of the equipment needed would therefore also have to be modified to ensure proper connection to the testing apparatus. This brings us to the next section of the experimental set-up, the equipment used for the testing.

4.3 Testing Equipment

In this experiment there are three main pieces of equipment needed. The first piece of equipment is the testing apparatus or specimen holder. The other two major pieces of equipment are the signal generator and the receiver. A Tektronix AFG 3021B Single Channel

Arbitrary/Function Generator at 250 Ms/s and 25 MHz signal generator was used. For the receiver a Tektronix TDS5054B Digital Phosphor Oscilloscope at 5 Gs/s and 500 MHz was used to collect the data. Shown below in Figures 14 and 15 are the Signal Generator and Receiver or Oscilloscope used to conduct the testing.

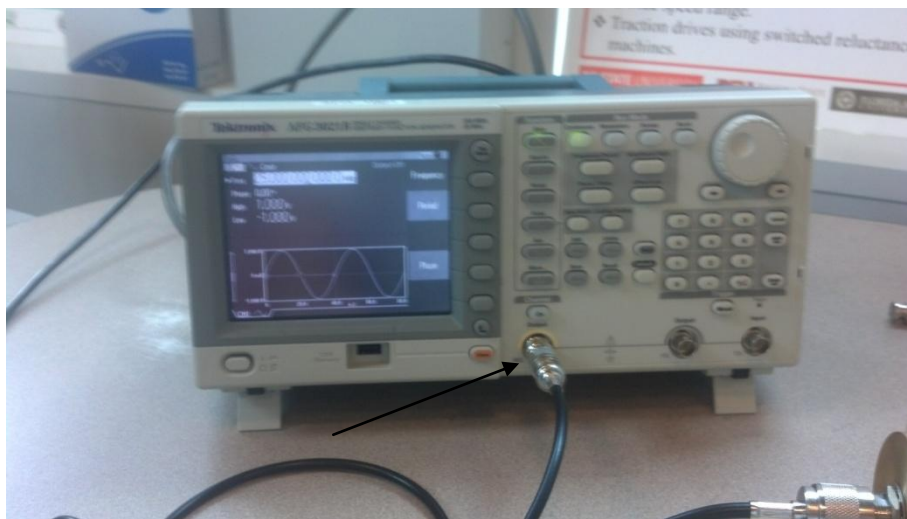


Figure 14: Tektronix AFG 3021B Signal Generator

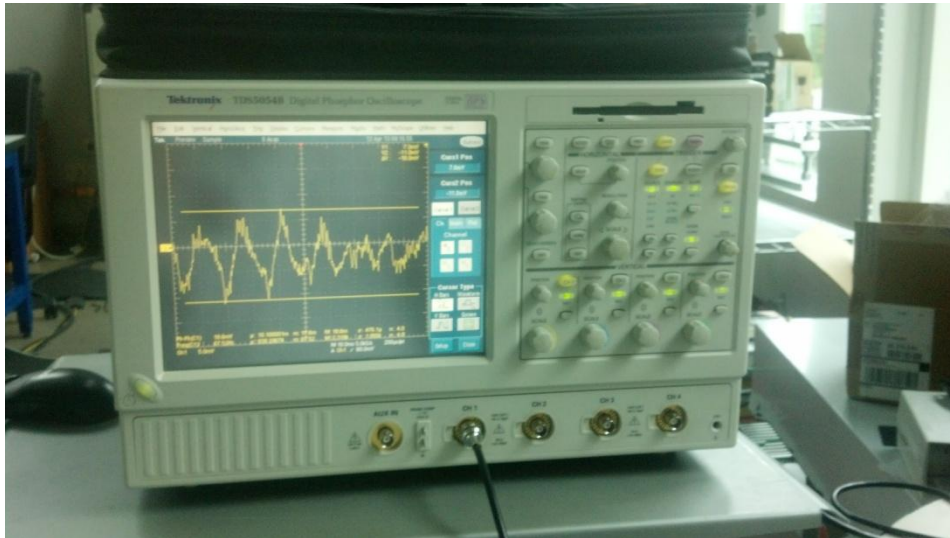


Figure 15: Tektronix TDS5054B Digital Phosphor Oscilloscope

In addition to the major equipment needed, there is also some minor equipment needed. The first being coaxial cables. These cables connect the signal generator to the testing apparatus and then the testing apparatus to the oscilloscope. The cables are required to have 50 ohm impedance which is standard for the cables. Due to the modification made to the parts of the testing apparatus, the cables need to be a type N connector on one end of the cable. However, they also need to be BNC on the other end in order to connect to the equipment being used. “Type N connectors provide more reliability and less leakage than BNC connectors” [19]. It is for this reason that the testing apparatus has type N connectors. Due to the cable needing to have both an N connection and a BNC connection, a cable had to be specially ordered to allow the testing set-up to be achieved.

The final piece of equipment needed is also a minor one, but is still very important. The attenuator is that final and very important piece. The attenuator serves to help with impedance matching. A 10 dB fixed attenuator was ordered and placed on the signal generator. In addition to impedance matching the attenuator also helps to prevent the

equipment from being overloaded with signal in the chance that all or part of the signal is reflected back into the signal generator. A close look at Figure 14 shows the attenuator attached to the signal generator and the cable attached to the attenuator (depicted by the arrow).

The equipment discussed in this section is the equipment used in this experiment. Shown below in figure 16 is a picture of the test set-up used.

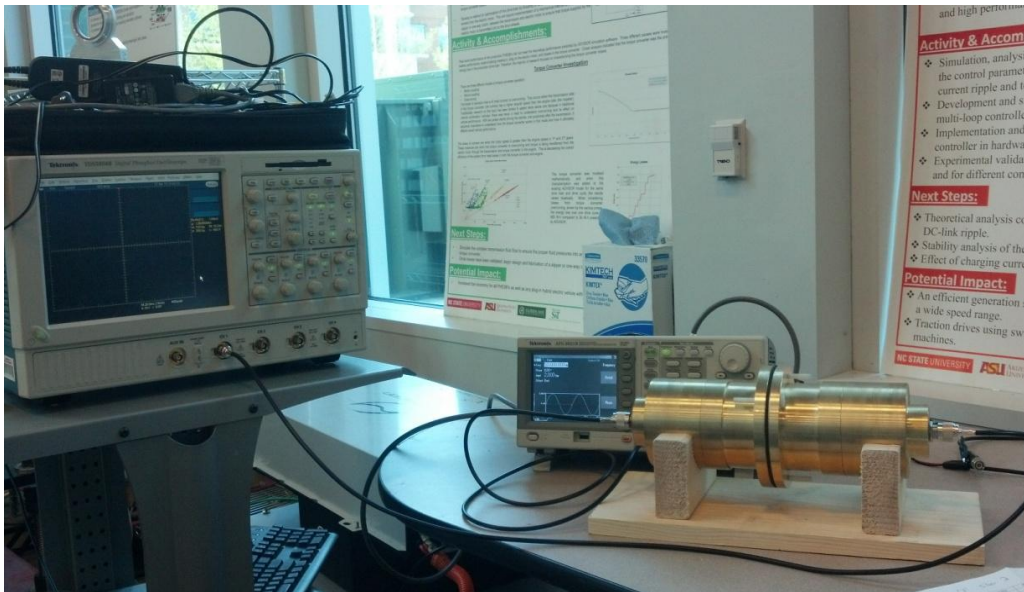


Figure 16: Test set-up of the experiment

4.4 Composite Samples

For this experiment it was decided that several different materials would be tested. The samples to be tested were flat circular panels of 5.24 inch diameter. The material that will be used in the EMI shielding of the lithium ion batteries for the NCSU ECOCar2 will be Aluminum. The purpose of this experiment was to determine if composites could provide

sufficient shielding in the place of the current material used. In this case aluminum is the current material that is used and thus this test will include composite samples as well as an aluminum sample to make a comparison.

It was decided that there would be five different composite samples to test. The composite samples consisted of: fiberglass, carbon fiber, carbon fiber with silver paint, carbon fiber with aluminum powder mixed into the resin, and carbon fiber with an aluminum mesh. There are several different methods available to make these composite samples. The samples could be made through prepreg, hand lay-up, Vacuum Assisted Resin Transfer Molding (VARTM), or Resin Transfer Molding (RTM). In this experiment the processing used to make the samples was hand lay-up. This method was chosen as the amount of samples made was small and of a simple design. Thus there was no justification to make a mold for testing purposes and thus eliminating VARTM and RTM. While prepreg is a better option for making flat panels, it would have posed a problem when trying to mix the aluminum powder into the sample and because of this it was determined hand lay-up would be the best fabrication method for this experiment. Shown below in figures 17-20 are pictures of the hand lay-up process.



Figure 17: Lay-up of the 6 layers of the Fiberglass panel



Figure 18: Peel Ply added to ensure nothing sticks to the fiberglass panel



Figure 19: Breather and Bleeder added to the fiberglass panel to soak up excess resin

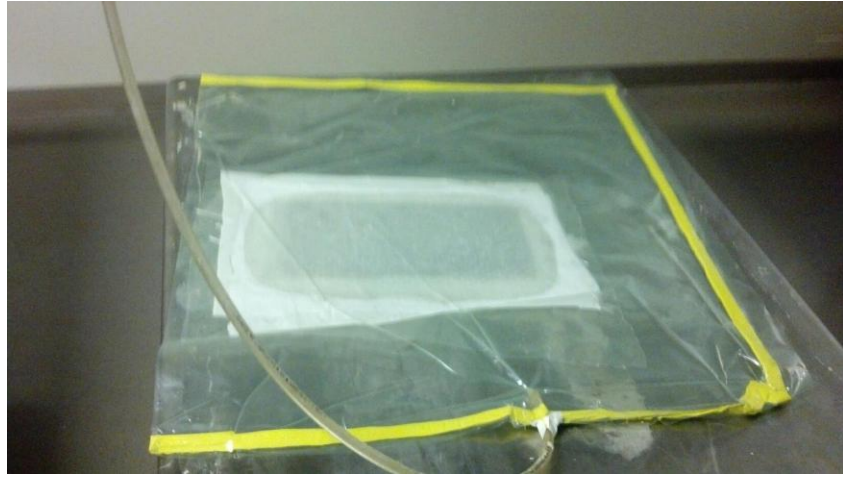


Figure 20: Vacuum bag sealed and vacuum applied to the Fiberglass panel

In order to make the samples some additional materials were needed. These materials included: vacuum bagging, 25 foot roll of adhesive tape, bleeder material, breather material, peel ply, squeegees, mixing containers, epoxy resin, hardener, silver microscopy paint, carbon fiber, fiberglass, aluminum powder, and an aluminum mesh. Most of the materials were supplied, however some of the materials needed to be bought. The Epoxy Resin system was West System 105 and a West System 206 hardener was used with the resin. In addition to this was a West System pump system that ensures the proper resin to hardener ratios. Since the resin and hardener system was West System it was decided that the aluminum powder should also be from West System. Shown below in figure 21 is a picture of the resin and hardener used.



Figure 21: West System Epoxy Resin and Hardener

The carbon fiber and fiberglass were both woven cloth. The samples were six layers thick and had dimensions of twelve inches by 6 inches. Only one panel of each of the five sample types was made. From these five panels, two circular test specimens were cut out of each panel. There were two samples from each panel to be tested to ensure proper mixing occurred and if there were any differences in resin quantity how it would affect the shielding effectiveness of the sample. There were two carbon fiber only panels that were made. One panel was used for just carbon fiber, and the other panel would later have Electron Microscopy silver paint adhesive applied to it. The carbon fiber aluminum powder sample was made with one and a half tablespoons of aluminum powder to ten pumps of epoxy resin and hardener. This is a standard mixing ratio recommended by West Systems for the resin and hardener used. Once mixed the resin/aluminum powder mix was applied to the carbon fiber layers. The final sample was the carbon fiber with aluminum mesh sample. The aluminum mesh was 8-mesh and was inserted in between the third and fourth layers of the panel.

Once vacuum was applied the samples were left to cure for 24 hours. After curing all of the samples were cut into the circular shape for testing. The cutting of the samples was done using the NCSU MAE department's water jet. This allowed the samples to be cut

accurately. Next the samples had holes drilled to allow mounting to the testing apparatus. Shown below in figures 22-27 are the finished samples ready for testing.



Figure 22: Aluminum sample



Figure 23: Fiberglass samples

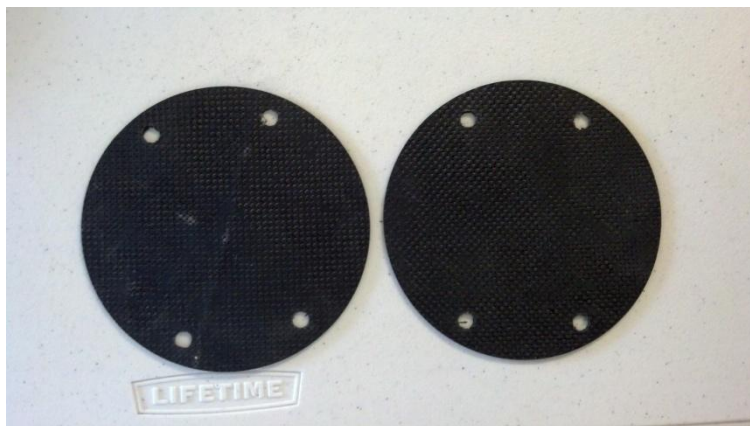


Figure 24: Carbon Fiber samples



Figure 25: Carbon Fiber with Silver Paint samples

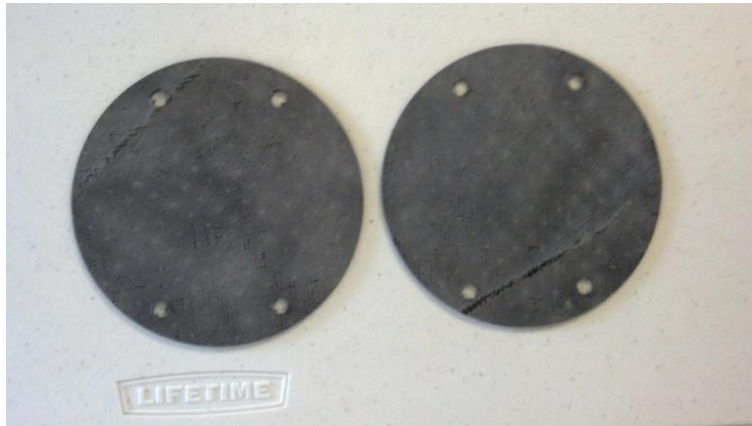


Figure 26: Carbon Fiber with Aluminum powder samples



Figure 27: Carbon Fiber with Aluminum mesh samples

5. RESULTS AND DISCUSSION

The testing of the different samples was done over a frequency range of 50 Hz to 25 MHz. The samples were all tested in the same environment under the same conditions. Voltage values were recorded in the frequency range tested for all of the samples as well as with no material present. The voltage values were the only values sought since that was the information needed to calculate shielding effectiveness. The voltage values measured were recorded and summarized in Table 3. A more complete list can be found in Appendix 2.

Table 3: Voltages of the tested samples (mV)

	V2	V1											
	Air	Fiberglass			Carbon Fiber		CF Silver		CF Al Powder		CF Al Mesh		Al
Frequency (Hz)	V	V	V	V	V	V	V	V	V	V	V	V	
50	19.6	16	15.8	1.6	1.64	1.12	1.24	0.96	1.12	1.36	1.2	0.76	
1000	238	76	67.2	1.92	1.52	1.24	1.12	1.08	1.04	1.36	1.12	0.8	
100000	306	91.2	88	2.4	2.04	1.36	1.16	1.04	1.04	1.4	1.4	0.76	
1000000	310	91.2	87.2	2.24	1.72	1.12	1.04	1.04	1	1.32	1.28	0.8	
25000000	392	100	94	2.2	1.52	1	1.16	1.04	1	1.32	1.36	0.76	

As can be seen in the Table 3 the samples have very minimal variance in the voltage values measured. However, the carbon fiber samples have some considerable variance in voltage values. This variance could be attributed to a few different possibilities. The first possibility is that the variance is due to matrix inconsistencies in the two samples or resin rich areas causing higher voltages to be measured. These higher voltages would then cause

a decrease in shielding effectiveness as the epoxy resin is not as conductive as that of carbon fiber. Another possibility is that there were more cracks/voids in one sample than in the other sample. There are several different possibilities; however these are the most likely two causes. These possibilities behind the variances were the reasons that two samples of each material were tested. It was done to ensure that there was consistency throughout the panels made. Shown below is equation 1 that was used in the ASTM D4935 and this experiment to calculate shielding effectiveness.

$$\textit{Shielding Effectiveness (SE)} = 20 * \log \frac{V_1}{V_2} \textit{ (dB) ... equation 1}$$

where V_1 = Voltage with material present

where V_2 = Voltage without material present

The calculated values of shielding effectiveness can be seen below in Table 4. A more complete list can be found in Appendix 3. When comparing Tables 4 and 5 the voltage differences and how they affect the shielding effectiveness can be seen. As stated above the addition of resin rich areas would provide less shielding due to the lack of conductivity. This is evident and is depicted in Table 3 and Appendix 2 from the frequency range of 700 KHz to the 25 MHz.

Table 4: Shielding Effectiveness Values (-dB)

	Fiberglass		Carbon Fiber		CF Silver		CF Al Powder		CF Al Mesh	
Frequency (Hz)	SE 1	SE2	SE1	SE2	SE1	SE2	SE1	SE2	SE1	SE2
50	1.762722	1.87198	21.76272	21.54824	24.86076	23.97669	26.1997	24.86076	23.17434	24.2615
1000	9.915267	10.98415	41.86551	43.89467	45.66311	46.54718	46.86306	47.19087	44.86076	46.54718
100000	10.51453	10.82478	42.1102	43.52183	47.04365	48.42527	49.37376	49.37376	46.79187	46.79187
1000000	10.62734	11.0169	42.82227	45.11666	48.84287	49.48657	49.48657	49.82723	47.41576	47.68303
25000000	11.86572	12.40316	45.01727	48.22885	51.86572	50.57656	51.52505	51.86572	49.45424	49.19494

From the data above it can be concluded that the carbon fiber samples did not have consistent resin distribution thus causing resin rich areas. Those resin rich areas caused differences in voltages and thus differences in shielding effectiveness. It was determined that an average of the shielding effectiveness values should be used. Shown below in Table 5 are the average values for each material tested. A more complete list can be found in Appendix 4.

Table 5: Averaged Shielding Effectiveness Values (-dB)

	Al	Fiberglass	CF	CF Silver	CF Al Powder	CF Al Mesh
Frequency (Hz)	SE	SE	SE	SE	SE	SE
50	28.22885	1.817351	21.65548	24.41872	25.5302289	23.71792
1000	49.46974	10.44971	42.88009	46.10514	47.0269682	45.70397
1000000	51.76543	10.82212	43.96947	49.16472	49.6569005	47.549395
25000000	54.24945	12.13444	46.62306	51.22114	51.6953879	49.324593

Each value calculated was then plotted for a better visual representation of the shielding effectiveness of the materials and how they compare. Shown below in figures 28-31 are the graphs of shielding effectiveness vs. frequency.

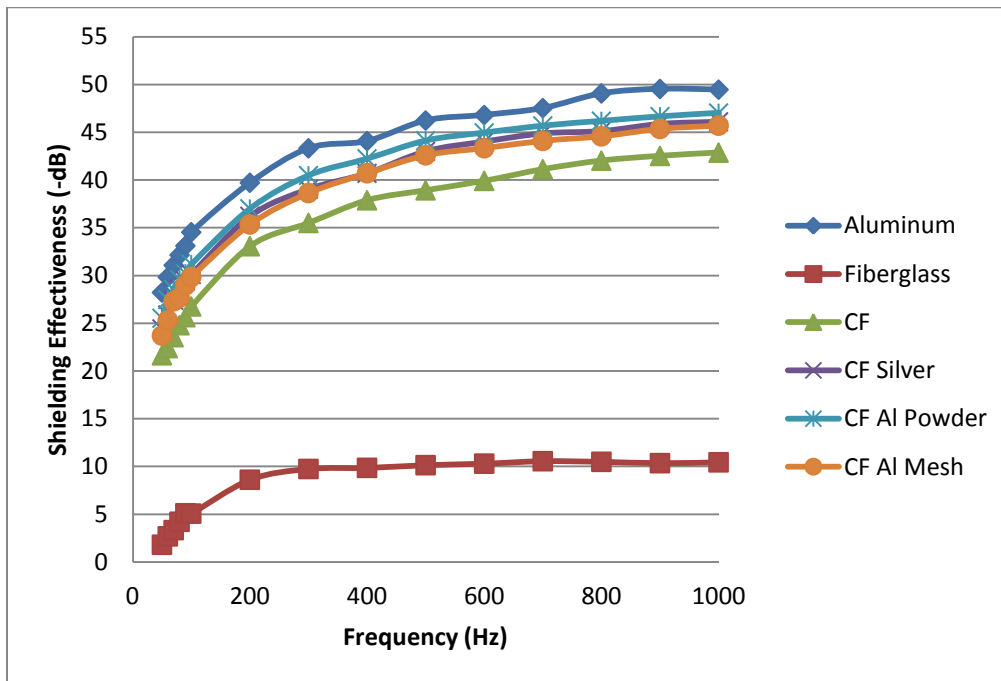


Figure 28: Shielding Effectiveness in the Hz to KHz range

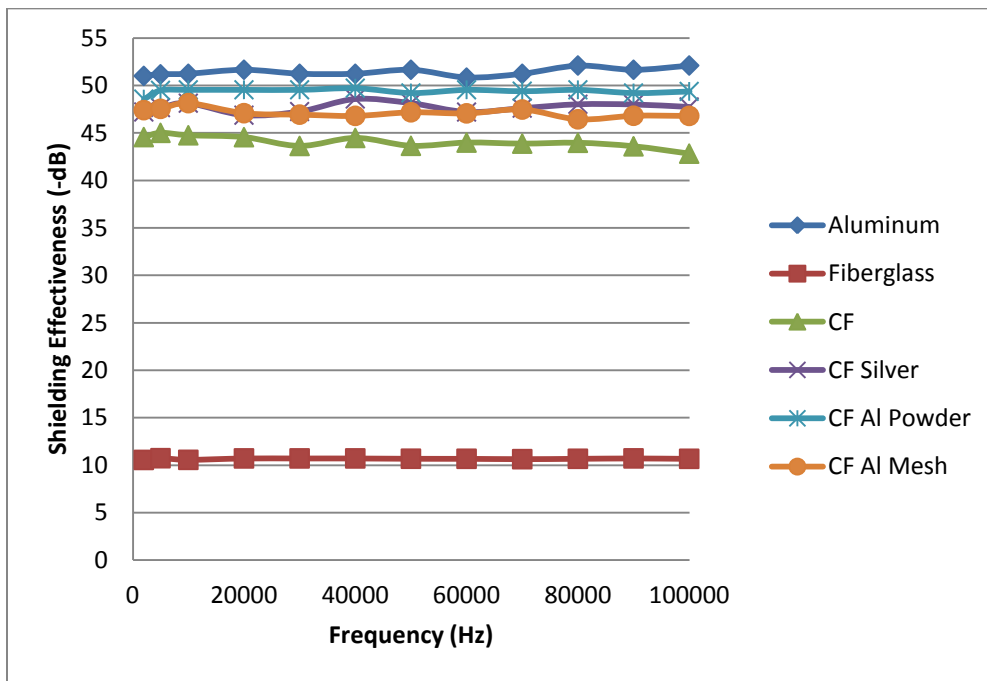


Figure 29: Shielding Effectiveness in the KHz range

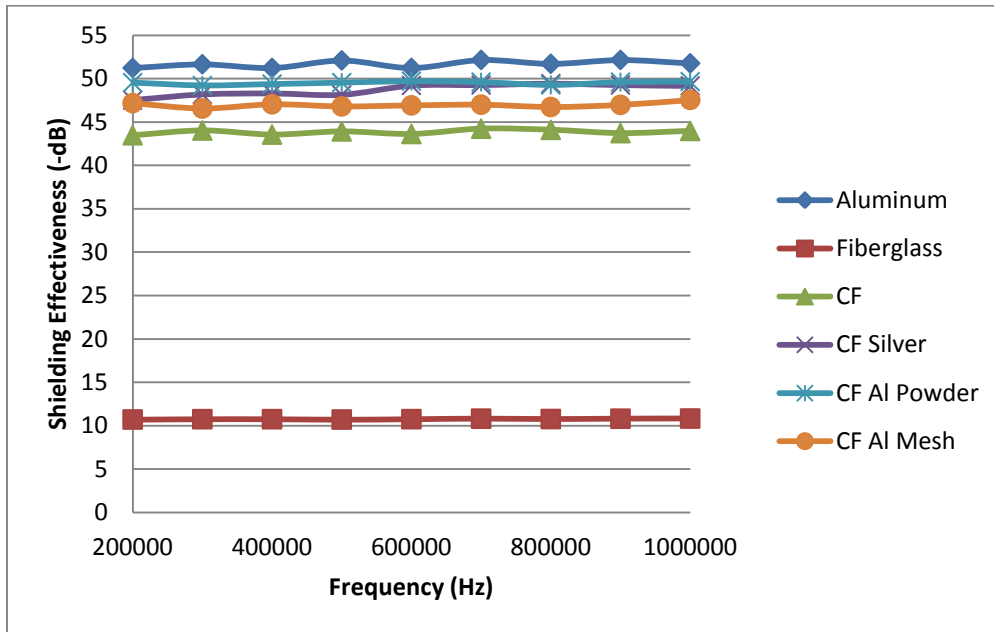


Figure 30: Shielding Effectiveness in the KHz to MHz range

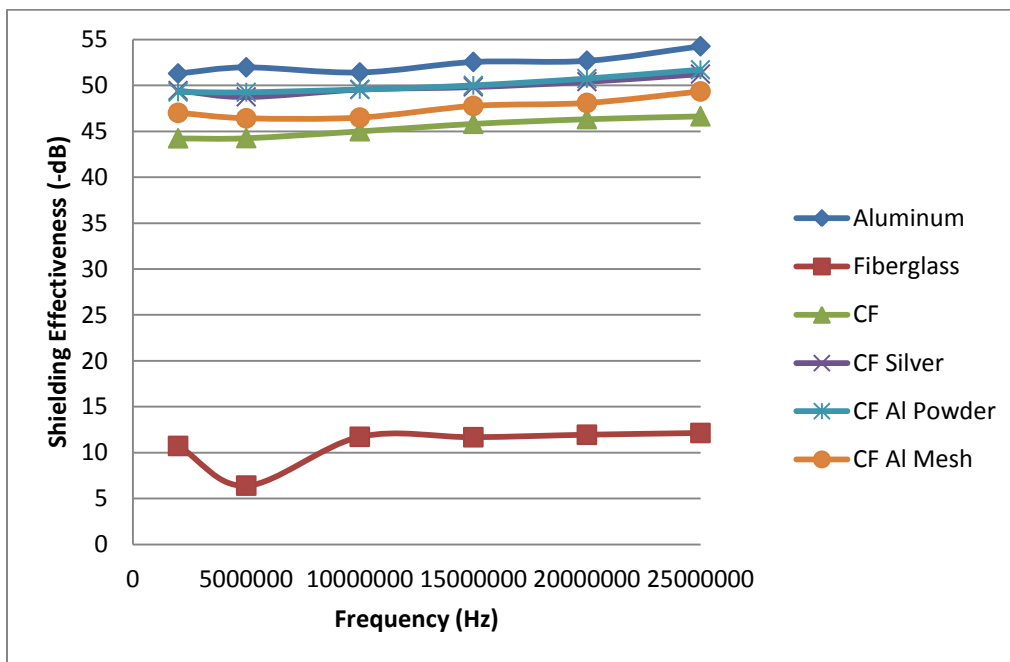


Figure 31: Shielding Effectiveness in the MHz range.

There are several things of importance to discuss from the graphs shown above. The first thing is that all of the carbon fiber samples performed very well and were within 10 dB of the aluminum material. This is an acceptable difference between the materials because the frequency range is so small that in normal instances wave propagation that would come into contact with any instrumentation would be lower than the 45 dB of shielding effectiveness. However, the fiberglass sample performed very poorly and could not be used as a replacement to aluminum. While it performed poorly, this was expected from the test as fiberglass is known to have very poor conductive properties.

The next thing of importance from these graphs is to note how the shielding effectiveness of the samples normalizes after the KHz range. The initial part of the graph from the 50 Hz to 1 KHz frequency range has a slope that increases. This is due to the specimen holder acting as a high pass filter. The specimen holder is designed to deliver the source signal to the sample under test at the 50 ohm impedance as the transmission itself. The function generator and the transmission cables are 50 ohm impedance. This is the standard for generating, transmitting, and receiving signals. The design of the specimen holder is to match this 50 ohm impedance. Its design gives way to its inherent feature to create a high pass filter. The specimen holder uses air as its separator of the input signal, center conductor, and its input return, commonly known as signal ground or ground, outer brass shell. This design causes a high capacitive reactance in the overall impedance of the specimen holder. This capacitive reactance is what makes a high pass filter.

As stated above, all of the carbon fiber samples could be used as a replacement for aluminum. The carbon fiber sample with aluminum mesh sample did not perform as expected. While it performed well and can be used as a replacement, it was expected to perform higher and more closely to that of aluminum. This performance could be explained by a simple concept of grounding. The aluminum mesh and carbon fiber provide good conductivity, however the aluminum mesh is not grounded to anything. Grounding is very important in dissipating EMI. In numerous articles good grounding plays a crucial role to

EMI shielding and is talked about extensively. When talking with professionals in the electronics field, it is known that all attempts to provide a good ground is crucial in reducing or eliminating EMI. So had the sample with aluminum mesh been grounded it could have performed better than what is shown above in the graphs.

As the frequencies are increased the mechanisms of reflection, absorption, and multiple reflections are not the only contributors for EMI. There is an additional affect known as the skin effect. What this entails is that at the high frequencies the signals tend to follow the outside of the conductive material. What this means is that the wave will not penetrate the material and thus the shielding effectiveness of conductors should be higher at the higher frequencies. As the frequencies are increased further into the MHz and GHz frequencies it would be expected that the shielding effectiveness stays the same from the graphs. However, it would be expected that the aluminum shielding effectiveness would increase as it is a conductive material and the skin effect would occur. If the composite samples have conductivity similar to that of aluminum or other metals it would be expected that the shielding effectiveness of the composites would increase as well.

While the data collected was sufficient for the application of a battery case for NCSU's EcoCAR2, for mass production vehicles the use of this composite in such applications requires a more professional electrical test and further mechanical testing. At the professional level EMI testing is conducted in special enclosed rooms and with more accurate equipment. There are also several different testing methods that should be explored including closed horn and open dipole antenna testing.

6. CONCLUSION

The purpose of the testing in this thesis was to determine if composites could provide enough shielding effectiveness to replace aluminum in the EcoCAR2's Lithium Ion Battery Case. According to the results of the testing conducted, it can be concluded that all of the samples excluding fiberglass can be used as a sufficient replacement for the aluminum case. The carbon fiber samples with aluminum powder and silver paint are the best of the four carbon fiber samples. These are the two samples that should be seriously considered for replacing the aluminum material in the battery case in the EcoCAR2. These two were determined to be more suitable as there is less than a 5 db variance in shielding in both samples when compared to the aluminum sample tested. In the experiment conducted both the aluminum powder and silver paint were about the same price, \$45. However, the quantity of each received varied drastically. The amount of aluminum powder for \$45 was 36 ounces, whereas the amount of silver paint adhesive for \$45 was 15 grams. In making the samples the entire 15g bottle of silver paint adhesive was used for coating two samples. There were five coats of silver adhesive per sample with a 4 inch diameter. However, the aluminum powder sample only used one and half tablespoons of the 36 oz container. In terms of cost effectiveness of the samples the aluminum powder is the more cost effective option. The testing frequency range was a low frequency range, however since the application of this composite is for the lithium ion battery case it is acceptable. The reasoning behind this acceptance is due to the battery operating under DC current instead of AC. In DC current or in this case the charging and discharging of the lithium ion battery the emissions will be of a lower frequency than most other electrical devices. For this reason the frequency range tested should be sufficient for the battery case and the carbon fiber aluminum powder sample could be used as a replacement.

7. FUTURE WORKS/RECOMMENDATIONS

As stated earlier, the purpose of the testing in this thesis was to determine if composites could provide enough shielding effectiveness to replace aluminum in the EcoCAR2's Lithium Ion Battery Case. The work done in this thesis was very specific. However, there is much more that could be done to further the research done on this subject. It was determined that the Aluminum powder mixed into the epoxy matrix and the silver paint layers added to the carbon fiber composite were the closest to the solid aluminum piece in terms of shielding effectiveness. The first thing to test would be varying the amount of reinforcement/additives to see if varying these will increase or decrease the shielding effectiveness. The second thing that could be modified is the frequency range. Testing the samples from the Hz to GHz frequency range would provide an accurate shielding effectiveness over the full EMI frequency range. This would allow for potential uses for other applications if the composites would provide sufficient amount of shielding. It has also been determined that most problems that occur in vehicles occur in the 88-108 MHz range [22]. While the current test found these composites acceptable to use as a replacement for aluminum for the battery case, it is possible that these materials will not shield enough EMI from other devices. Another test that could be done is on different types of composite samples. These samples could include nanotubes and carbon-carbon composites. Finally, testing could be done on materials which are grounded to see if there is any variation of the shielding effectiveness. As was stated earlier in the discussion, there should be some form of an increase in shielding effectiveness when the material is grounded. Several different avenues have been left open and allow for further research to be done in this area. These are just a few of the possible avenues that can be explored as the field of composites is growing and there is plenty of other research to explore.

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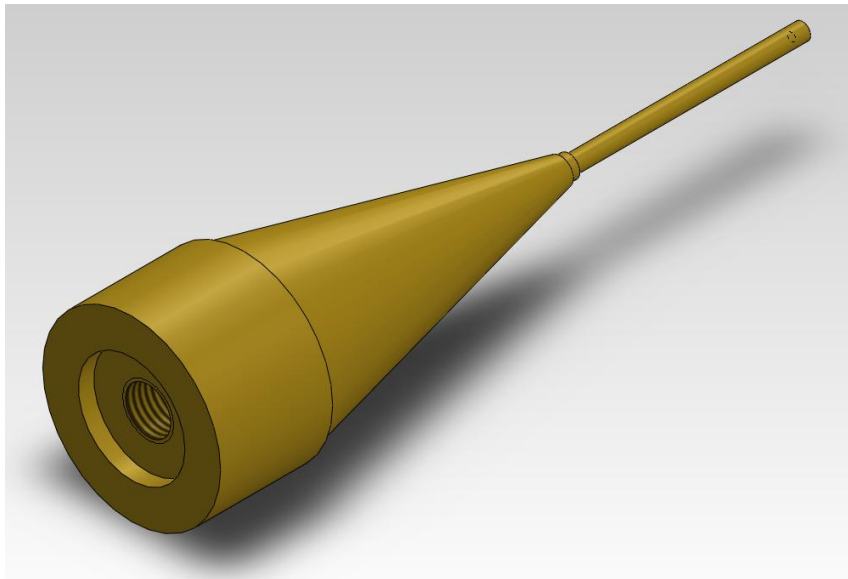
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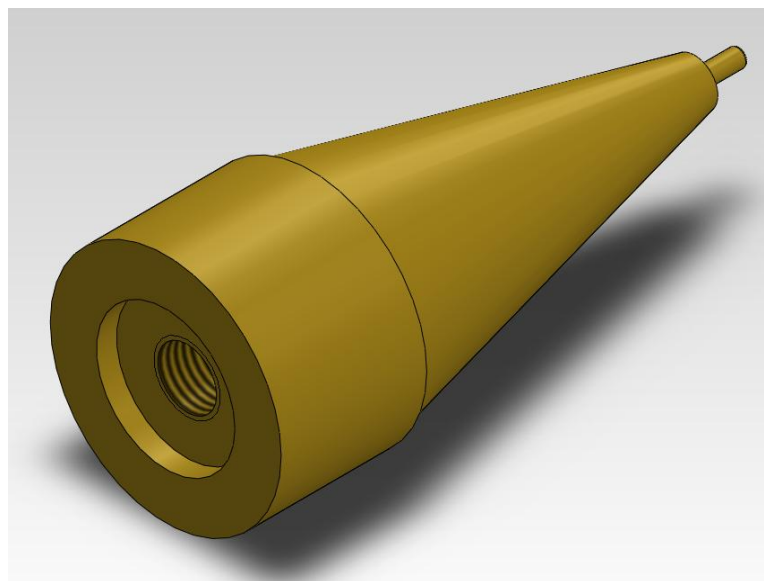
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APPENDICES

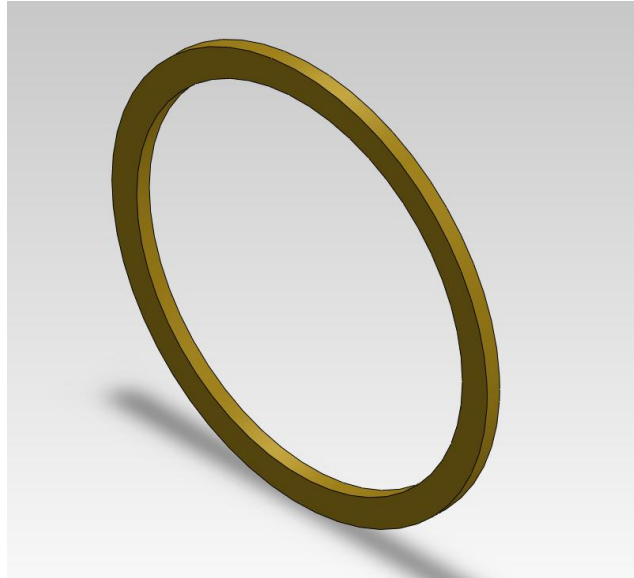
Appendix 1: Testing Apparatus Parts and Assemblies



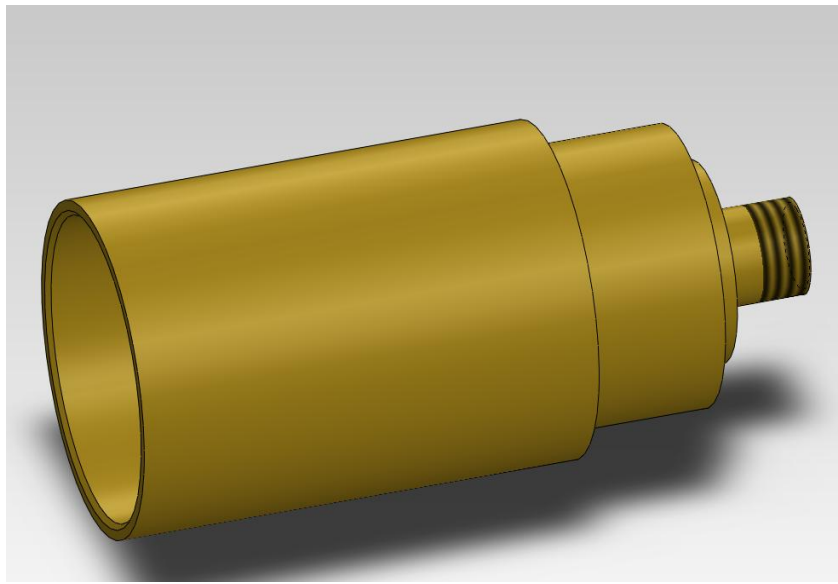
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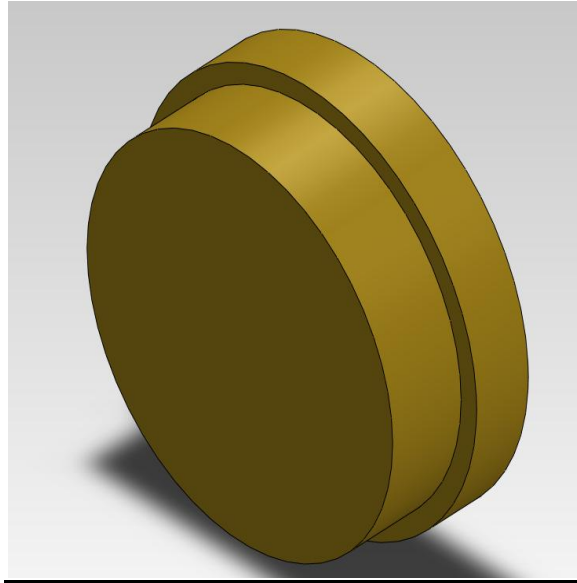
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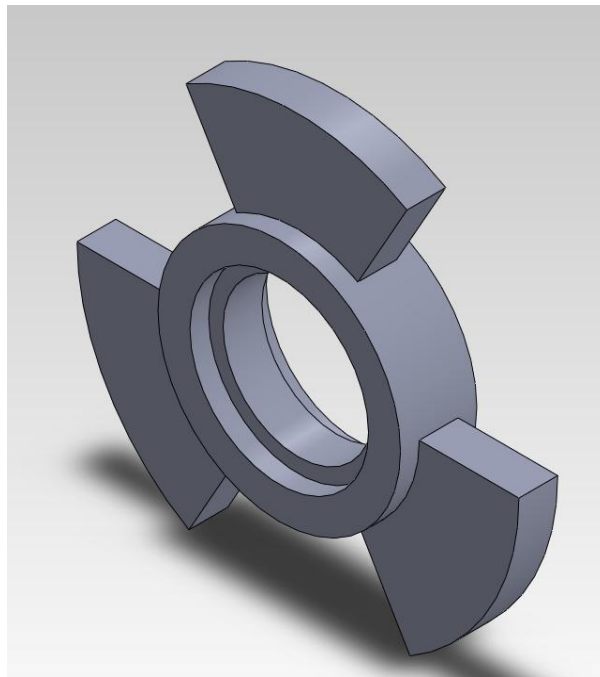
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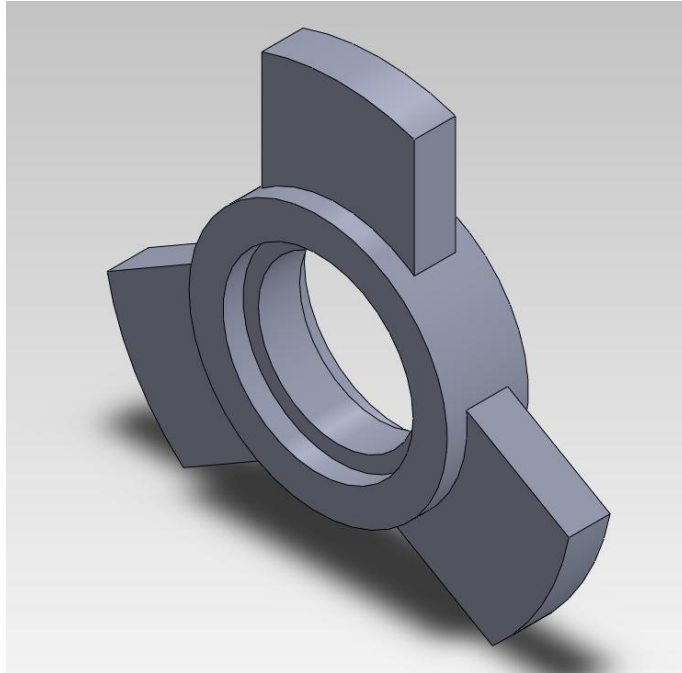
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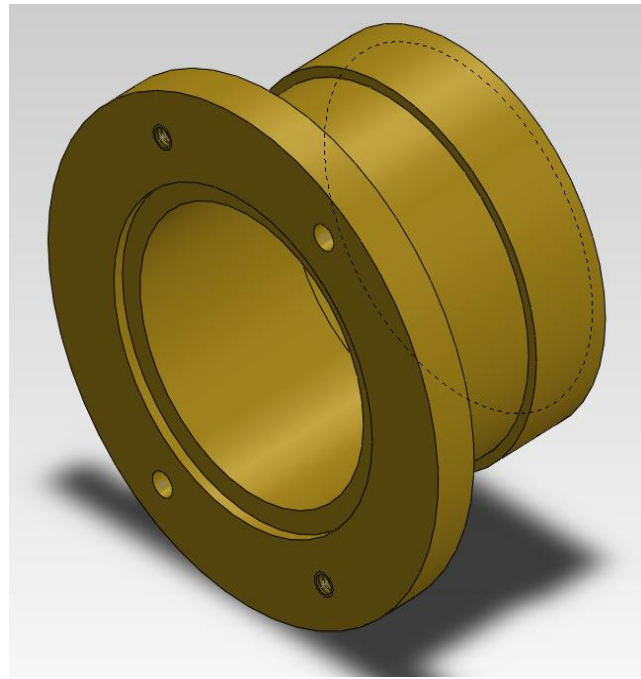
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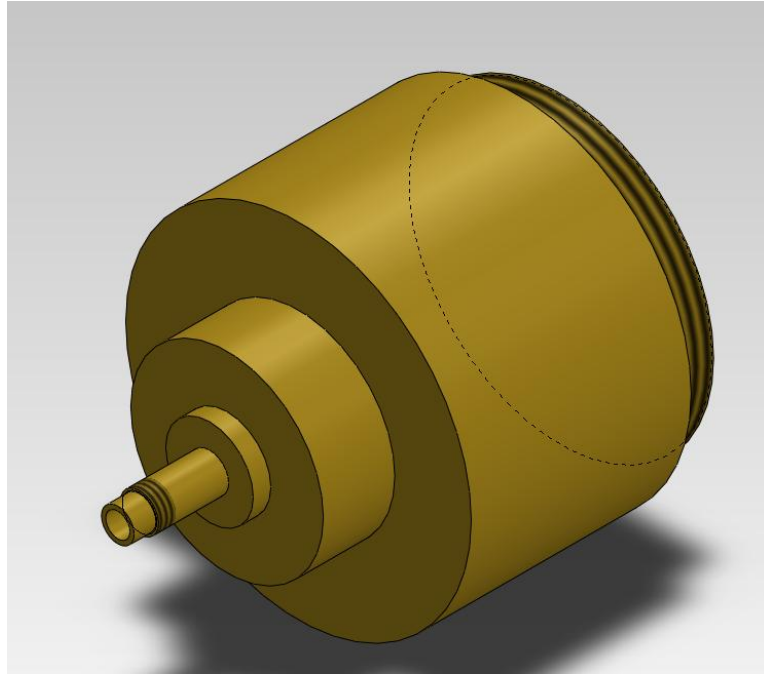
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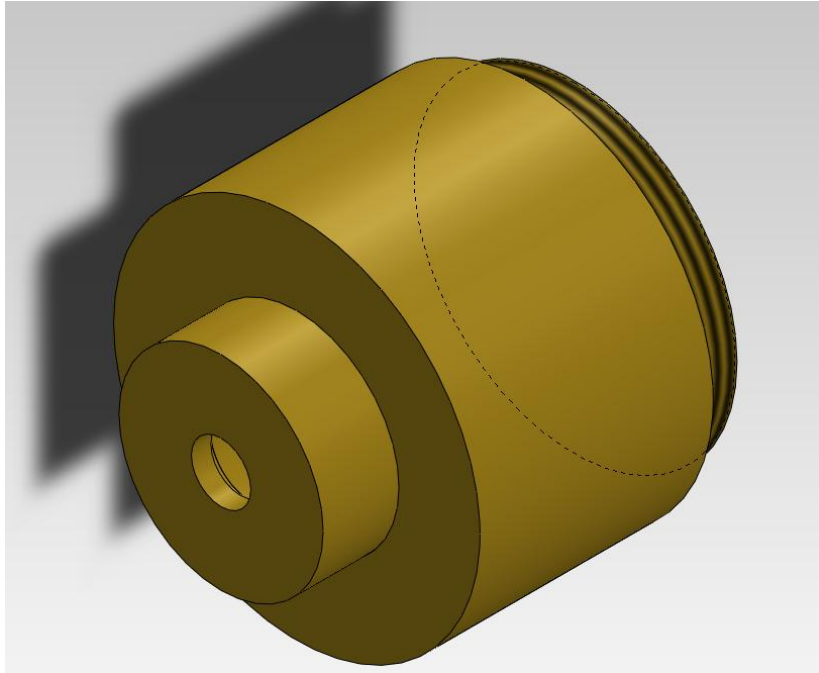
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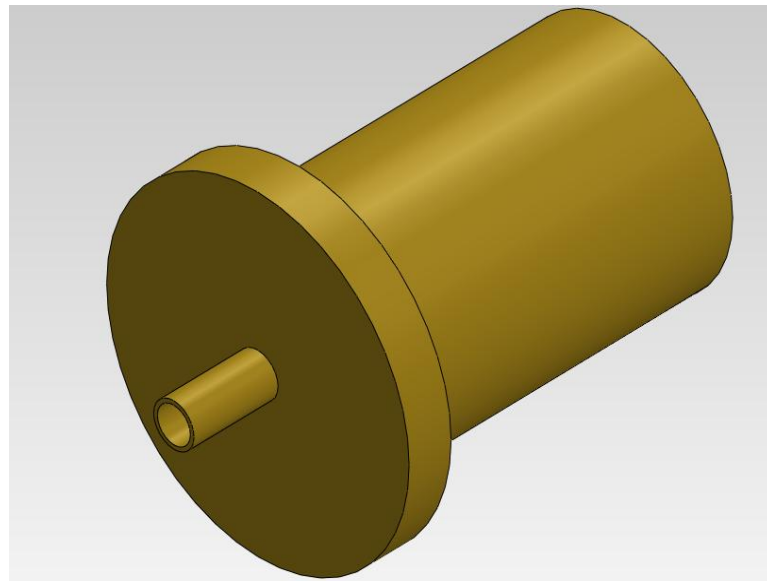
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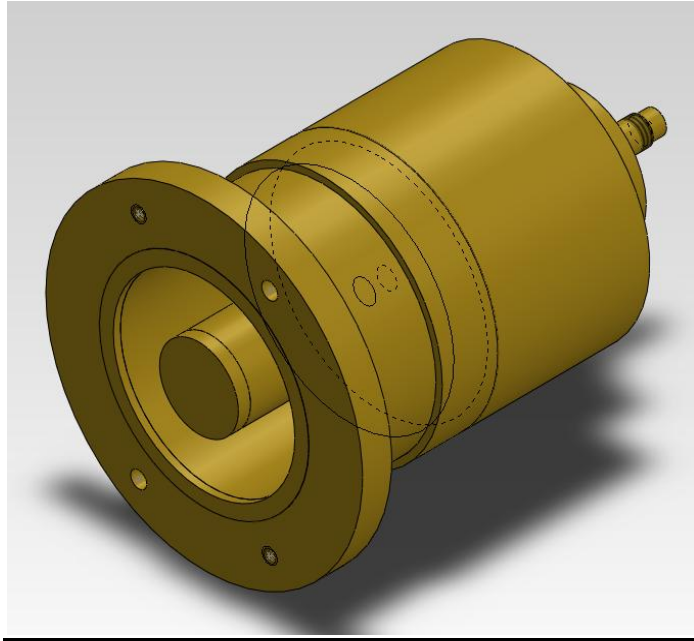
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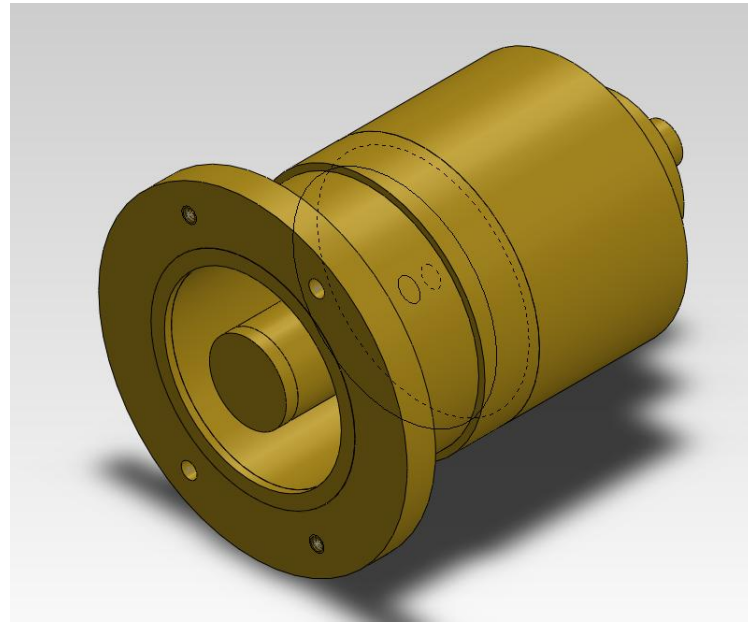
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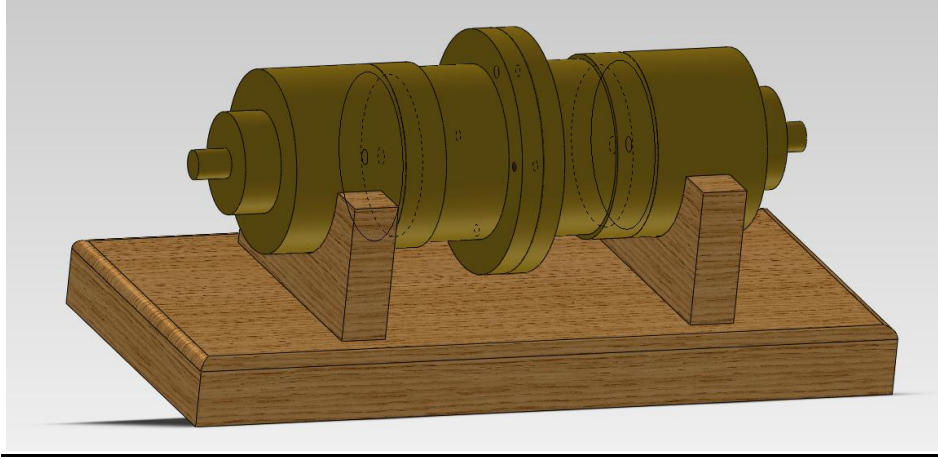
Special N Connector



ASTM Half Assembly



Modified Half Assembly



Modified Assembly on its wooden stand

Appendix 2: Voltage Values of the tested samples (mV)

	V2	V1										
	Air	Fiberglass		Carbon Fiber		CF Silver		CF Al Powder		CF Al Mesh		Al
Frequency (Hz)	V	V	V	V	V	V	V	V	V	V	V	V
50	19.6	16	15.8	1.6	1.64	1.12	1.24	0.96	1.12	1.36	1.2	0.76
60	23.6	17.4	17.2	2	1.6	1.16	1.24	0.92	1.08	1.36	1.2	0.76
70	27.2	18.4	18.6	2.04	1.6	1.08	1.24	0.96	1.08	1.32	1.04	0.76
80	30.8	20.4	17.6	1.96	1.6	1.12	1.16	1.04	1	1.44	1.12	0.76
90	34.4	19.2	19	1.92	1.68	1.16	1.16	1.04	1.08	1.44	1.04	0.76
100	38.4	21.4	21.4	2.04	1.52	1.12	1.28	1.08	1.04	1.36	1.12	0.72
200	73.6	28.6	26	1.96	1.36	1.08	1.2	1	1.08	1.36	1.16	0.76
300	105.6	36	32.8	2.24	1.4	1.24	1.12	0.96	1.04	1.36	1.12	0.72
400	134.4	45.2	41.2	2.04	1.44	1.2	1.28	1	1.08	1.32	1.16	0.84
500	164	52.8	49.2	2	1.72	1.2	1.12	1	1.04	1.32	1.12	0.8
600	184	58.4	54	1.96	1.76	1.24	1.08	1.04	1.04	1.4	1.12	0.84
700	200	63.6	55.2	2.08	1.48	1.16	1.12	1.04	1.04	1.44	1.08	0.84
800	216	68.4	60.8	1.92	1.52	1.28	1.12	1.04	1.08	1.4	1.16	0.76
900	228	71.2	67.2	1.96	1.48	1.2	1.12	1.08	1.04	1.4	1.08	0.76
1000	238	76	67.2	1.92	1.52	1.24	1.12	1.08	1.04	1.36	1.12	0.8
2000	284	88.8	80	1.96	1.44	1.28	1.2	1.08	1.04	1.36	1.08	0.8
5000	304	92	84.8	1.92	1.52	1.32	1.2	1	1.04	1.36	1.2	0.84
10000	306	94.4	87.2	1.96	1.6	1.2	1.2	1.04	1	1.24	1.16	0.84
20000	306	92	86.4	2.16	1.52	1.72	1.12	1.04	1	1.48	1.24	0.8
30000	306	92	86.4	2.16	1.88	1.52	1.16	1	1.04	1.44	1.32	0.84
40000	306	92	86.4	2.04	1.64	1.16	1.12	1	1	1.44	1.36	0.84
50000	306	93.6	85.6	2.2	1.84	1.24	1.16	1.08	1.04	1.32	1.36	0.8

60000	306	92	87.2	2.08	1.8	1.44	1.24	1.04	1	1.44	1.28	0.88
70000	306	92.8	87.2	2.4	1.6	1.4	1.16	1.12	0.96	1.4	1.2	0.84
80000	306	92.8	86.4	2.24	1.68	1.32	1.12	1.04	1	1.4	1.52	0.76
90000	306	92.8	85.6	2.44	1.68	1.28	1.16	1.04	1.08	1.48	1.32	0.8
100000	306	91.2	88	2.4	2.04	1.36	1.16	1.04	1.04	1.4	1.4	0.76
200000	306	92	86.4	2.24	1.88	1.48	1.12	1.04	1	1.32	1.36	0.84
300000	306	91.2	86.4	2.32	1.6	1.32	1.08	1.08	1.04	1.4	1.48	0.8
400000	306	91.2	86.4	2.2	1.88	1.24	1.12	1.04	1.04	1.36	1.36	0.84
500000	306	91.2	87.2	2.32	1.64	1.2	1.2	1.04	1	1.36	1.44	0.76
600000	306	92	85.6	2.12	1.92	1.04	1.08	1	1	1.36	1.4	0.84
700000	308	91.2	86.4	2.24	1.6	1.08	1.04	1.04	1	1.28	1.48	0.76
800000	308	92	86.4	2.2	1.68	1.04	1.04	1.04	1.08	1.44	1.4	0.8
900000	308	90.4	87.2	2.4	1.68	1.08	1.04	1.04	1	1.4	1.36	0.76
1000000	310	91.2	87.2	2.24	1.72	1.12	1.04	1.04	1	1.32	1.28	0.8
2000000	308	89.6	89.6	2.24	1.6	1.04	1.04	1.08	1.04	1.48	1.28	0.84
5000000	301	146	142	2.24	1.52	1.08	1.12	1.08	1	1.44	1.44	0.76
10000000	312	84	78	2.08	1.48	1	1.08	1.04	1.04	1.52	1.44	0.84
15000000	322	86	82	1.84	1.48	1	1.08	1.04	1	1.28	1.36	0.76
20000000	344	90	84	1.92	1.44	1.04	1.04	1	1	1.28	1.44	0.8
25000000	392	100	94	2.2	1.52	1	1.16	1.04	1	1.32	1.36	0.76

Appendix 3: Shielding Effectiveness Values (-dB)

Frequency (Hz)	Fiberglass		Carbon Fiber		CF Silver		CF Al Powder		CF Al Mesh	
	SE 1	SE2	SE1	SE2	SE1	SE2	SE1	SE2	SE1	SE2
50	1.762722	1.87198	21.76272	21.54824	24.86076	23.97669	26.1997	24.86076	23.17434	24.2615
60	2.647255	2.747671	21.43764	23.37584	26.16908	25.58981	28.18248	26.78976	24.78746	25.87462
70	3.395022	3.301119	22.49877	24.60898	28.0229	26.82294	29.04595	28.0229	26.2799	28.35071
80	3.578411	4.860761	23.92589	25.68861	28.78665	28.48185	29.43035	29.77101	26.60376	28.78665
90	5.065144	5.156097	25.06514	26.22498	29.44201	29.44201	30.3905	30.06269	27.56392	30.3905
100	5.078349	5.078349	25.49402	28.04975	30.70226	29.54243	31.01815	31.34596	29.01585	30.70226
200	8.210236	9.038089	31.49243	34.66678	36.66908	35.75393	37.33756	36.66908	34.66678	36.0484
300	9.347228	10.1558	33.46832	37.55072	38.60484	39.48892	40.82785	40.13261	37.8025	39.48892
400	9.465217	10.27004	36.37538	39.40074	40.98436	40.42379	42.56799	41.89951	40.15651	41.27883
500	9.844199	10.45757	38.27628	39.58631	42.71325	43.31252	44.29688	43.95621	41.8854	43.31252
600	9.9681	10.64848	39.45124	40.3861	43.42792	44.62788	44.95569	44.95569	42.3738	44.312
700	9.951458	11.18182	39.65933	42.61537	44.73144	45.03624	45.67993	45.67993	42.85335	45.35212
800	9.987953	11.011	41.02305	43.0522	44.54488	45.70471	46.34841	46.0206	43.76651	45.39992
900	10.1091	10.61131	41.31358	43.75346	45.57507	46.17434	46.49022	46.81803	44.23614	46.49022
1000	9.915267	10.98415	41.86551	43.89467	45.66311	46.54718	46.86306	47.19087	44.86076	46.54718

2000	10.09811	11.00457	43.22125	45.89912	46.92217	47.48274	48.39789	48.7257	46.39559	48.39789
5000	10.38172	11.08955	43.99145	46.0206	47.24599	48.07385	49.65747	49.3168	46.98669	48.07385
10000	10.21499	10.9041	43.86931	45.63203	48.1308	48.1308	49.37376	49.71443	47.84599	48.42527
20000	10.43867	10.98415	43.02535	46.07756	45.00386	48.73007	49.37376	49.71443	46.30919	47.84599
30000	10.43867	10.98415	43.02535	44.23127	46.07756	48.42527	49.71443	49.37376	46.54718	47.30295
40000	10.43867	10.98415	43.52183	45.41755	48.42527	48.73007	49.71443	49.71443	46.54718	47.04365
50000	10.28891	11.06495	42.86597	44.41807	47.84599	48.42527	49.04595	49.37376	47.30295	47.04365
60000	10.43867	10.9041	43.35316	44.60898	46.54718	47.84599	49.37376	49.71443	46.54718	47.57023
70000	10.36347	10.9041	42.1102	45.63203	46.79187	48.42527	48.73007	50.069	46.79187	48.1308
80000	10.36347	10.98415	42.70947	45.20824	47.30295	48.73007	49.37376	49.71443	46.79187	46.07756
90000	10.36347	11.06495	41.96663	45.20824	47.57023	48.42527	49.37376	49.04595	46.30919	47.30295
100000	10.51453	10.82478	42.1102	43.52183	47.04365	48.42527	49.37376	49.37376	46.79187	46.79187
200000	10.43867	10.98415	42.70947	44.23127	46.30919	48.73007	49.37376	49.71443	47.30295	47.04365
300000	10.51453	10.98415	42.40467	45.63203	47.30295	49.04595	49.04595	49.37376	46.79187	46.30919
400000	10.51453	10.98415	42.86597	44.23127	47.84599	48.73007	49.37376	49.37376	47.04365	47.04365
500000	10.51453	10.9041	42.40467	45.41755	48.1308	48.1308	49.37376	49.71443	47.04365	46.54718
600000	10.43867	11.06495	43.18771	44.0484	49.37376	49.04595	49.71443	49.71443	47.04365	46.79187
700000	10.57112	11.04074	42.76605	45.68861	49.10254	49.43035	49.43035	49.77101	47.62681	46.36578
800000	10.49526	11.04074	42.92256	45.26483	49.43035	49.43035	49.43035	49.10254	46.60376	46.84845

900000	10.64765	10.96068	42.16679	45.26483	49.10254	49.43035	49.43035	49.77101	46.84845	47.10024
1000000	10.62734	11.0169	42.82227	45.11666	48.84287	49.48657	49.48657	49.82723	47.41576	47.68303
2000000	10.72485	10.72485	42.76605	45.68861	49.43035	49.43035	49.10254	49.43035	46.36578	47.62681
5000000	6.284273	6.525563	42.56637	45.93446	48.90285	48.58697	48.90285	49.57133	46.40408	46.40408
10000000	11.39751	12.0412	43.52183	46.47786	49.88309	49.21462	49.54243	49.54243	46.24622	46.71584
15000000	11.46715	11.88084	44.86076	46.75188	50.15712	49.48864	49.81645	50.15712	48.01292	47.48634
20000000	11.64632	12.24558	45.06514	47.56392	50.3905	50.3905	50.73117	50.73117	48.58697	47.56392
25000000	11.86572	12.40316	45.01727	48.22885	51.86572	50.57656	51.52505	51.86572	49.45424	49.19494

Appendix 4: Averaged Shielding Effectiveness Values (-dB)

	Al	Fiberglass	CF	CF Silver	CF Al Powder	CF Al Mesh
Frequency (Hz)	SE	SE	SE	SE	SE	SE
50	28.22885	1.817351	21.65548	24.41872	25.5302289	23.71792
60	29.84197	2.697463	22.40674	25.87944	27.4861242	25.331039
70	31.07511	3.34807	23.55388	27.42292	28.5344282	27.315305
80	32.15474	4.219586	24.80725	28.63425	29.6006809	27.695209
90	33.1149	5.110621	25.64506	29.44201	30.2265979	28.977211
100	34.53997	5.078349	26.77189	30.12234	31.1820535	29.859055
200	39.72128	8.624162	33.07961	36.21151	37.0033187	35.357587
300	43.32663	9.751515	35.50952	39.04688	40.4802326	38.645709
400	44.0824	9.867629	37.88806	40.70407	42.2337478	40.717666
500	46.23508	10.15089	38.93129	43.01288	44.1265436	42.598957
600	46.81077	10.30829	39.91867	44.0279	44.9556897	43.342896
700	47.53501	10.56664	41.13735	44.88384	45.6799331	44.102737
800	49.0728	10.49948	42.03763	45.1248	46.1845041	44.583215
900	49.54243	10.3602	42.53352	45.8747	46.654126	45.363179
1000	49.46974	10.44971	42.88009	46.10514	47.0269682	45.70397
2000	51.00457	10.55134	44.56018	47.20245	48.5617959	47.39674
5000	51.17189	10.73563	45.00602	47.65992	49.4871383	47.53027
10000	51.22884	10.55954	44.75067	48.1308	49.5440951	48.135632
20000	51.65263	10.71141	44.55146	46.86696	49.5440951	47.077595
30000	51.22884	10.71141	43.62831	47.25141	49.5440951	46.925064
40000	51.22884	10.71141	44.46969	48.57767	49.7144285	46.795415
50000	51.65263	10.67693	43.64202	48.13563	49.2098576	47.1733
60000	50.82478	10.67139	43.98107	47.19659	49.5440951	47.058704

70000	51.22884	10.63378	43.87112	47.60857	49.399536	47.461336
80000	52.09816	10.67381	43.95886	48.01651	49.5440951	46.434712
90000	51.65263	10.71421	43.58744	47.99775	49.2098576	46.806072
100000	52.09816	10.66965	42.81601	47.73446	49.3737617	46.791868
200000	51.22884	10.71141	43.47037	47.51963	49.5440951	47.1733
300000	51.65263	10.74934	44.01835	48.17445	49.2098576	46.550531
400000	51.22884	10.74934	43.54862	48.28803	49.3737617	47.04365
500000	52.09816	10.70932	43.91111	48.1308	49.5440951	46.795415
600000	51.22884	10.75181	43.61806	49.20986	49.7144285	46.917759
700000	52.15474	10.80593	44.22733	49.26644	49.6006809	46.996297
800000	51.70921	10.768	44.09369	49.43035	49.2664434	46.726109
900000	52.15474	10.80417	43.71581	49.26644	49.6006809	46.974345
1000000	51.76543	10.82212	43.96947	49.16472	49.6569005	47.549395
2000000	51.28543	10.72485	44.22733	49.43035	49.2664434	46.996297
5000000	51.95506	6.404918	44.25041	48.74491	49.2370924	46.40408
10000000	51.39751	11.71935	44.99984	49.54885	49.5424251	46.481031
15000000	52.54085	11.67399	45.80632	49.82288	49.986784	47.749629
20000000	52.66937	11.94595	46.31453	50.3905	50.7311689	48.075444
25000000	54.24945	12.13444	46.62306	51.22114	51.6953879	49.324593