Shielding Effectiveness of Superalloy, Aluminum, and Mumetal Shielding Tapes

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In Partial Fulfillment
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Master of Science in Aerospace Engineering
With Specialization in Space Systems Engineering

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ABSTRACT

Shielding Effectiveness of Superalloy, Aluminum, and Mumetal Shielding Tapes

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Ms. Cheung performed this project as part of his Cal Poly distance-learning curriculum for a Master of Science degree in Aerospace Engineering with specialization in Space Systems Engineering. The project was performed over the Fall 2006 and Winter 2007 quarters.

Using MIL-HDBK-419A, MATLAB and Nomographs, Shielding Effectiveness for the Magnetic Field, Electric Field, and Plane Wave were calculated over a frequency range from 10 Hz to 1 GHz. The three shielding tapes used included superalloy, aluminum, and mumetal. Calculations for Shielding Effectiveness involve the computation of Absorption Loss, Reflection Loss, and Re-Reflection Correction Factor. From the outcome of the calculations, it was suitable to conclude that all three metals fulfill the 40 dB Shielding Effectiveness requirements for SGEMP fields for frequencies greater or equal to 1 MHz. Accordingly, all three shielding tapes provide at least 40 dB of shielding to protect certain frequencies against SGEMP Magnetic Field. However, results vary for frequencies below 1 MHz.

Acknowledgments

I would like to acknowledge and express my gratitude for the expertise and support that I gained during the course of this project. I wish to thank Mr. Thomas “Tom” Chin of Lockheed Martin as a senior expert in the Electromagnetic Compliance and Shielding Division for being my mentor for this project. I appreciate all of the time and efforts he spent in order to allow me to develop my understanding in the area of Electromagnetic Shielding. I would also like to thank Dr. Eric Mehiel of the Cal Poly Aerospace Engineering Department for his guidance as my academic faculty advisor. I also want to express my appreciation to Dr. Jordi Puig-Sauri and Dr. David Marshall of the Cal Poly Aerospace Engineering Department for being the other members of my project review committee.

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1.0 INTRODUCTION

In the aerospace industry, electromagnetic shielding plays an intricate part in the design process of any space vehicle. Electromagnetic fields from various electronic devices such as motors, batteries, and meters may have tremendous effects on each other if proper shielding protection is not appropriately implemented. It will prevent any magnetic and electric field from entering and exiting the shielded device according to requirements specified in military *Military Standard Handbook MIL-HDBK-419A* in the case presented. As industry standard, electromagnetic shielding is called shielding effectiveness.

Derived from Maxwell's Equations of Electromagnetic Theory, the objectives of the shielding effectiveness calculations were to determine whether or not the selected shielding tapes would conform to the 40 dB shielding effectiveness Requirement as indicated in EMC Specifications for magnetic field, electric field, and plane Waves from the System Generated Electro-magnetic Pulse (SGEMP). With the use of *Military Standard Handbook 419A* and MathWorks' MATLAB mathematical software program, the absorption loss, reflection loss, re-reflection correction factor, and the shielding effectiveness were computed for three types of shielding tape: superalloy, aluminum, and mumetal. The examined frequencies ranged from 10 Hz to 1 GHz. Moreover, for absorption loss and reflection loss, the results from MATLAB were also verified by nomographs, a traditional graphing method that approximates the losses.

2.0 DISCUSSION AND CALCULATIONS

For the completion of these shielding calculations, references to the document, MIL-HDBK-419A, Volume I, were made in addition to the textbook, *Introduction to Electromagnetic Compatibility* by Clayton R. Paul.

2.1 Assumptions

2.1.1 Shielding Tapes

Shielding tapes with a thickness of 0.35×10^{-3} inches (889 μm) were placed at a distance of one meter from the electromagnetic source. The shielding tapes were assumed to be an infinite sheet, consequently eliminating edging effect.

2.1.2 Calculations

In order to coincide to requirements exclusively identified by the shielding equations stated in this report, some assumptions needed to be made.

First, the selected tapes were assumed to be infinite sheets of metal without geometric dependencies. As previously stated, superalloy, aluminum, and mumetal shielding tapes were selected for these calculations. The only criteria for this selection was each metal must have a permeability value drastically different from each other. By doing so, a range of possible shielding effectiveness values were obtainable.

Second, for the lower frequencies (10 Hz to 10 KHz) of the magnetic field case, the calculated shielding range, which is roughly from –30 dB to 1800 dB, could quite possibly be impractical because geometric discrepancies exist in reality. Using these assumptions, the following quantities were calculated.

2.2 Shielding Effectiveness

Originating from Maxwell Equations, shielding effectiveness depicts the Faraday’s principle.

2.2.1 Magnetic Field

In terms of magnetic field, Faraday’s principle does not apply, for magnetic charges do not exist. Nevertheless, magnetic material with high permeability ($\mu >> 1$) and of ample thickness can create magnetic field attenuation by means of forming a low-reluctance path that draws the material’s magnetic field.

On the other hand, thin conductive materials with low permeability also have the capability to provide shielding effectiveness for magnetic field. The shield made of the material will form an alternating magnetic field that generates eddy current on the shield to provide shielding effectiveness. Eddy currents produce this alternating magnetic field of opposing orientation inside the shield. As a result, as frequency increase, shielding effectiveness will increase proportionally as well.

2.2.2 Electric Field

Faraday's principle states that the electric field inside a conductive, spherical enclosure is nearly zero. The electric field generates both positive and negative charges which, in turn, generate a separate electric field that cancels out the original field. The thickness of the shield plays an insignificant role since electrons travel freely in conductive material.

2.2.3 Plane Wave

Plane wave deems the magnetic field and electric field to be completely developed, in which case:

$$\frac{MagneticField}{ElectricField} = 377\Omega$$

In order to achieve this condition, the distance to the radiation source needs to be far enough, or, in other words, in the Far-field region. Both the magnetic field and the electric field decrease in amplitude by 20 dB if the distance is increased ten times.

In the Near-field region, however, shielding effectiveness must be observed separately for magnetic field and electric field. The ratio between the fields depends on the distance from the radiation source. Magnetic field controls the Near-field when the source has low impedance; conversely, the electric field takes over when the source has high impedance. Moreover, when the distance to the source is λ/2π, the wave impedance converges to 377Ω, and decrease linearly as the distance approach λ/2.

2.2.4 Shielding Effectiveness Calculations

Shielding effectiveness indicates the capability of a given metal material to operate as protection against external electromagnetic fields and as barrier preventing internal fields from damaging other devices. Its elements consist of simply the addition of the absorption loss, reflection loss, and re-reflection correction factor:

$$
\begin{aligned}
SE_{Magnetic} &= A + R_{Magetic} - C_{Magnetic} \\
SE_{Electric} &= A + R_{Electric} - C_{Electric} \\
SE_{PlaneWave} &= A + R_{PlaneWave} - C_{PlaneWave}
\end{aligned}
\qquad \text{Eq. 1}
$$

where

SE = Shielding Effectiveness
A = Absorption Loss
R = Reflection Loss
C = Re-Reflection Correction Factor

Ultimately, the complete shielding effectiveness of a metal sheet is the summation of three factors: absorption loss, reflection loss, and re-reflection correction factor. The calculation must be applied to all three fields: electric field, magnetic field, and plane wave. Nevertheless, one should keep in mind that these calculations are only a means to predict the shielding effectiveness of the metal, and should not be considered absolute.

2.3 Absorption Loss

2.3.1 Equations

Using the MIL-HDBK-419A as reference, the absorption loss was computed first since all three fields have identical absorption losses. The absorption loss equation is a function of the EMI Shielding Characteristic of the metal used (as shown in Appendix B) and the thickness of the tape:

$$A = K_1 l \sqrt{f \mu_r g_r} \qquad \text{(in dB)} \qquad \text{Eq. 2}$$

where

K_1 = 131.4 if l is in meters
= 3.34 if l is in inches
l = shield thickness
f = frequency
μ_r = permeability
g_r = conductivity

The results of this equation were evaluated using Matlab, and applied to magnetic field, electric field, and plane wave. The outcome was also confirmed using nomographs.

In order to determine which shielding material is appropriate for usage, metals can be selected according to its' relative permeability and conductivity for appropriate absorption loss. Table 1 in Appendix B contains the relative EMI shielding characteristics, including permeability and relative conductivity for a wide range of metals.

2.3.2 Nomograph

For absorption loss, a nomograph is a viable instrument for quick results. Figure 1 illustrates the nomograph for absorption loss:

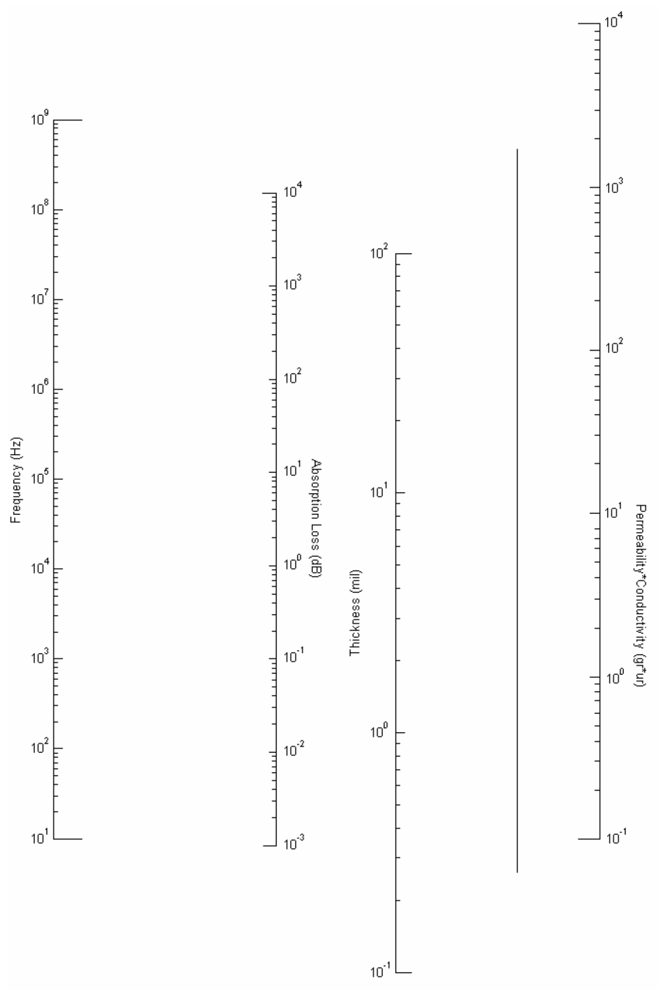

Figure 1. Nomograph for Absorption Loss

In order to use the nomograph for absorption loss, the following steps are used:

1. Multiply the permeability and conductivity of the metal and locate the result on the scale on the right side of the nomograph.
2. Draw a line from that location to the desired thickness on the thickness scale of the nomograph. Notice that this will cross a line between the permeability-conductivity line and the thickness line. This is called the pivot line.
3. From the intersection of the pivot line and the drawn line, draw another line to the frequencies that the shield will encounter on the frequency scale on the left side of the nomograph
4. Wherever that line intersects with the absorption loss scale is the estimated absorption loss of the metal material being used.

These were the steps used in this report; however, the steps are reversible, and can be done in any necessary order should there be unknown characteristics. In this case, only the absorption loss was unknown, and the calculations were done within a range of frequencies. Therefore, rather than a single value, absorption loss had a range of values. The same applied to the Nomographs for reflection loss.

2.4 Reflection Loss

Reflection loss of a shield reassembles the reflection loss of a transmission line. It peaks when the impedance of the electromagnetic field is much higher or lower than impedance of the shield. When this occurs, there is an imbalance between the two impedances, and power transfers from the field to the shield to put the two in equilibrium. In cases in which reflection loss is low, metals with higher permeability and increased thickness can be utilized in order to amplify shielding effectiveness.

In the magnetic field, the impedance of the shield and the impedance of the field are close to equilibrium at low frequencies. This produces a minimum reflection loss. As frequency increases, so does reflection loss in the magnetic field. Thus, reflection loss is nearly directly proportional to frequency.

In the electric field, the opposite is true; the higher the frequency, the closer the impedances of the shield and the field are to equilibrium, and the smaller reflection loss becomes. Hence, reflection loss is nearly inversely proportional to frequency in the electric field.

2.4.1 Equations

Each field possesses separate reflection loss Equations. For magnetic field, the equation is:

$$R_M = 20\log\left(\frac{C_1}{r\sqrt{\frac{fg_r}{\mu_r}}} + C_2 r\sqrt{\frac{fg_r}{\mu_r}} + 0.354\right) \qquad \text{Eq. 3}$$

where

C_1 = 0.0117 if r is in meters
= 0.462 if r is in inches
C_2 = 5.35 if r is in meters
= 0.136 if r is in inches
r = distance from Electromagnetic source to shield
f = frequency
μ_r = permeability
g_r = conductivity

The reflection loss equation used here is for low impedance magnetic field. This is considered near field in which r, the distance from the electromagnetic source, is less than the wavelength, λ, of the magnetic field divided by 2π ($r < \lambda/2\pi$). Unlike absorption loss, which depends on shielding thickness, reflection loss depends on the distance from the electromagnetic source.

For electric field, the equation is:

$$R_E = C_3 - 10\log\frac{\mu_r f^3 r^2}{g_r} \qquad \text{Eq. 4}$$

where

C_3 = 322 if r is in meters
= 354 if r is in inches
r = distance from Electromagnetic source to shield
f = frequency
μ_r = permeability
g_r = conductivity

For the plane wave, the equation is:

$$R_P = 168 - 20\log\sqrt{\frac{f\mu_r}{g_r}} \qquad \text{Eq. 5}$$

where

f = frequency
μ_r = permeability
g_r = conductivity

The results were calculated using Matlab and verified by Nomographs.

2.4.2 Nomographs

Figure 2a represents the nomograph for reflection Loss for magnetic field. Figure 2b is for electric field, and 2c is for plane wave.

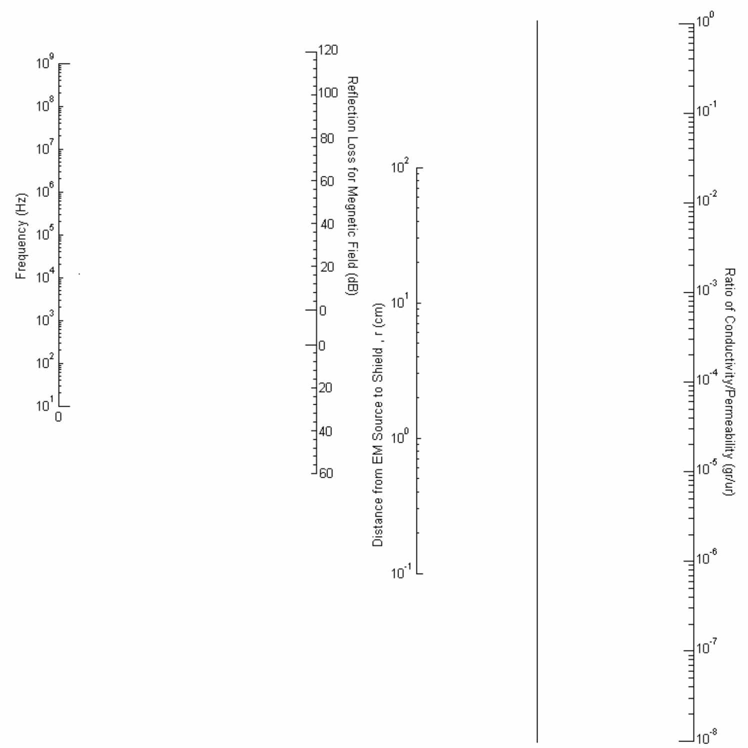

Figure 2a. Reflection Loss Nomograph for Magnetic Field

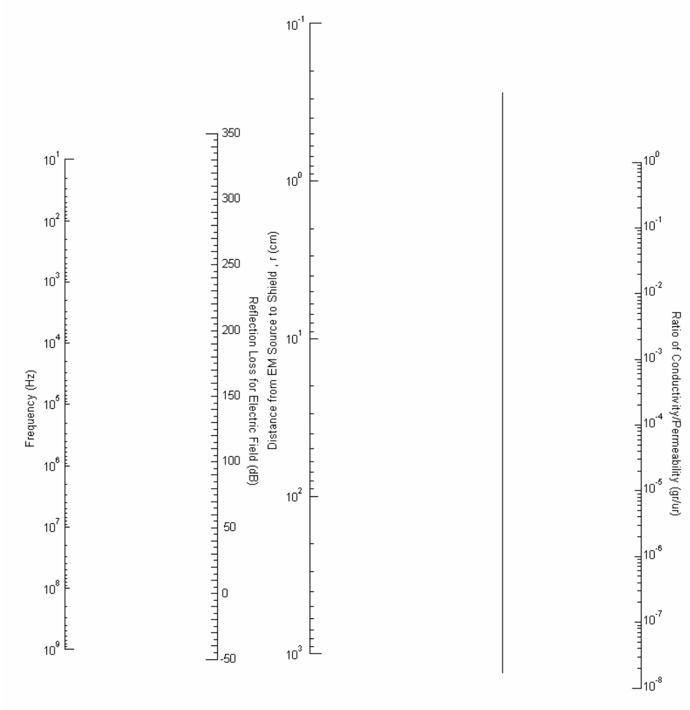

Figure 2b. Reflection Loss Nomograph for Electric Field

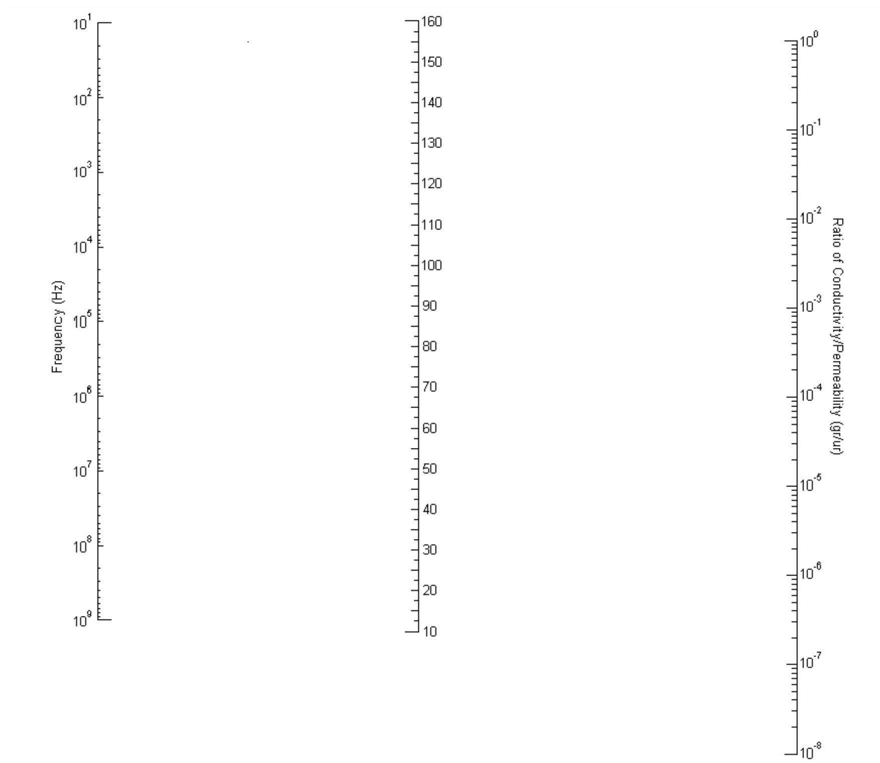

Figure 2c. Reflection Loss Nomograph for Plane Wave

The procedure for drawing graphical estimates on the nomograph for reflection loss is similar to that of absorption loss. Magnetic field and electric field have identical processes; plane wave, on the other hand, is not dependent on the distance between the electromagnetic source to the shield, and, therefore, simplifies the process:

Magnetic Field and Electric Field

1. Determine the ratio of conductivity/permeability of the metal and locate the result on the scale on the right side of the nomograph.
2. On the distance from EM source to the shield scale, pinpoint where on the scale corresponds to the distance between the EM source and the shield
3. Draw a line between the locations found on step 1 and 2. Notice that this will cross a line between the conductivity- permeability line and the distance line. This is the pivot line for this nomograph.

4. From the intersection of the pivot line and the drawn line, draw another line to the frequencies that the shield will encounter on the frequency scale on the left side of the nomograph
5. Wherever that line intersects with the reflection loss scale is the estimated reflection loss of the metal material being used.

Plane Wave

1. Determine the ratio of conductivity/permeability of the metal and locate the result on the scale on the right side of the nomograph.
2. Draw a line from there to the frequencies that the shield will encounter on the frequency scale on the left side of the nomograph
3. Wherever that line intersects with the reflection loss scale is the estimated reflection loss of the metal material being used.

Again, these were the steps used in this report; however, the steps are reversible, and can be done in any necessary order should there be unknown characteristics. In this case, only the absorption loss was unknown, and the calculations were done within a range of frequencies. Therefore, rather than a single value, absorption loss had a range of values. The same applied to the Nomographs for reflection loss.

2.5 Shielding Effectiveness when Absorption Loss > 10 dB

For situations in which absorption loss is greater than 10 dB, the reflected energy cannot penetrate beyond the shielding, which deems the computation of the re-reflection factor unnecessary. Hence, the total losses for shielding effectiveness in all three cases if absorption losses are greater than 10 dB can be calculated by summing the absorption loss and the reflection loss:

$$\begin{aligned} Total_{Magnetic} &= A + R_{Magnetic} \\ Total_{Electric} &= A + R_{Electric} \\ Total_{PlaneWave} &= A + R_{PlaneWave} \end{aligned} \qquad \text{Eq. 6}$$

where

A = Absorption Loss
R = Reflection Loss

Note: The total loss is the shielding effectiveness if absorption loss is greater than 10 dB.

However, from the results of the calculations as shown in the Results Section of this report, absorption loss of each metal exceeded 10 dB in certain frequency ranges, demonstrating the possibility of reflected energy passing through the shielding. This required the computation of the re-reflection correction factor.

2.6 Re-Reflection Correction Factor

The equation for the re-reflection correction factor, C, is:

$$C = 20\log\left[1 - \Gamma 10^{\frac{-A}{10}}\left(\cos 0.23A - j\sin 0.23A\right)\right] \qquad \text{Eq. 7}$$

where

Γ = two-boundary reflection coefficient
A = Absorption Loss

Each of the three fields has its' own two-boundary reflection coefficient, Γ, which is given in terms of its' own precalculation parameter, m. For magnetic field, the equations are:

$$\Gamma = 4\frac{\left(1-m^2\right)^2 - 2m^2 + j2\sqrt{2}m\left(1-m^2\right)}{\left[\left(1+\sqrt{2}m\right)^2 + 1\right]^2}$$
$$m = \frac{4.7\times 10^{-2}}{r}\sqrt{\frac{\mu_r}{fg_r}} \qquad \text{Eq. 8}$$

where

r = distance from Electromagnetic source to shield
f = frequency
μ_r = permeability
g_r = conductivity

For the electric field, the equations are:

$$\Gamma = 4\frac{\left(1-m^2\right)^2 - 2m^2 - j2\sqrt{2}m\left(1-m^2\right)}{\left[\left(1-\sqrt{2}m\right)^2 + 1\right]^2}$$

$$m = 0.205\times10^{-16}\, r\sqrt{\frac{\mu_r f^3}{g_r}}$$

Eq. 9

where

r = distance from Electromagnetic source to shield
f = frequency
μ_r = permeability
g_r = conductivity

For the plane wave, the equations are:

$$\Gamma = 4\frac{\left(1-m^2\right)^2 - 2m^2 - j2\sqrt{2}m\left(1-m^2\right)}{\left[\left(1+\sqrt{2}m\right)^2 + 1\right]^2} \cong 1$$

$$m = 9.77\times10^{-10}\sqrt{\frac{f\mu_r}{g_r}}$$

Eq. 10

where

r = distance from Electromagnetic source to shield
f = frequency
μ_r = permeability
g_r = conductivity

Using the proper two-boundary reflection coefficient, Γ, and its' precalculation parameter, m, the appropriate corresponding re-reflection correction Factors for each case were calculated in order to adjust shielding effectiveness accurately.

As established earlier, the re-reflection correction factor is necessary for absorption losses less than 10 dB in order to prevent reflected energy from penetrating beyond the shielding. This factor can be either positive or negative if the shield is very thin.

2.7 Equations vs. Nomographs

As shown, shielding effectiveness equations can be quite problematic and time-consuming without the use of a computational software such as MATLAB. Hence, for rapid results, Nomographs can be used with minimal inaccuracies when available.

3.0 RESULTS

Because of the large quantity of calculations, the probability of computational errors is fairly high; therefore, a software computational script was created using MathWorks' MATLAB program.

For all of the figures in the Results Sections, superalloy is indicated in blue, aluminum in green, and mumetal in red.

3.1 Absorption Loss

The following absorption losses produced by Matlab after inputting the established initial conditions. This figure applied to all three fields being the magnetic field, electric field, as well as plane wave:

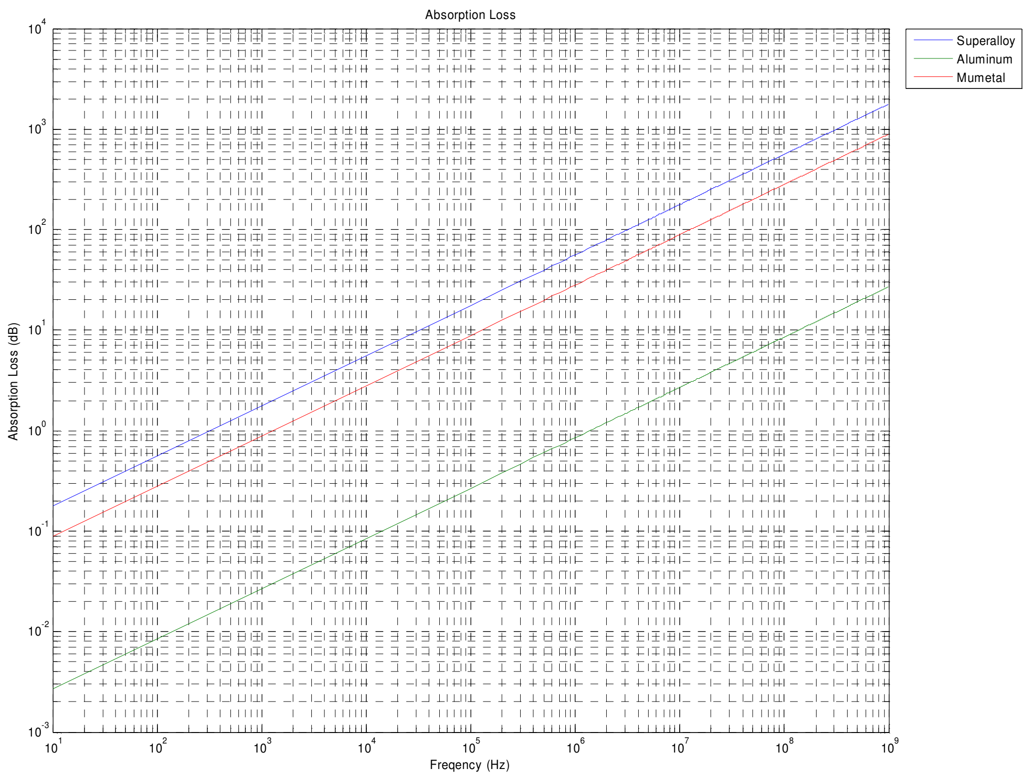

Figure 3. Absorption Loss for Magnetic Field, Electric Field, and Plane Wave produced by Matlab

Similar findings were confirmed by a nomograph. As a reminder, because Nomographs are handdrawn, it is only appropriate to use it as an approximation and not taken as the ultimate answer.

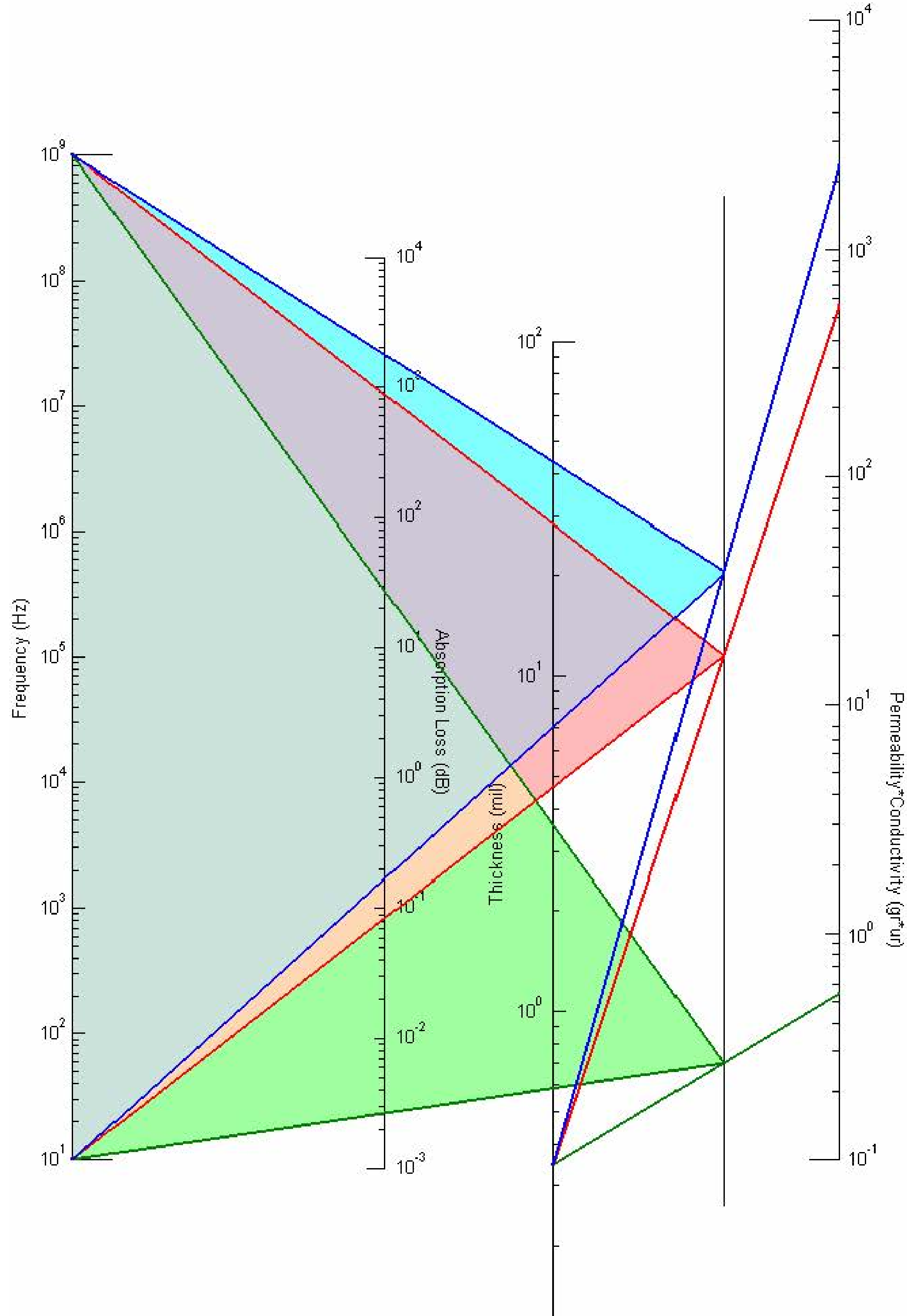

Figure 4. Nomograph to Calculate the Absorption Loss for Magnetic Field, Electric Field, and Plane Wave

With close examination of both Figure 3 and 4, it was confirmed that a) the mathematical equations and the nomograph result in identical conclusions and can be done independently, and b) the calculated absorption losses where correct and accurate. In addition, both figures show that aluminum shielding tape had the least absorption loss, making it he most vulnerable to reflected energy. Thus, although it was evident that all three materials would require the use of the re-reflection correction factor, aluminum in particular would rely on this facter for the widest range of frequencies. Further confirmation could be seen in Table 1, which was produced by Microsoft Excel and Matlab, in *Appendix A* section of this report.

3.2 Reflection Loss

The following graphs shows the reflection losses for the magnetic field, electric field, and plane wave, respectively, produced by Matlab along with the corresponding Nomographs:

Magnetic Field

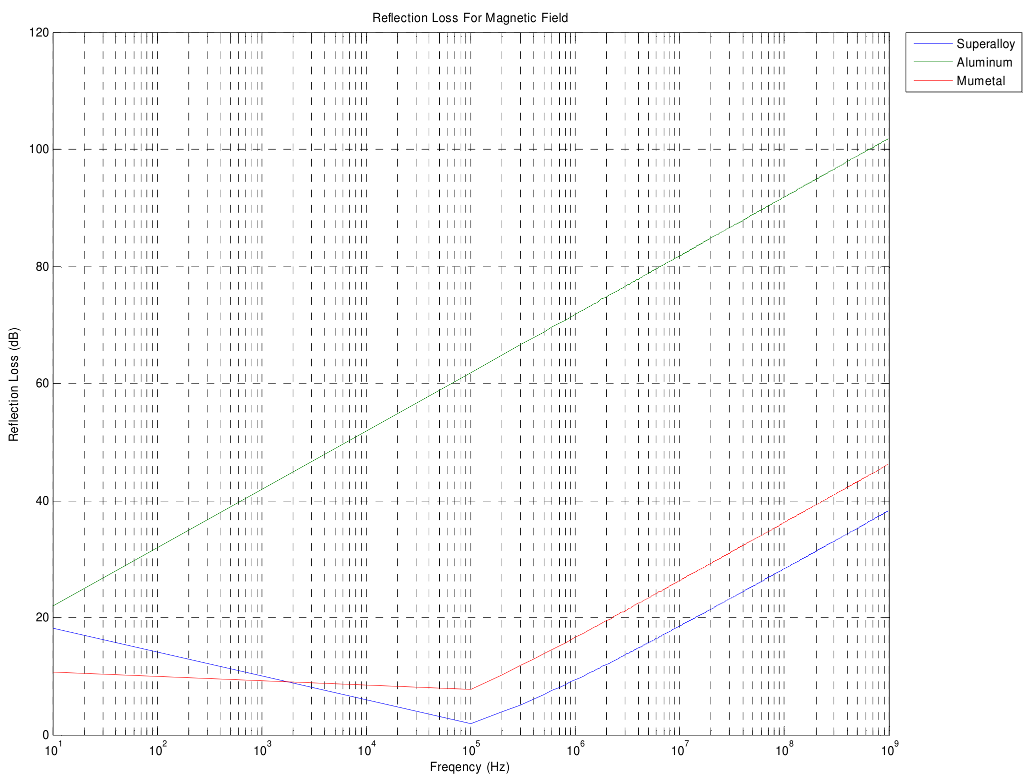

Figure 5. Reflection Loss for Magnetic Field produced by Matlab

The results of Figure 5 could be verified by the nomograph in Figure 6:

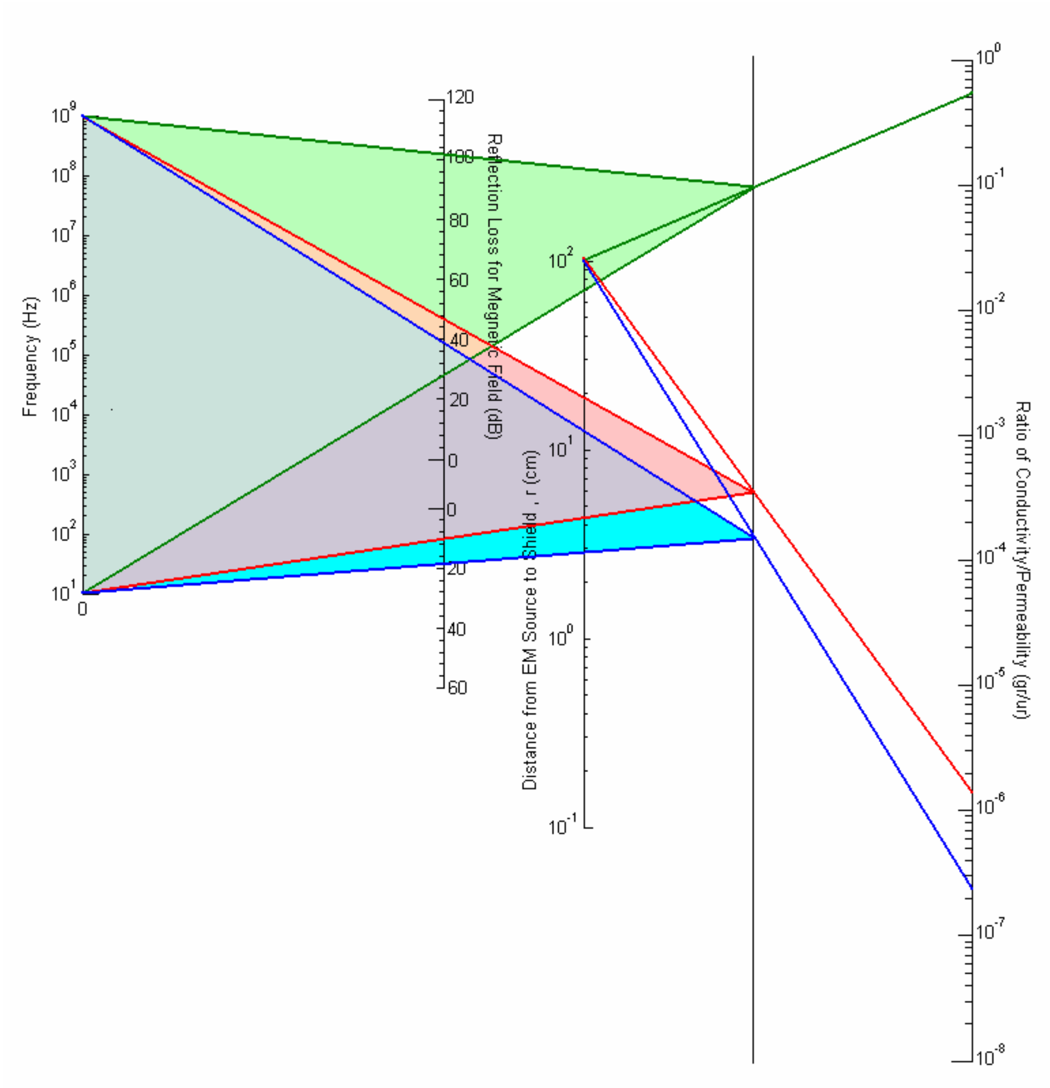

Figure 6. Nomograph to Calculate the Reflection Loss for Magnetic Field

With close examination of both Figure 5 and 6, aluminum demonstrated the most reflection loss in the magnetic field while superalloy and mumetal projected similar levels even though their relative permeability values are greatly different. Further confirmation could be seen in Table 2, which was produced by Microsoft Excel and Matlab, in the *Appendix A* section of this memorandum.

Electric Field

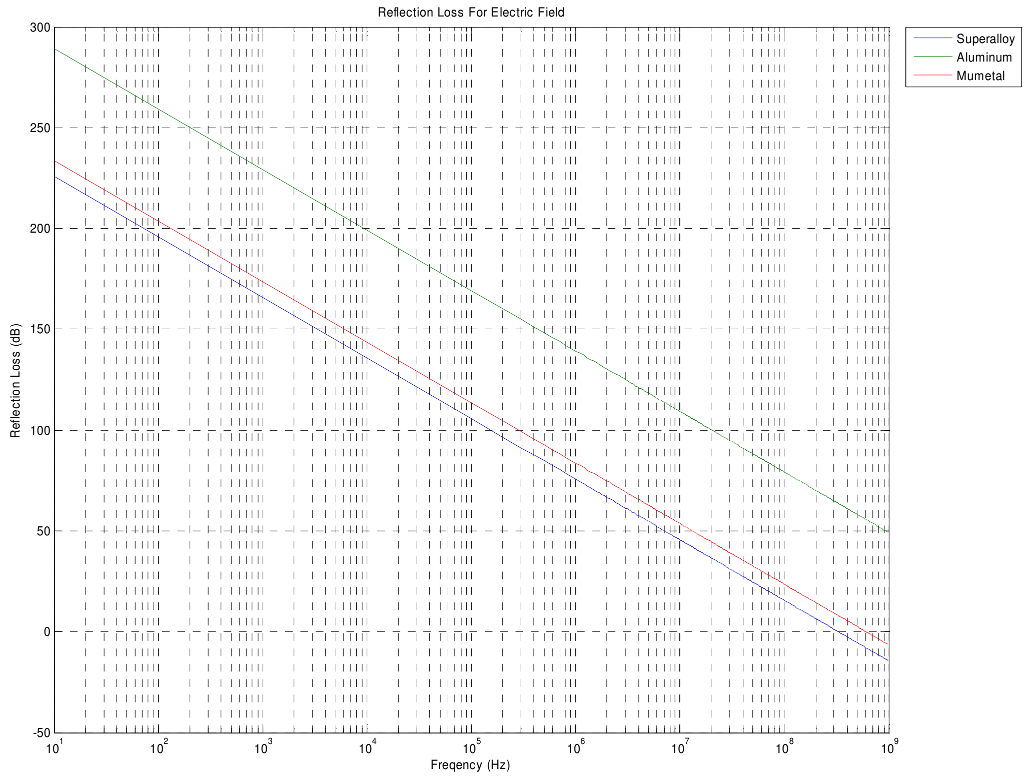

Figure 7. Reflection Loss for Electric Field produced by Matlab

The results of Figure 7 could be verified by the nomograph in Figure 8:

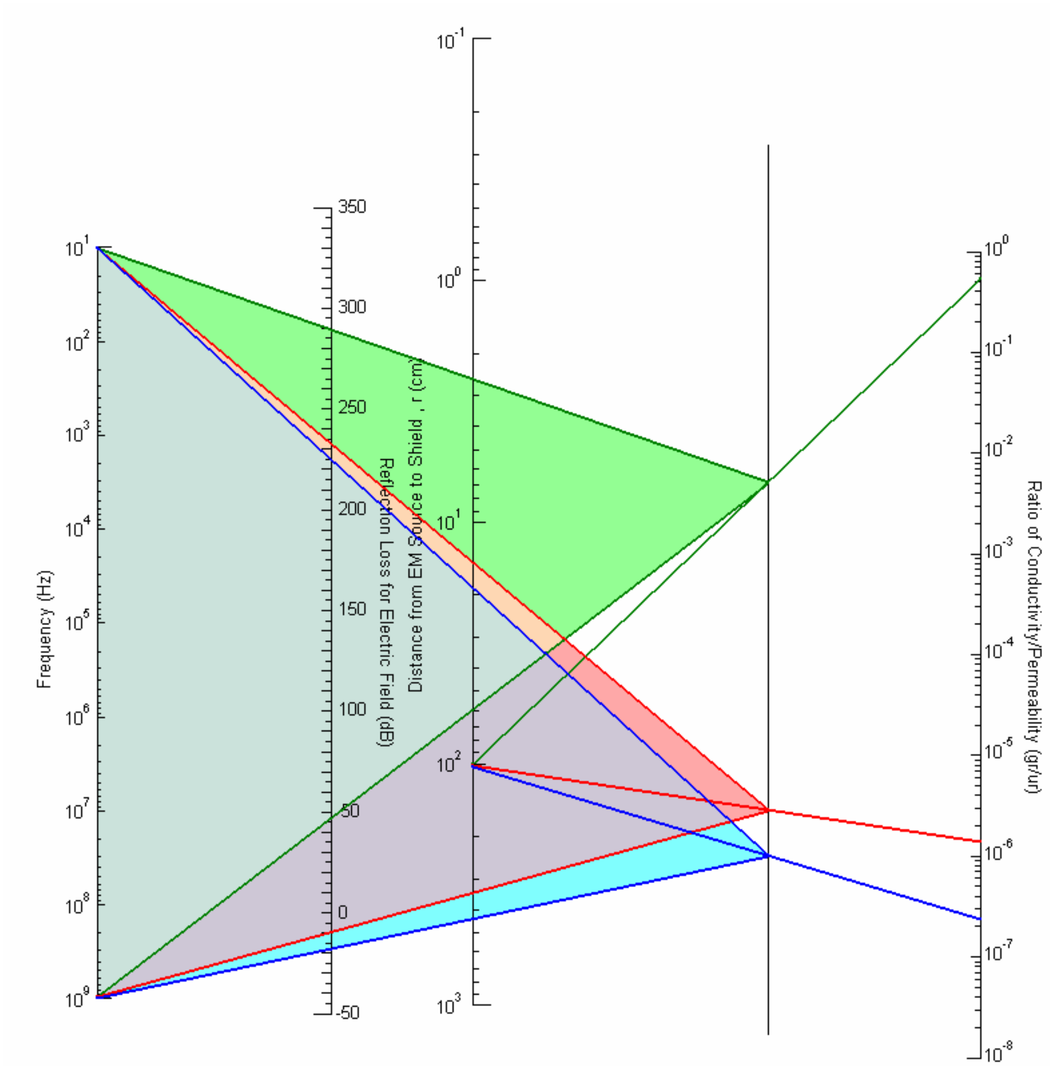

Figure 8. Nomograph to Calculate the reflection Loss for Electric Field

Similarly, Figures 7 and 8 shows that aluminum demonstrated the most reflection loss in the electric field as well while superalloy and mumetal projected levels close to each other. Further confirmation could be seen in Table 2, which was produced by Microsoft Excel and Matlab, in the *Appendix A* section of this report.

Plane Wave

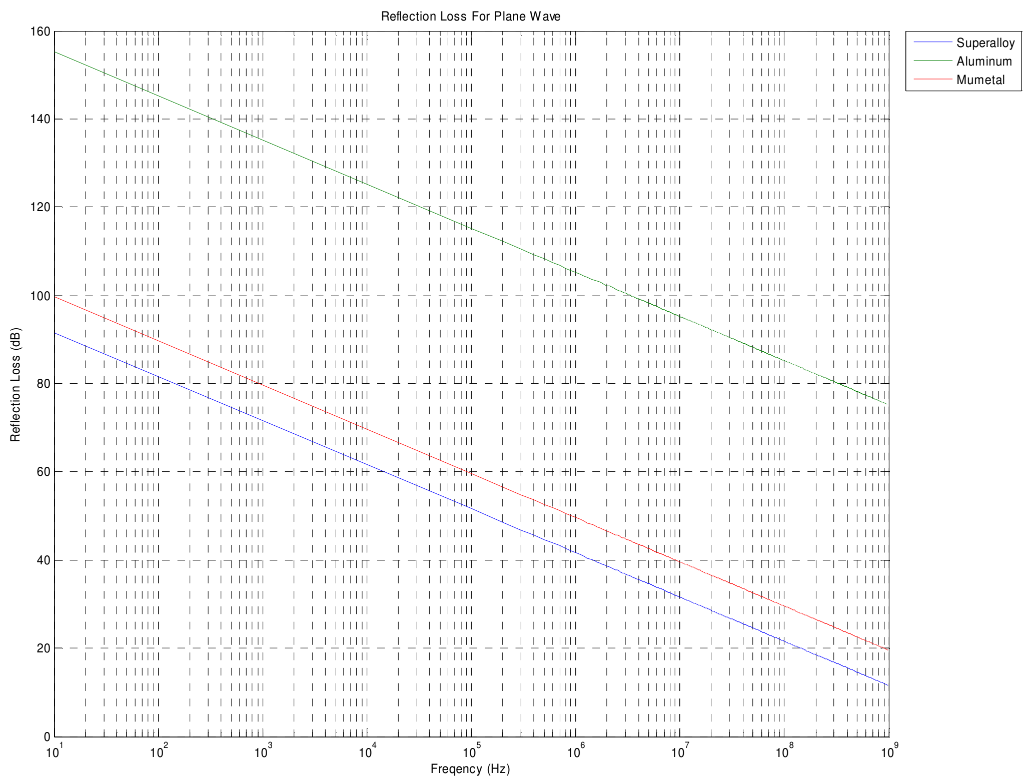

Figure 9. Reflection Loss for Plane Wave

The results of Figure 9 could be verified by the nomograph in Figure 10:

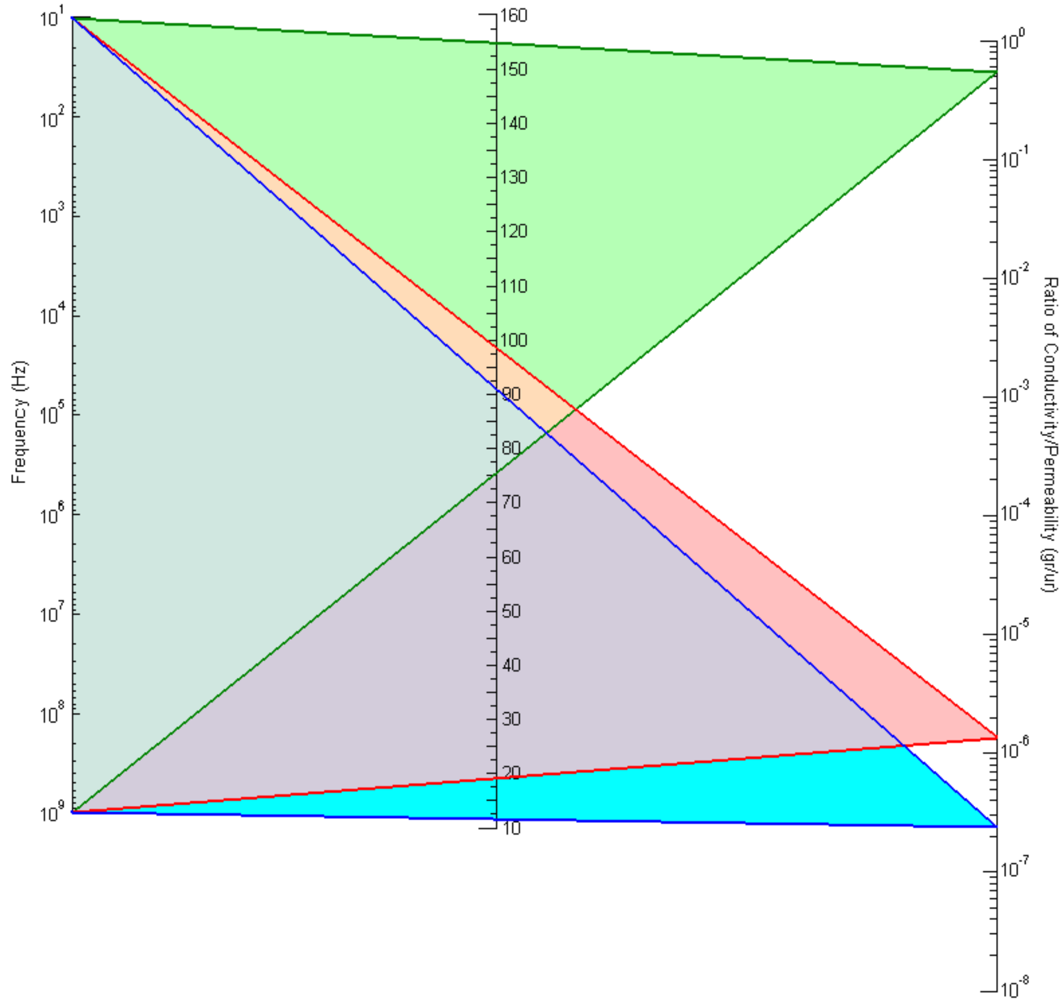

Figure 10. Nomograph to Calculate the Reflection Loss for plane Wave

Again, Figure 9 and 10, aluminum demonstrated the most reflection loss in the plane wave while superalloy and mumetal projected similar levels. Further confirmation could be seen in Table 2, which was produced by Microsoft Excel and Matlab, in the *Appendix A* section of this report.

3.3 Shielding Effectiveness when Absorption Loss > 10 dB

These are the resulting shielding effectiveness graphs produced by Matlab for cases in which absorption losses are greater than 10 dB. Again, this is the sum of the absorption loss and the reflection loss. The re-reflection correction factor is unnecessary since the addition of the factor will not greatly hinder shielding effectiveness results.

Because Nomographs cannot be used to estimate the re-reflection correction factor, their usage was eliminated from here on out.

Magnetic Field

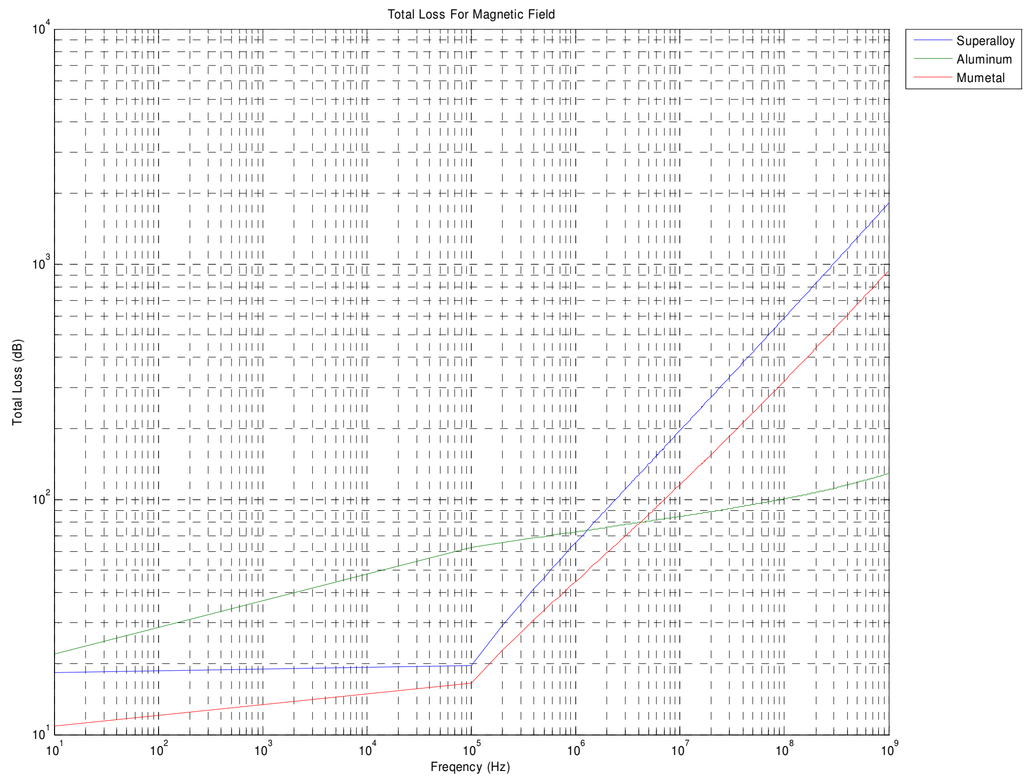

Figure 11. Total Loss for Magnetic Field

Electric Field

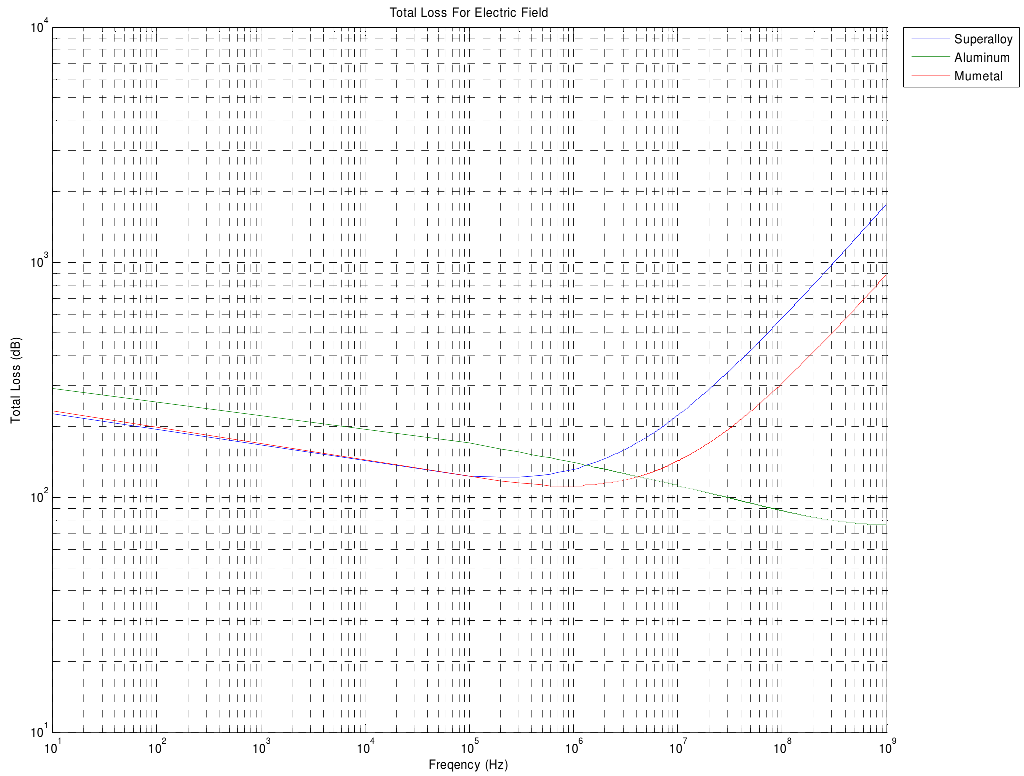

Figure 12. Total Loss for Electric Field

Plane Wave

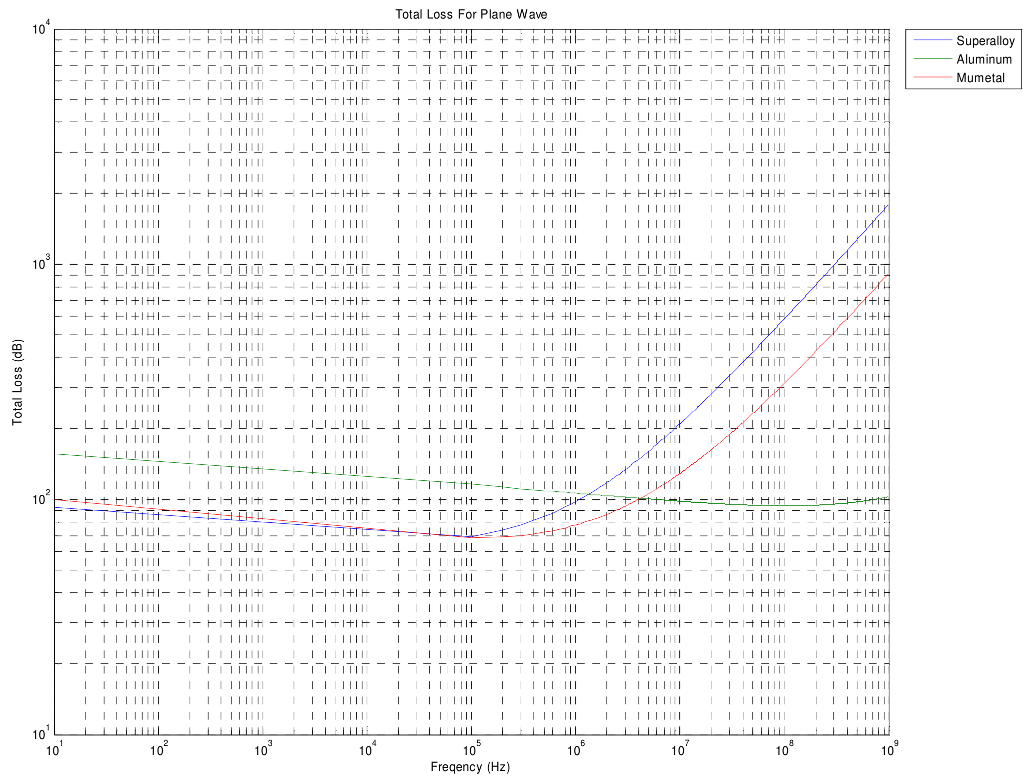

Figure 13. Total Loss for Plane Wave

For all three fields, aluminum had the shortest range of shielding effectiveness, from approximatedly 20 dB to 150 dB, in the frequency range of 10 Hz to 1 GHz. From 10 Hz to 1 MHz, aluminum had greater shielding effectiveness because of greater reflection loss as opposed to superalloy and mumetal. Nevertheless, for frequencies grater than 1 MHz, the absorption loss of superalloy and mumetal surpassed that of aluminum, and as a result, exceeded the shielding effectiveness of aluminum. One must keep in mind, however, that at this point in the calculations, only shielding effectiveness with an absorption loss of less than 10 dB could be considered accurate as the re-reflection correction factor had been excluded thus far.

Tabulated results of shielding effectiveness without the re-reflection correction factor could be observed in Table 3 of the *Appendix A* section.

3.4 Re-Reflection Correction Factor

Since a large portion of the absorption loss results exceeded 10 dB, calculations of the re-reflection correction factor were required for proper shielding effectiveness results. The following graphs represent the re-reflection correction factor for each of the three situations.

Magnetic Field

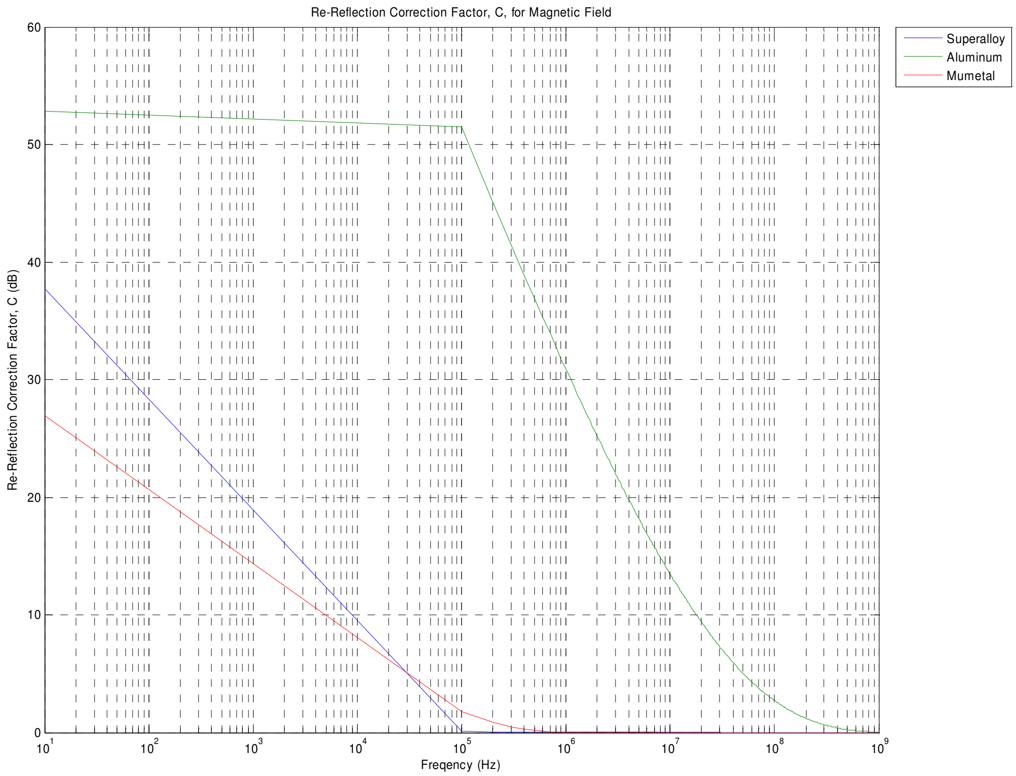

Figure 14. Re-Reflection Correction Factor for Magnetic Field

Electric Field

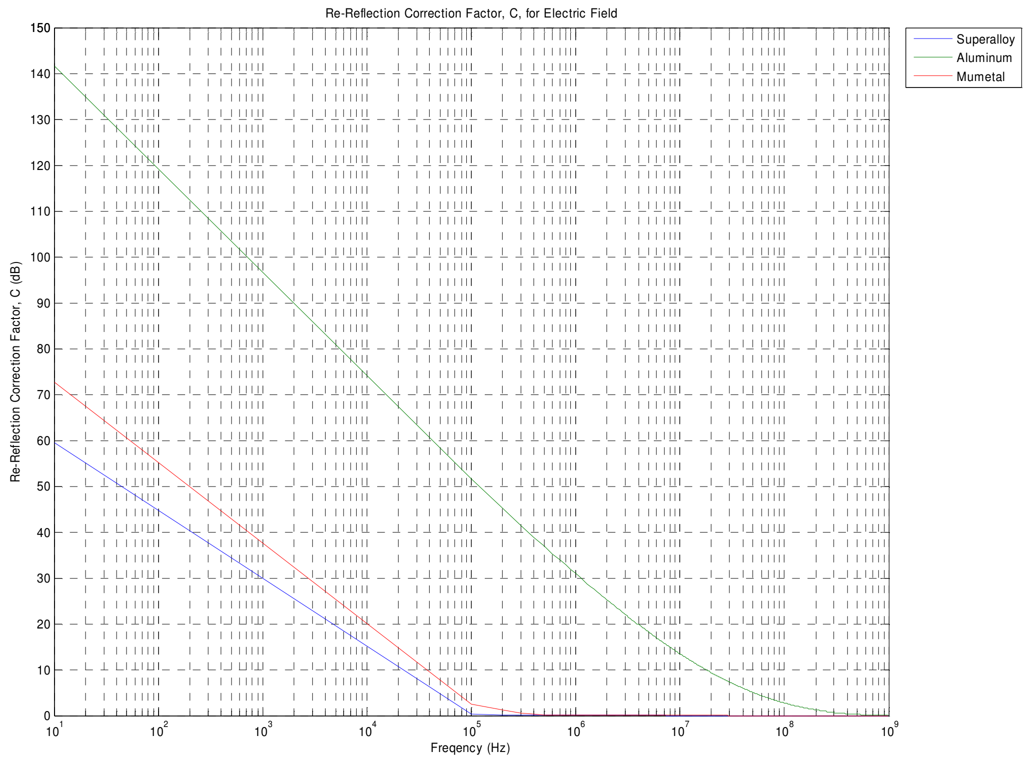

Figure 15. Re-Reflection Correction Factor for Electric Field

Plane Wave

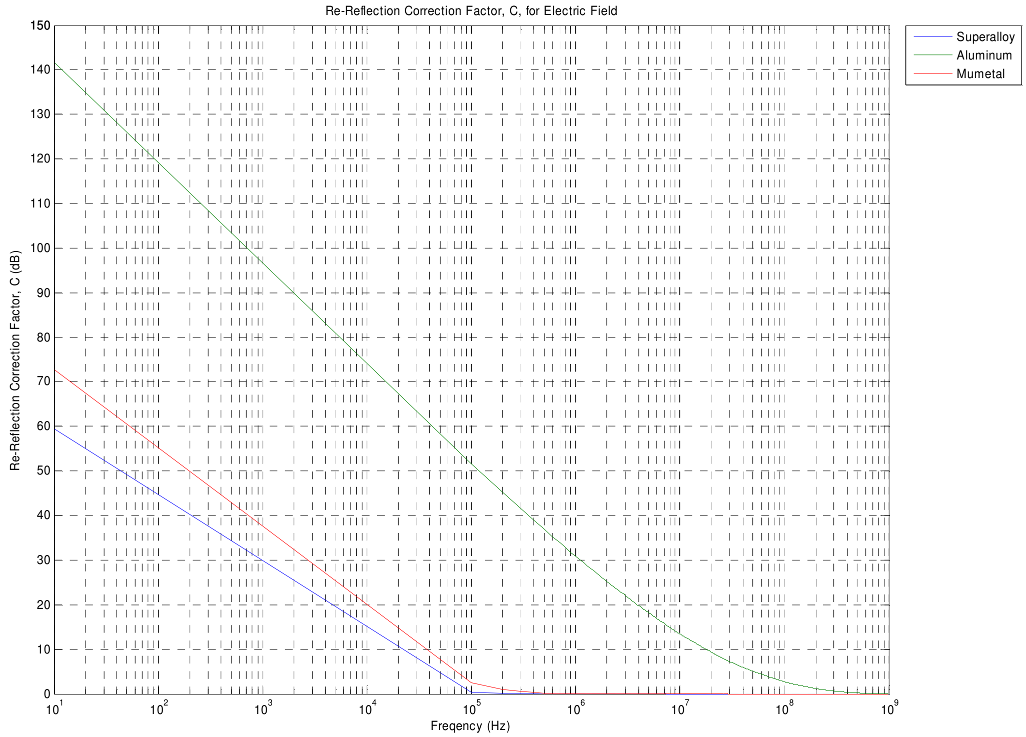

Figure 16. Re-Reflection Correction Factor for Plane Wave

Tabulated results of re-reflection correction factor could by observed in Table 4 of the *Appendix A* section.

When Figure 14, 15, and 16 where examined along with Figure 3, it was evident that the re-reflection correction factor was necessary only when absorption losses were less than 10 dB. Referring back to Figure 3, absorption loss for aluminum did not pass beyond 10 dB until approximately 100 MHz, and for superalloy and mumetal, between 10 KHz and 100 KHz. This directly corresponds to the re-reflection correction factor figures. In all three of the latter figures, the factor approached zero when frequency reached 100 MHz for aluminum and 100 KHz for superalloy and mumetal. Therefore, this confirmed the unessential computation of the re-reflection correction factor when absorption loss is greater than 10 dB.

3.5 Shielding Effectiveness

These figures represent the shielding effectiveness from Matlab with the use of the re-reflection correction factor, for each case.

Magnetic Field

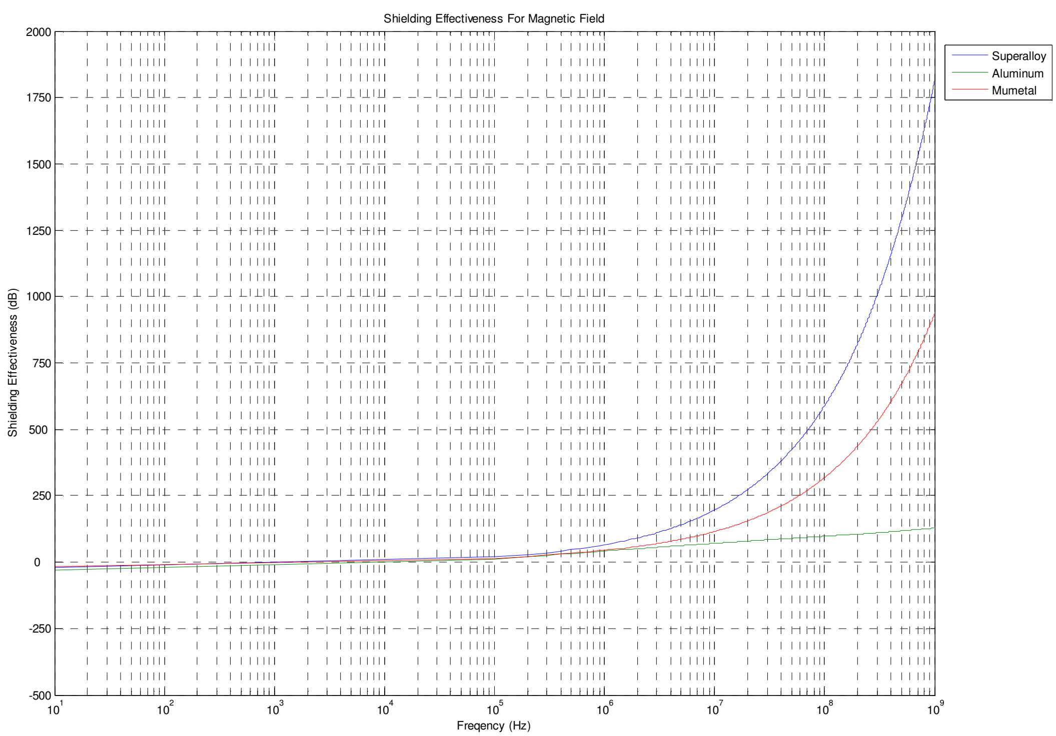

Figure 17a. Shielding Effectiveness for Magnetic Field

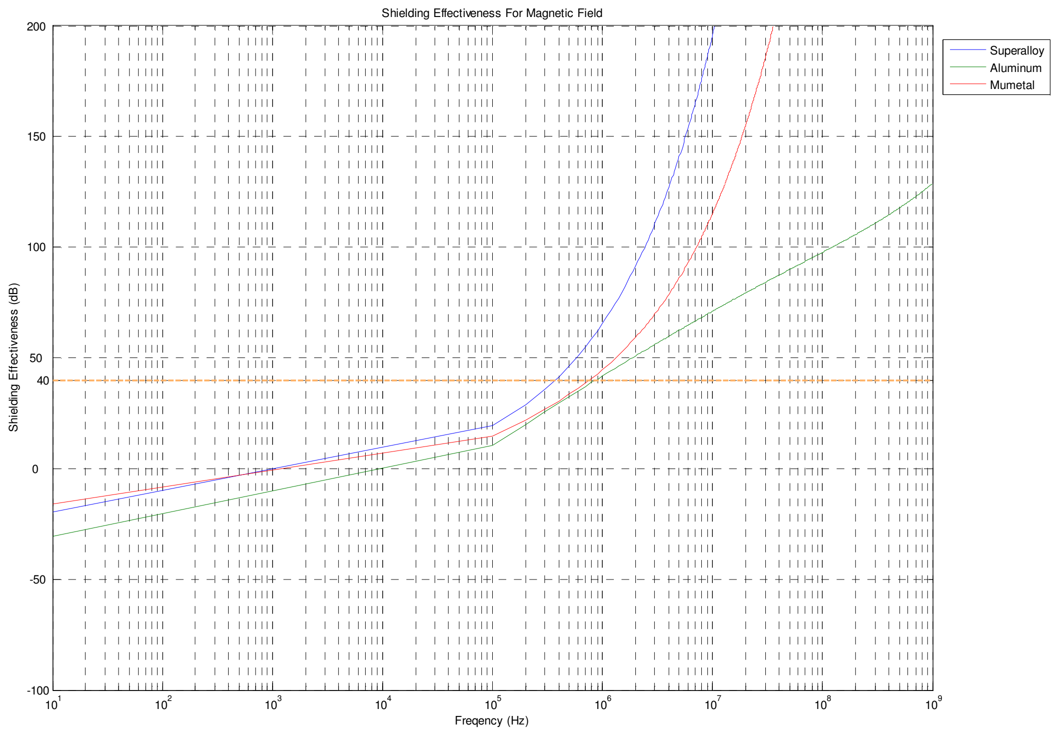

Figure 17b. Shielding Effectiveness for Magnetic Field Up to 200 dB

Electric Field

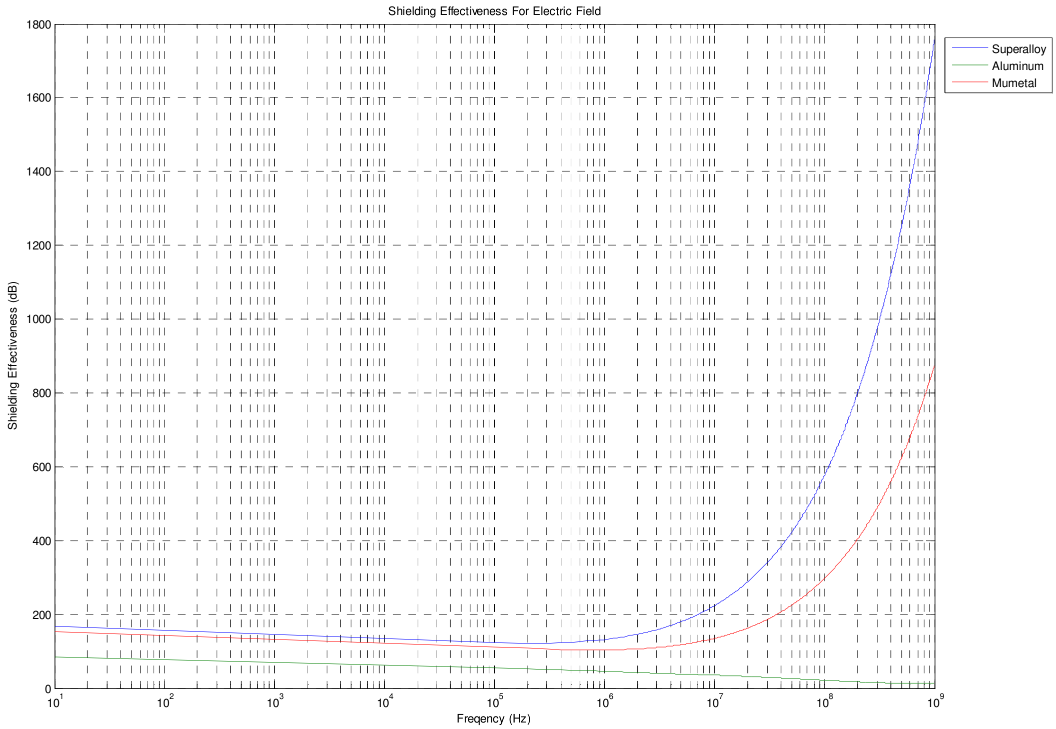

Figure 18a. Shielding Effectiveness for Electric Field

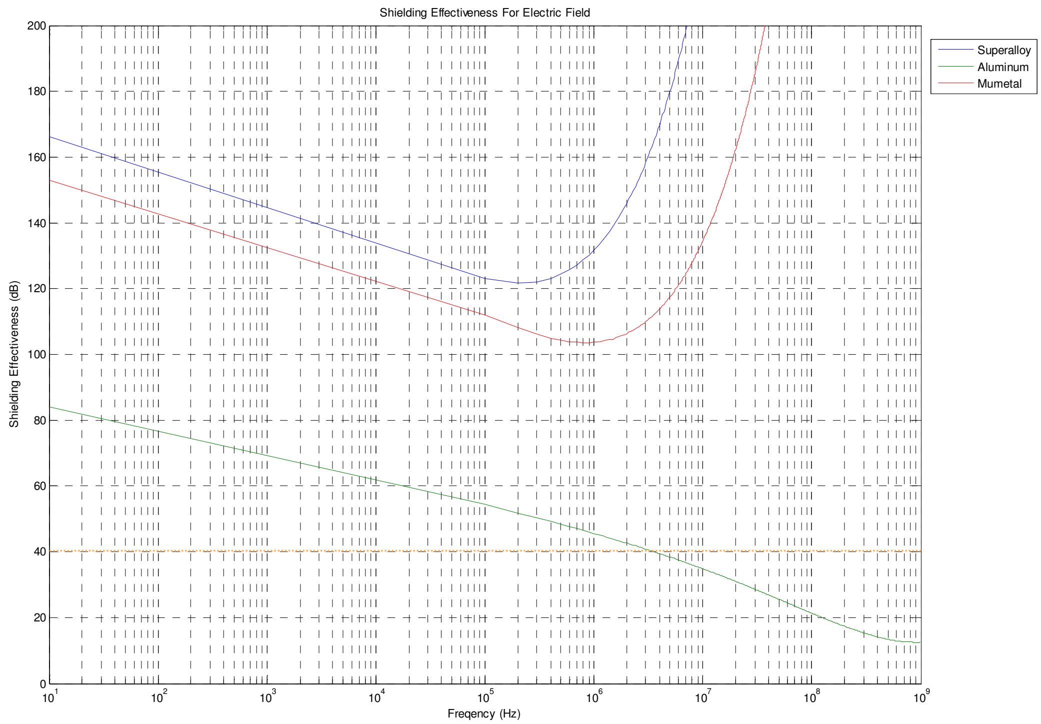

Figure 18b. Shielding Effectiveness for Electric Field Up to 200 dB

Plane Wave

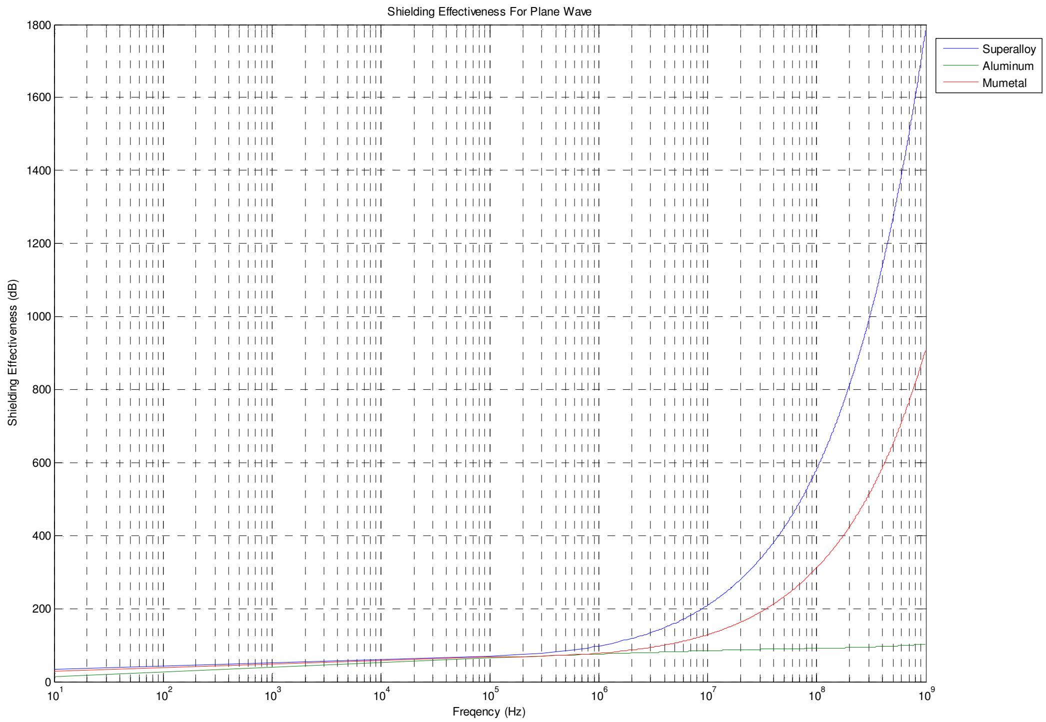

Figure 19a. Shielding Effectiveness for Plane Wave

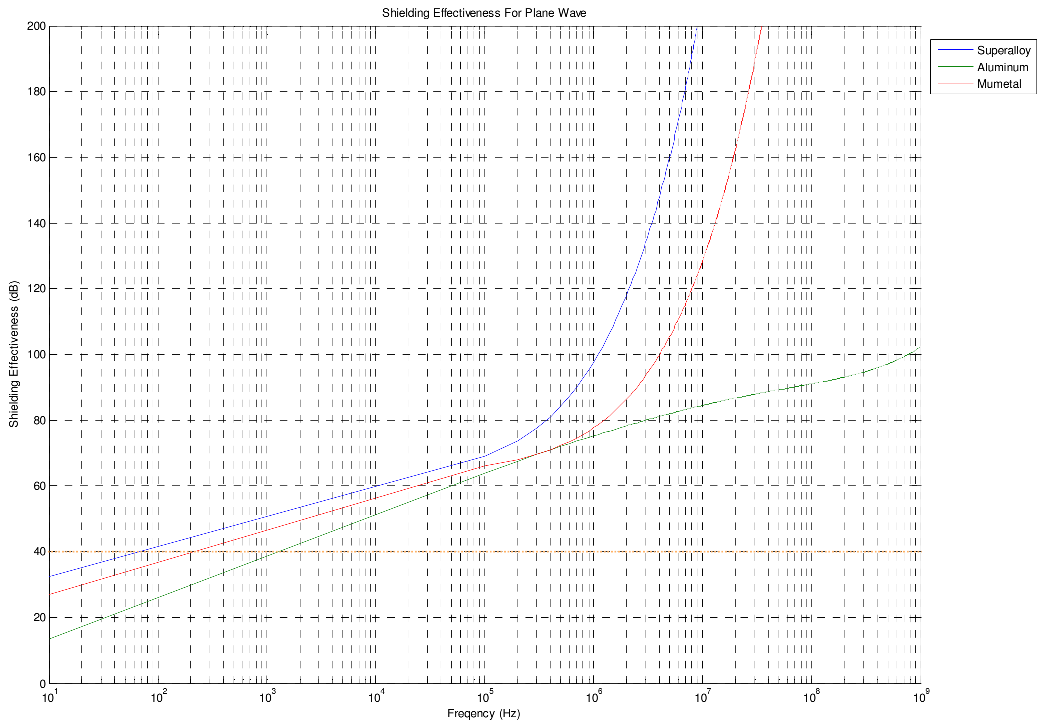

Figure 19b. Shielding Effectiveness for Plane Wave Up to 200 dB

Tabulated results of shielding effectiveness could by observed in Table 5 of the *Appendix A* section.

Figures 17a through 19b illustrates the complete shielding effectiveness for all three shielding tapes in all three fields. For all three situations, aluminum was evidently the least effective while superalloy was the most effective. Even so, aluminum is still capability of providing adequate shielding of 40 dB for frequencies greater than or equal to 1 MHz in the magnetic field, less than or equal to 1 MHz in the electric field, and greater than or equal to 5 KHz in plane wave.

The minimum frequency for superalloy to be sufficient in the magnetic field proved to be 5 KHz. Conversely, superalloy was efficient in the electric field for the entire frequency spectrum, and from 50 Hz in the plane wave.

Mumetal demonstrated results similar to superalloy. The minimum frequency for effective shielding proved to be 1 MHz in the magnetic field, the entire frequency spectrum in the electric field, and 500 Hz in plane wave.

In reality, shielding tapes that provide nearly 2,000 dB of shielding effectiveness is unnecessary. In fact, no system to date ever required a shielding effectiveness beyond 200 dB. Therefore, Figure 17b, 18b, and 19b show the more realistic shielding effectiveness range to be used for SGEMP fields.

4.0 CONCLUSIONS

The shielding effectiveness of superalloy, aluminum, and mumetal shielding tapes satisfies the 40 dB shielding requirement as specified in the EMC Specifications of Military Standard Handbook 419A depending on the frequency and the SGEMP fields. Overall, the results confirmed that all three tapes were the most efficient in the electric field, which attested to being the easiest to protect against, even though aluminum was the weakest for frequencies greater than 1 MHz. Plane wave placed second in sufficiency among the fields for the selected metals. Lastly, magnetic field proved to be the most difficult to shield against for frequencies less than 1 MHz.

Despite the fact that in reality, a shielding effectiveness of 200 dB is well beyond satisfactory, should there ever be a situation in which shielding is needed beyond that level, a shielding effectiveness up to 2,000 dB can be produced from these three metals, especially superalloy and mumetal.

5.0 BIBLIOGRAPHY

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APPENDIX A—TABULATED VALUES

	Absorption Loss		
Frequency	Superalloy	Aluminum	Mumetal
10	0.17729	0.0026912	0.088875
50	0.39643	0.0060178	0.19873
100	0.56063	0.0085104	0.28105
500	1.2536	0.01903	0.62844
1.00E+03	1.7729	0.026912	0.88875
5.00E+03	3.9643	0.060178	1.9873
1.00E+04	5.6063	0.085104	2.8105
5.00E+04	12.536	0.1903	6.2844
1.00E+05	17.729	0.26912	8.8875
5.00E+05	39.643	0.60178	19.873
1.00E+06	56.063	0.85104	28.105
5.00E+06	125.36	1.903	62.844
1.00E+07	177.29	2.6912	88.875
5.00E+07	396.43	6.0178	198.73
1.00E+08	560.63	8.5104	281.05
5.00E+08	1253.6	19.03	628.44
1.00E+09	1772.9	26.912	888.75

Table 1. Absorption Loss for Magnetic Field, Electric Field, and Plane Wave

	Reflection Loss								
	Magnetic Field			Electric Field			Plane Wave		
Frequency	Superalloy	Aluminum	Mumetal	Superalloy	Aluminum	Mumetal	Superalloy	Aluminum	Mumetal
10	18.145	22.059	10.762	225.62	289.24	233.6	91.617	155.24	99.599
50	11.646	28.911	4.9886	204.65	268.27	212.63	84.628	148.25	92.609
100	9.0028	31.889	2.8704	195.62	259.24	203.6	81.617	145.24	89.599
500	3.5357	38.835	-0.6016	174.65	238.27	182.63	74.628	138.25	82.609
1.00E+03	1.6314	41.835	-1.2581	165.62	229.24	173.6	71.617	135.24	79.599
5.00E+03	-1.106	48.811	-0.47853	144.65	208.27	152.63	64.628	128.25	72.609
1.00E+04	-1.3654	51.818	0.78388	135.62	199.24	143.6	61.617	125.24	69.599
5.00E+04	0.31412	58.803	5.2754	114.65	178.27	122.63	54.628	118.25	62.609
1.00E+05	1.886	61.812	7.6709	105.62	169.24	113.6	51.617	115.24	59.599
5.00E+05	6.8594	68.801	13.831	84.648	148.27	92.63	44.628	108.25	52.609
1.00E+06	9.3792	71.811	16.644	75.617	139.24	83.599	41.617	105.24	49.599
5.00E+06	15.71	78.8	23.369	54.648	118.27	62.63	34.628	98.253	42.609
1.00E+07	18.563	81.81	26.317	45.617	109.24	53.599	31.617	95.243	39.599
5.00E+07	25.344	88.8	33.223	24.648	88.274	32.63	24.628	88.253	32.609
1.00E+08	28.304	91.81	36.214	15.617	79.243	23.599	21.617	85.243	29.599
5.00E+08	35.228	98.8	43.177	-5.3518	58.274	2.6296	14.628	78.253	22.609
1.00E+09	38.222	101.81	46.181	-14.383	49.243	-6.4013	11.617	75.243	19.599

Table 2. Reflection Loss for Magnetic Field, Electric Field, and Plane Wave

Frequency	Total Loss (without Re-Reflection Correction Factor)								
	Magnetic Field			Electric Field			Plane Wave		
	Superalloy	Aluminum	Mumetal	Superalloy	Aluminum	Mumetal	Superalloy	Aluminum	Mumetal
10	18.322	22.062	10.851	225.79	289.25	233.69	91.795	155.25	99.688
50	12.043	28.917	5.1873	205.04	268.28	212.83	85.024	148.26	92.808
100	9.5634	31.897	3.1515	196.18	259.25	203.88	82.178	145.25	89.88
500	4.7893	38.854	0.026843	175.9	238.29	183.26	75.881	138.27	83.237
1.00E+03	3.4042	41.862	-0.36934	167.39	229.27	174.49	73.39	135.27	80.487
5.00E+03	2.8583	48.871	1.5088	148.61	208.33	154.62	68.592	128.31	74.596
1.00E+04	4.241	51.903	3.5943	141.22	199.33	146.41	67.224	125.33	72.409
5.00E+04	12.85	58.993	11.56	127.18	178.46	128.91	67.164	118.44	68.893
1.00E+05	19.615	62.081	16.558	123.35	169.51	122.49	69.346	115.51	68.486
5.00E+05	46.502	69.402	33.704	124.29	148.88	112.5	84.27	108.85	72.482
1.00E+06	65.443	72.662	44.748	131.68	140.09	111.7	97.681	106.09	77.703
5.00E+06	141.07	80.703	86.213	180.01	120.18	125.47	159.99	100.16	105.45
1.00E+07	195.85	84.501	115.19	222.9	111.93	142.47	208.9	97.934	128.47
5.00E+07	421.77	94.817	231.95	421.08	94.291	231.36	421.05	94.271	231.34
1.00E+08	588.94	100.32	317.26	576.25	87.753	304.65	582.25	93.753	310.65
5.00E+08	1288.8	117.83	671.62	1248.3	77.304	631.07	1268.2	97.283	651.05
1.00E+09	1811.1	128.72	934.93	1758.5	76.155	882.35	1784.5	102.16	908.35

Table 3. Total Loss for Magnetic Field, Electric Field, and Plane Wave

Frequency	Re-Reflection Correction Factor								
	Magnetic Field			Electric Field			Plane Wave		
	Superalloy	Aluminum	Mumetal	Superalloy	Aluminum	Mumetal	Superalloy	Aluminum	Mumetal
10	37.741	52.839	26.894	59.459	141.68	72.735	59.45	141.68	72.728
50	24.157	67.982	14.915	44.407	125.71	57.29	44.399	125.71	57.283
100	18.886	74.433	10.688	38.152	118.84	50.767	38.144	118.84	50.76
500	8.7624	87.012	4.0344	24.517	102.93	36.132	24.51	102.93	36.126
1.00E+03	5.6014	88.615	2.7836	19.208	96.097	30.159	19.201	96.096	30.153
5.00E+03	1.521	79.377	3.2453	8.9187	80.32	17.558	8.9139	80.319	17.553
1.00E+04	0.93894	73.142	4.0053	5.6297	73.576	12.909	5.6259	73.575	12.905
5.00E+04	0.35224	58.022	3.0032	1.0863	58.112	4.7204	1.0849	58.112	4.7177
1.00E+05	0.14413	51.529	1.8116	0.33572	51.577	2.5045	0.33511	51.577	2.5027
5.00E+05	0.001471	36.885	0.17592	0.0021715	36.896	0.20578	0.0021626	36.896	0.20545
1.00E+06	3.76E-05	30.885	0.027724	4.95E-05	30.891	0.030968	4.92E-05	30.891	0.030895
5.00E+06	5.14E-12	18.176	9.89E-06	5.83E-12	18.178	1.04E-05	5.75E-12	18.178	1.03E-05
1.00E+07	5.19E-18	13.458	2.50E-08	2.28E-18	13.459	2.60E-08	1.70E-18	13.459	2.57E-08
5.00E+07	1.44E-40	5.0551	2.61E-19	5.44E-40	5.0553	2.69E-19	4.92E-40	5.055	2.60E-19
1.00E+08	1.89E-56	2.7371	1.51E-27	5.04E-56	2.7374	1.58E-27	3.21E-56	2.7371	1.48E-27
5.00E+08	5.59E-125	0.24953	6.52E-64	2.03E-124	0.24976	2.65E-62	4.11E-125	0.24951	2.15E-63
1.00E+09	6.22E-177	0.040759	5.41E-89	9.10E-177	0.040863	9.97E-88	3.84E-177	0.040755	6.88E-89

Table 4. Re-Reflection Correction Factor for Magnetic Field, Electric Field, and Plane Wave

	Shielding Effectiveness								
	Magnetic Field			Electric Field			Plane Wave		
Frequency	Superalloy	Aluminum	Mumetal	Superalloy	Aluminum	Mumetal	Superalloy	Aluminum	Mumetal
10	-19.419	-30.777	-16.044	166.34	83.936	152.97	32.344	13.562	26.959
50	-12.114	-39.064	-9.7279	160.64	78.947	147.56	40.625	22.552	35.525
100	-9.3225	-42.536	-7.5366	158.03	76.788	145.13	44.034	26.413	39.119
500	-3.9731	-48.158	-4.0075	151.38	71.741	139.14	51.371	35.346	47.111
1.00E+03	-2.1971	-46.754	-3.1529	148.18	69.548	136.35	54.189	39.173	50.335
5.00E+03	1.3372	-30.506	-1.7365	139.69	64.389	129.08	59.678	47.994	57.043
1.00E+04	3.302	-21.239	-0.41098	135.59	62.127	125.52	61.598	51.752	59.504
5.00E+04	12.498	0.97176	8.5566	126.1	56.726	116.21	66.079	60.332	64.176
1.00E+05	19.471	10.552	14.747	123.01	54.309	112	69.011	63.935	65.983
5.00E+05	46.501	32.517	33.528	124.29	48.354	104.32	84.268	71.959	72.277
1.00E+06	65.442	41.776	44.721	131.68	45.577	103.69	97.68	75.203	77.672
5.00E+06	141.07	62.526	86.213	180.01	38.373	117.49	159.99	81.979	105.45
1.00E+07	195.85	71.043	115.19	222.9	34.85	134.49	208.9	84.475	128.47
5.00E+07	421.77	89.762	231.95	421.08	25.611	223.38	421.05	89.216	231.34
1.00E+08	588.94	97.583	317.26	576.25	21.39	296.66	582.25	91.016	310.65
5.00E+08	1288.8	117.58	671.62	1248.3	13.428	623.09	1268.2	97.033	651.05
1.00E+09	1811.1	128.68	934.93	1758.5	12.489	874.36	1784.5	102.11	908.35

Table 5. Shielding Effectiveness for Magnetic Field, Electric Field, and Plane Wave

6.0 APPENDIX B—EMI SHIELDING CHARACTERISTICS OF METALS

EMI SHIELDING CHARACTERISTICS OF METALS

METAL	SPECIFIC ELECTRIC CONDUCTIVITY σ_r	SPECIFIC PERMEABILITY μ_r (≤ 10 kHz)	SPECIFIC ABSORPTION LOSS $A = k_1 \sqrt{\sigma_r \mu_r}$	SPECIFIC REFLECTION LOSS $R = k\sqrt{\sigma_r / \mu_r}$	SPECIFIC REFLECTION LOSS R (dB)	DENSITY ρ (g/cm^3)
Silver	1.064	1	1.03	1.3	0.3	10.501
Copper (solid)	1	1	1	1	0	8.96
Copper (flame spray)	0.1	1	0.32	0.32	-10	N/A
Gold	0.7	1	0.88	0.88	-1.1	19.282
Chromium	0.664	1	0.81	0.81	-1.8	7.19
Aluminum (soft)	0.63	1	0.78	0.78	-2.1	2.6
Aluminum (tempered)	0.4	1	0.63	0.63	-4	N/A
Aluminum (household foil, 1 mil)	0.53	1	0.73	0.73	-2.8	2.698
Aluminum (flame spray)	0.036	1	0.19	0.19	-14.4	N/A
Brass (91% Cu, 9% Zn)	0.47	1	0.69	0.69	-3.3	8.7
Brass (66% Cu, 34% Zn)	0.35	1	0.52	0.52	-5.7	8.5
Zinc	0.305	1	0.57	0.57	-4.9	7.134
Tin	0.151	1	0.39	0.39	-8.2	7.287
Superalloy	0.023	100,000	53.7	0.0005	-65.4	8.9
78 Permalloy	0.108	8,000	29.4	0.0037	-48.7	8.6
Purified Iron	0.17	5,000	29.2	0.0058	-44.7	7.85
Conetic AA	0.031	20,000	28.7	0.0011	-58.8	N/A
4-79 Permalloy	0.0314	20,000	25.1	0.0013	-58	N/A
Mumetal	0.0289	20,000	24	0.0012	-58.4	8.75
Permedur(50 Cu, 1-2 V, % Fe)	0.247	800	14.1	0.0018	-35.1	N/A
Hypernick	0.0345	4,500	12.5	0.0028	-51.1	N/A
45 Permalloy (1200 anneal)	0.0384	4,000	12.4	0.0031	-50.2	8.25
45 Permalloy (1050 anneal)	0.0384	2,500	9.8	0.0039	-48.1	8.25
Hot-Rolled Silicon Steel	0.0384	1,500	7.59	0.0051	-45.9	3.58
Sinimax	0.0192	3,000	7.59	0.0025	-51.9	1.04
4% Silicon Iron (grain oriented)	0.037	1,500	7.45	0.005	-46.1	N/A

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TABLE 6. EMI Shielding Characteristics of Metals

APPENDIX C—MATLAB SOURCE CODE FOR ABSORPTION LOSS, REFLECTION LOSS, RE-REFLECTION CORRECTION FACTOR, AND SHIELDING EFFECTIVENESS

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  Author: Cindy S Cheung
%  Last Updated: November 10, 2008
%  Function: Matlab Source Code that Calculates and Plots Absorption Loss,
%          Reflection Loss, Re-Reflection Correction Factor, and
%          Shielding Effectiveness for a Superalloy, Aluminum, and
%          Mumetal Shielding 0.00035 inches thick and located 1 meter
%          from EM source
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Clear Output Windows
clear all;
clc;

% Frequency Range
Freq=10:10e4:1e9;    %Frequencies used for Plots
%Freq = [1e1 5e1 1e2 5e2 1e3 5e3 1e4 5e4 1e5 5e5 1e6 5e6 1e7 5e7 1e8 5e8 1e9];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Absorption Loss for all Fields
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

K1 = 3.34;      %Constant = 131.4 if l is meters; 3.34 if l is inches
l = 0.00035;    %Thickness in inches

% Superalloy Parameters
SA_ur = 1e5;      %Permability
SA_gr = 0.023;     %Conductivity

% Aluminum Parameters
Al_ur = 1;        %Permability
Al_gr = 0.53;      %Conductivity

% Mumetal Parameters
Mu_ur = 2e4;       %Permability
Mu_gr = 0.0289;    %Conductivity

% Absorption Loss Equations
A_SA = K1 * l * sqrt(Freq * SA_ur * SA_gr);
A_Al = K1 * l * sqrt(Freq * Al_ur * Al_gr);
A_Mu = K1 * l * sqrt(Freq * Mu_ur * Mu_gr);
```

```
% Plot Absorption Loss
figure (1);
loglog(Freq, A_SA, Freq, A_Al, Freq, A_Mu);
grid on;
title('Absorption Loss');
xlabel('Freqency (Hz)');
ylabel('Absorption Loss (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Reflection Loss
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

C1 = 0.0117;    %Coefficient for Magnetic = 0.0117 if r is meters
          %                   = 0.462 if r is inches
C2 = 5.35;     %Coefficient for Magnetic = 5.35 if r is meters
          %                   = 0.136 if r is inches
C3 = 322;
r = 1;       %Distance from EM Source to Shield in meters

% Reflection Loss for Magnetic Field
Rm_SA = 20 * log10((C1 ./ (r .* sqrt((Freq .* SA_gr) ./ SA_ur))) +...
     (C2 .* (r .* sqrt((Freq .* SA_gr) ./ SA_ur))) + 0.354);
Rm_Al = 20 * log10((C1 ./ (r .* sqrt((Freq .* Al_gr) ./ Al_ur))) +...
     (C2 .* (r .* sqrt((Freq .* Al_gr) ./ Al_ur))) + 0.354);
Rm_Mu = 20 * log10((C1 ./ (r .* sqrt((Freq .* Mu_gr) ./ Mu_ur))) +...
     (C2 .* (r .* sqrt((Freq .* Mu_gr) ./ Mu_ur))) + 0.354);

% Plot Reflection Loss for Magnetic Field
figure(2);
semilogx(Freq, Rm_SA, Freq, Rm_Al, Freq, Rm_Mu);
grid on;
title('Reflection Loss For Magnetic Field');
xlabel('Freqency (Hz)');
ylabel('Reflection Loss (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);

% Reflection Loss For Electric Field
Re_SA = C3 - (10 * log10((SA_ur * Freq.^3 * r.^2) / SA_gr));
Re_Al = C3 - (10 * log10((Al_ur * Freq.^3 * r.^2) / Al_gr));
Re_Mu = C3 - (10 * log10((Mu_ur * Freq.^3 * r.^2) / Mu_gr));

% Plot Reflection Loss For Electric Field
figure (3);
semilogx(Freq, Re_SA, Freq, Re_Al, Freq, Re_Mu);
```

```
grid on;
title('Reflection Loss For Electric Field');
xlabel('Freqency (Hz)');
ylabel('Reflection Loss (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);

% Reflection Loss For Plane Wave
Rp_SA = 168 - 20 * log10(sqrt((Freq * SA_ur) / SA_gr));
Rp_Al = 168 - 20 * log10(sqrt((Freq * Al_ur) / Al_gr));
Rp_Mu = 168 - 20 * log10(sqrt((Freq * Mu_ur) / Mu_gr));

% Plot Reflection Loss For Plane Wave
figure(4);
semilogx(Freq, Rp_SA, Freq, Rp_Al, Freq, Rp_Mu);
grid on;
title('Reflection Loss For Plane Wave');
xlabel('Freqency (Hz)');
ylabel('Reflection Loss (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Total Loss For Magnetic Field
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

TotalM_SA = A_SA + Rm_SA;
TotalM_Al = A_Al + Rm_Al;
TotalM_Mu = A_Mu + Rm_Mu;

% Plot Total Loss For Magnetic Field
figure (5);
loglog(Freq, TotalM_SA, Freq, TotalM_Al, Freq, TotalM_Mu);
grid on;
title('Total Loss For Magnetic Field');
xlabel('Freqency (Hz)');
ylabel('Total Loss (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Total Loss For Electric Field
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

TotalE_SA = A_SA + Re_SA;
TotalE_Al = A_Al + Re_Al;
TotalE_Mu = A_Mu + Re_Mu;

% Plot Total Loss For Electric Field
```

```
figure (6);
loglog(Freq, TotalE_SA, Freq, TotalE_Al, Freq, TotalE_Mu);
grid on;
title('Total Loss For Electric Field');
xlabel('Freqency (Hz)');
ylabel('Total Loss (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Total Loss For Plane Wave
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

TotalP_SA = A_SA + Rp_SA;
TotalP_Al = A_Al + Rp_Al;
TotalP_Mu = A_Mu + Rp_Mu;

% Plot Total Loss for Plane Wave
figure(7);
loglog(Freq, TotalP_SA, Freq, TotalP_Al, Freq, TotalP_Mu);
grid on;
title('Total Loss For Plane Wave');
xlabel('Freqency (Hz)');
ylabel('Total Loss (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Re-Reflection Correction Factor
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Parameter m for r in meters for Magnetic Field
mM_SA = (4.7e-2 ./ r) .* sqrt(SA_ur ./ (Freq .* SA_gr));
mM_Al = (4.7e-2 ./ r) .* sqrt(Al_ur ./ (Freq .* Al_gr));
mM_Mu = (4.7e-2 ./ r) .* sqrt(Mu_ur ./ (Freq .* Mu_gr));

% Reflection Coefficient for Magnetic Field
GammaM_SA = 4 .* (((1 - (mM_SA.^2)).^2 - (2 .* (mM_SA.^2)) +...
        (i * (2 .* sqrt(2)) .* mM_SA .* (1 - (mM_SA.^2)))) ./...
        (((1 + (sqrt(2) .* mM_SA)).^2 + 1).^2));

GammaM_Al = 4 .* (((1 - (mM_Al.^2)).^2 - (2 .* (mM_Al.^2)) +...
        (i * (2 .* sqrt(2)) .* mM_Al .* (1 - (mM_Al.^2)))) ./...
        (((1 + (sqrt(2) .* mM_Al)).^2 + 1).^2));

GammaM_Mu = 4 .* (((1 - (mM_Mu.^2)).^2 - (2 .* (mM_Mu.^2)) +...
        (i * (2 .* sqrt(2)) .* mM_Mu .* (1 - (mM_Mu.^2)))) ./...
```

```
        (((1 + (sqrt(2) .* mM_Mu)).^2 + 1).^2));

%Re-Reflection Correction Factor for Magnetic Field
CM_SA = 20 .* log(1 - (GammaM_SA .* (10.^(-A_SA ./ 10)) .*...
      (cos(0.23 .* A_SA) - (i .* sin(0.23 .* A_SA)))));
CM_Al = 20 .* log(1 - (GammaM_Al .* (10.^(-A_Al ./ 10)) .*...
      (cos(0.23 .* A_Al) - (i .* sin(0.23 .* A_Al)))));
CM_Mu = 20 .* log(1 - (GammaM_Mu .* (10.^(-A_Mu ./ 10)) .*...
      (cos(0.23 .* A_Mu) - (i .* sin(0.23 .* A_Mu)))));

% Magnitude of Correction Factor for Magnetic Field
magCM_SA = abs(CM_SA);
magCM_Al = abs(CM_Al);
magCM_Mu = abs(CM_Mu);

%Plot Correction Factor for Magnetic Field
figure (8);
semilogx(Freq, magCM_SA, Freq, magCM_Al, Freq, magCM_Mu);
grid on;
title('Re-Reflection Correction Factor, C, for Magnetic Field');
xlabel('Freqency (Hz)');
ylabel('Re-Reflection Correction Factor, C (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);

%----------------------------------------------------------------------

%Parameter m for r in meters for Electric Field
mE_SA = 0.205e-16 * r * sqrt((SA_ur * Freq.^3) / SA_gr);
mE_Al = 0.205e-16 * r * sqrt((Al_ur * Freq.^3) / Al_gr);
mE_Mu = 0.205e-16 * r * sqrt((Mu_ur * Freq.^3) / Mu_gr);

%Reflection Coefficient for Electric Field
GammaE_SA = 4 .* (((1 - (mE_SA.^2)).^2 - (2 .* (mE_SA.^2)) -...
        (i * (2 .* sqrt(2)) .* mE_SA .* (1 - (mE_SA.^2)))) ./...
        (((1 - (sqrt(2) .* mE_SA)).^2 + 1).^2));
GammaE_Al = 4 .* (((1 - (mE_Al.^2)).^2 - (2 .* (mE_Al.^2)) -...
        (i * (2 .* sqrt(2)) .* mE_Al .* (1 - (mE_Al.^2)))) ./...
        (((1 - (sqrt(2) .* mE_Al)).^2 + 1).^2));
GammaE_Mu = 4 .* (((1 - (mE_Mu.^2)).^2 - (2 .* (mE_Mu.^2)) -...
        (i * (2 .* sqrt(2)) .* mE_Mu .* (1 - (mE_Mu.^2)))) ./...
        (((1 - (sqrt(2) .* mE_Mu)).^2 + 1).^2));

%Re-Reflection Correction Factor for Electric Field
CE_SA = 20 .* log(1 - (GammaE_SA .* (10.^(-A_SA ./ 10)) .*...
      (cos(0.23 .* A_SA) - (i .* sin(0.23 .* A_SA)))));
CE_Al = 20 .* log(1 - (GammaE_Al .* (10.^(-A_Al ./ 10)) .*...
```

```
        (cos(0.23 .* A_Al) - (i .* sin(0.23 .* A_Al)))));
CE_Mu = 20 .* log(1 - (GammaE_Mu .* (10.^(-A_Mu ./ 10)) .*...
        (cos(0.23 .* A_Mu) - (i .* sin(0.23 .* A_Mu)))));

% Magnitude of Correction Factor for Electric Field
magCE_SA = abs(CE_SA);
magCE_Al = abs(CE_Al);
magCE_Mu = abs(CE_Mu);

%Plot Correction Factor for Electric Field
figure(9);
semilogx(Freq, magCE_SA, Freq, magCE_Al, Freq, magCE_Mu);
grid on;
title('Re-Reflection Correction Factor, C, for Electric Field');
xlabel('Freqency (Hz)');
ylabel('Re-Reflection Correction Factor, C (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);

%-----------------------------------------------------------------------

%Parameter m for r in meters for Plane Wave
mP_SA = 9.77e-10 .* sqrt((Freq .* SA_ur) / SA_gr);
mP_Al = 9.77e-10 .* sqrt((Freq .* Al_ur) / Al_gr);
mP_Mu = 9.77e-10 .* sqrt((Freq .* Mu_ur) / Mu_gr);

%Reflection Coefficient for Plane Wave
GammaP_SA = 4 .* (((1 - (mP_SA.^2)).^2 - (2 .* (mP_SA.^2)) -...
            (i * (2 .* sqrt(2)) .* mP_SA .* (1 - (mP_SA.^2)))) ./...
            (((1 + (sqrt(2) .* mP_SA)).^2 + 1).^2));
GammaP_Al = 4 .* (((1 - (mP_Al.^2)).^2 - (2 .* (mP_Al.^2)) -...
            (i * (2 .* sqrt(2)) .* mP_Al .* (1 - (mP_Al.^2)))) ./...
            (((1 + (sqrt(2) .* mP_Al)).^2 + 1).^2));
GammaP_Mu = 4 .* (((1 - (mP_Mu.^2)).^2 - (2 .* (mP_Mu.^2)) -...
            (i * (2 .* sqrt(2)) .* mP_Mu .* (1 - (mP_Mu.^2)))) ./...
            (((1 + (sqrt(2) .* mP_Mu)).^2 + 1).^2));

%Re-Reflection Correction Factor for Plane Wave
CP_SA = 20 .* log(1 - (GammaP_SA .* (10.^(-A_SA ./ 10)).*...
        (cos(0.23 .* A_SA) - (i .* sin(0.23 .* A_SA)))));
CP_Al = 20 .* log(1 - (GammaP_Al .* (10.^(-A_Al ./ 10)).*...
        (cos(0.23 .* A_Al) - (i .* sin(0.23 .* A_Al)))));
CP_Mu = 20 .* log(1 - (GammaP_Mu .* (10.^(-A_Mu ./ 10)).*...
        (cos(0.23 .* A_Mu) - (i .* sin(0.23 .* A_Mu)))));

% Magnitude of Correction Factor for Plane Wave
magCP_SA = abs(CP_SA);
```

```
magCP_Al = abs(CP_Al);
magCP_Mu = abs(CP_Mu);

%Plot Correction Factor for Plane Wave
figure (10);
semilogx(Freq, magCP_SA, Freq, magCP_Al, Freq, magCP_Mu);
grid on;
title('Re-Reflection Correction Factor, C, for Plane Wave');
xlabel('Freqency (Hz)');
ylabel('Re-Reflection Correction Factor, C (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Shielding Effectiveness For Magnetic Field
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

SEm_SA = A_SA + Rm_SA - magCM_SA;
SEm_Al = A_Al + Rm_Al - magCM_Al;
SEm_Mu = A_Mu + Rm_Mu - magCM_Mu;

% Plot Shielding Effectiveness For Magnetic Field
figure (11);
semilogx(Freq, SEm_SA, Freq, SEm_Al, Freq, SEm_Mu);
grid on;
title('Shielding Effectiveness For Magnetic Field');
xlabel('Freqency (Hz)');
ylabel('Shielding Effectiveness (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);

%Shielding Effectiveness For Electric Field
SEe_SA = A_SA + Re_SA - magCE_SA;
SEe_Al = A_Al + Re_SA - magCE_Al;
SEe_Mu = A_Mu + Re_SA - magCE_Mu;

figure (12);
semilogx(Freq, SEe_SA, Freq, SEe_Al, Freq, SEe_Mu);
grid on;
title('Shielding Effectiveness For Electric Field');
xlabel('Freqency (Hz)');
ylabel('Shielding Effectiveness (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);

%Shielding Effectiveness For Plane Wave
SEp_SA = A_SA + Rp_SA - magCP_SA;
SEp_Al = A_Al + Rp_Al - magCP_Al;
SEp_Mu = A_Mu + Rp_Mu - magCP_Mu;
```

```
figure (13);
semilogx(Freq, SEp_SA, Freq, SEp_Al, Freq, SEp_Mu);
grid on;
title('Shielding Effectiveness For Plane Wave');
xlabel('Freqency (Hz)');
ylabel('Shielding Effectiveness (dB)');
legend('Superalloy', 'Aluminum', 'Mumetal', -1);
```