Design of a Shielded Room against EMP Signal as per MIL-STD 461

Venkata Sai Charishma Pathala
Department of EECE, Gandhi Institute of Technology and Management, Deemed to be University, India
cpathala@gitam.in
(corresponding author)

Pappu V. Y. Jayasree
Department of EECE, Gandhi Institute of Technology and Management, Deemed to be University, India
jpappu@gitam.in

Received: 30 September 2022 | Revised: 3 November 2022 | Accepted: 5 November 2022

ABSTRACT

Electromagnetic shielding is the best technique to protect equipment from the Electromagnetic Pulse (EMP) signal. This paper explains how effectively the equipment will be protected within a shielded room against EMP signals. The shielded room is designed with different points of entry used to provide electrical connections to the Equipment Under Test (EUT) in a honeycomb structure for ventilation to protect the equipment from the EMP signal. The shielded room with four points of entry and honeycomb structures is designed, analyzed theoretically, and simulated in the CST Studio. The points of entry (PoE) and the honeycomb structure are designed based on MIL-STD-461 E/F/G (by following this standard the maximum frequency of EMP signal is 100MHz). It is observed that by increasing the size of the PoE the shielding effectiveness value decreases by 20dB for perfect electrical conductor (PEC) material of 2mm thickness. It is concluded that the equipment will be more protected when it is placed nearer to the front wall or in the middle of the shielded room. The performance of the shielded room will not be affected with honeycomb structures which will provide 220dB Shielding Effectiveness (SE).

Keywords-Electromagnetic Pulse (EMP); Point of Entry (PoE); honeycomb structure; MIL-STD-461 E/F/G; Shielding Effectiveness (SE); Perfect Electrical Conductor (PEC)

I. INTRODUCTION

In the present electromagnetic environment, the protection of equipment related to medical or military applications is of utmost priority. Equipment shielding is achieved by designing a shielded room. Usually, the shielded room will be designed by placing gaskets during the design of the door of the room, a honeycomb structure for ventilation, and apertures for the routing of cables. The main motto of this shielded room is to protect the electronic equipment from the interference of the dangerous signal strength of EMPs. The most effective method to safeguard the equipment from Electromagnetic Interference (EMI) is shielding and filtering [1-4]. The performance of a shield is defined by its SE value which is obtained from taking the difference between the received power with shield material and without it [5]. The shielding technique is used in many fields like aerospace engineering or medical and military equipment. In aerospace applications, different combinations of shielding materials are used to provide shielding to the aircraft [6]. Even the human brain can be protected from mobile radiation by placing shields coated with different types of shielding materials [7].

The simulated data for electromagnetic calculations can be acquired by various numerical methods [8], but the computations usually require long time. So, the analytic method has a better performance than the numerical methods. The analytical methods are classified in two types, i.e. based on aperture coupling between the aperture [9, 10] and based on the transmission line theory. The design of metallic shielded rooms is used to reduce the leakage signals from external electromagnetic fields. According to the IEEE Standard 299, the SE is used for the calculation of the effectiveness of metallic shielded enclosures [11]. The materials used in the design of shielded rooms are considered based on their conductivity and the frequency of operation. In this paper, the material used in the design was a perfect electrical conductor, in theoretical calculations the conductivity value of the materials is not considered while calculating the SE of the shielded room. The calculations of SE can be done with many methods. One of these is to add three parameters (Reflection loss (R), Absorption loss (A), Multiple reflections (M)) to obtain the SE value.

$$SE_{\mathrm{dB}} = R_{dB} + A_{dB} + M_{dB} \quad (1)$$

Another method for the calculation of electrical SE (ESE) is achieved by considering the difference between the field signal in the presence and the absence of the shield as in (2). E_A and E_P are the electric field intensities without and with an enclosure, respectively.

$$\mathrm{ESE} = 20 \log\frac{E_A}{E_P}[\mathrm{dB}] \quad (2)$$

The SE value depends on the size and the number of Points of Entry (PoE). The PoE is defined by the frequency of the input signal. The maximum frequency of the EMP signal is 100MHz, so that the PoE are designed with a cut of frequency greater than the frequency of the input signal. Leakage of signal occurs when the wavelength of the signal is shorter than the size of the PoE.

II. DESIGN OF THE SHIELDED ROOM

The shielded room was designed to protect equipment against EMP signals. The EMP signal has a high amplitude and short duration. The characteristics of an EMP signal is a double exponential voltage pulse with amplitude of 55kV, rise/fall time 2.3ns, pulse width 22.73ns as per MIL-STD 461 E/F/G [12] (Figure 1). The EMP signal is given as an input to the shielded room, the equipment in the shielded room is protected by providing all power connections to the equipment. The design of PoE for a shielded room must consider the frequency component of the EMP signal. The frequency of the EMP signal is calculated by taking the inverse of its period. The maximum frequency of the EMP signal is 100MHz, considered from the military standard MIL-STD 461 E/F/G and the PoE are designed such that they should not allow the entry of the EMP signal.

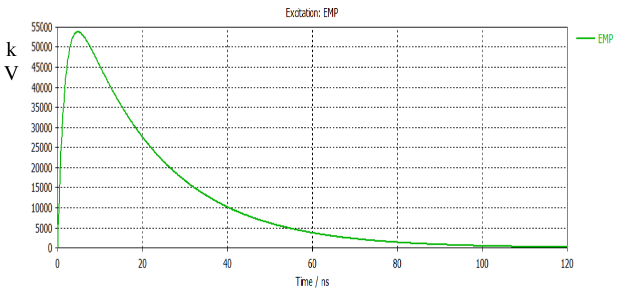

Fig. 1. EMP signal waveform.

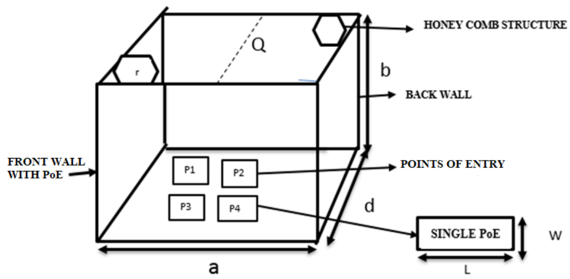

Fig. 2. A shielded room with different POE.

The shielded room with different PoE for routing the power cables and honeycomb structure to provide ventilation to the equipment is shown in Figure 2.

The shielded room was designed with 4 PoE with different cutoff frequencies to protect. The PoE is considered as the waveguide. The maximum frequency of the EMP signal is 100MHz so that the waveguides are designed with a cutoff frequency greater than that, so that the equipment is protected from the EMP signal. The frequency of the PoE is shown in Table I. Honeycomb structures were considered for vendilation. Two honeycomb structures with cutoff frequency of 40GHz were placed in parallel at the top of the room. The design dimensions of the shielded room with honeycomb structure are also given in Table I.

TABLE I. SHIELDED ROOM DIMENSIONS

Parameters	**Length**	**Width**	**Height**
RF shielded room	*d* = 2m	*a* = 2m	*b* = 2m
Honeycomb panel	*r* = 0.45m		
PoE	***l* (m)**	***w* (m)**	**Cutoff frequency (f_c)**
P1	0.1	0.05	1.5GHz
P2	0.075	0.0375	2 GHz
P3	0.06	0.03	2.5 GHz
P4	0.05	0.025	3 GHz

III. MATHMATICAL ANALYSIS

A. *Single Point of Entry*

The effectiveness of the metallic shielded room can be determined mathematically by considering a single PoE by using the Transmission Line Model (TLM) method [13]. The equivalent circuit of the shielded room with PoE is represented here.

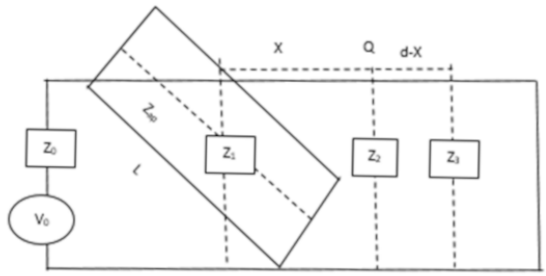

Fig. 3. Circuit model of the shielded room with PoE.

From the equivalent circuit model, Thevenin's theorem is applied to calculate the value of SE. The Q point represents the position of the equipment. The length of the PoE is *L*. The applied input voltage is denoted by V_0, the input impedance of the equivalent circuit is Z_0, a single PoE is considered in the circuit model, and its impedance is Z_{PoE}. The SE value is calculated at distance *X* from the aperture.

$$V_1 = \frac{V_0 Z_{PoE}}{Z_0+Z_{PoE}} \quad (3)$$

$$Z_{PoE} = \frac{1}{2}\frac{l}{a} jZ_0 \tan\left(\frac{P_0 l}{2}\right) \quad (4)$$

$$Z_1 = \frac{Z_0 Z_{PoE}}{Z_0+Z_{PoE}} \quad (5)$$

The dominant mode of propagation in the rectangular waveguide is the TE_{10} mode and its characteristic impedance is:

$$Z_g = \frac{z_0}{\sqrt{1-(f)^2}} \quad (6)$$

where $f = \frac{\lambda}{2a}$ and the propagation constant P_g is:

$$P_g = P_0 * \sqrt{1-(f)^2]} \quad (7)$$

where $P_0 = \frac{2\pi}{\lambda_0}$.

Z_g and P_g are imaginary frequencies below the cutoff frequency. Then V_1, Z_1, which are the short circuit terminals of the wave guide to Q are transformed by attributing an equivalent voltage V_2, source impedance Z_2, and load impedance Z_3:

$$V_2 = \frac{V_1}{\cos(P_g X)+j\left(\frac{Z_1}{Z_g}\right)\sin(P_g X)} \quad (8)$$

$$Z_2 = \frac{Z_1 + jI\tan(P_g X)}{1+j\left(\frac{Z_1}{Z_g}\right)\tan(P_g X)} \quad (9)$$

$$Z_3 = jZ_g \tan(d-X) \quad (10)$$

The voltage at point Q is:

$$V_Q = \frac{V2Z3}{(Z2+Z3)} \quad (11)$$

The SE is:

$$\text{SE} = -20 \log_{10}|2V_Q/V_0| \quad (12)$$

B. Multiple Points of Entry

A shielded room with multiple PoE of different sizes was designed to protect the equipment from the EMP signal. The maximum frequency of the EMP signal should be considered while designing the PoE, so that no external signal is allowed inside the room. The multiple PoE of the side wall of the shielded room can be seen in Figure 4.

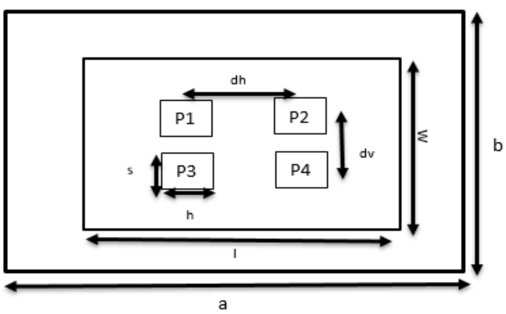

Fig. 4. Hardening of EMP signal with multiple PoE.

A shielded room with length and breadth a and b, respectively, with an array of entries with dimensions of l, w is considered. The distance between the PoE is defined as dh and dv. λ_0 and Y_0 are the free-space wavelength and the intrinsic admittance. Each PoE is considered as a rectangular hole denoted as d, where h, s are its length and width.

$$d = 0.636(h+s) \quad (13)$$

The SE calculation for multiple PoE when an EMP signal is applied to shielded room follows. The admittance of the equivalent circuit is given by [19]:

$$\frac{Y_{PoEs}}{Y_0} = -J\frac{3d_h\, d_v\, \lambda_0}{\pi d^3} + j\frac{288}{\pi\lambda_0 d^2}\left[\sum_{m=0}^{\alpha}\sum_{n=0}^{\alpha}\left(\frac{\epsilon_m n^2}{d_v^2} + \frac{\epsilon_n m^2}{d_h^2}\right)J_1^2(X)\right] \quad (14)$$

The argument of the Bessel function is:

$$X = \frac{[\pi d(m^2/d_h^2 + n^2/d_v^2)/2]^{1/2}]}{(m^2/d_h^2 + n^2/d_v^2)/2]^{1/2}} \quad (15)$$

$Z_{PoEs} = 1/Y_{PoEs}$ represents the PoE array connecting the free space [14]. Figure 4 shows multiple PoE placed on the shielded room wall. The effective wall impedance $Z_{PoEs}{}^{1}$ is the inverse of Z_{PoEs}. Using an impedance ratio concept, Z_{PoEs} becomes:

$$z_{ah}{}^{1} = Z_{ah}\left(\frac{W*L}{a*b}\right) \quad (16)$$

where the length l and width w of multiple PoE are:

$$l = \frac{dh}{2} + [(m-1)*dh] + \frac{dh}{2} \quad (17)$$

$$\text{w} = \frac{dv}{2} + [(n-1)*dv] + \frac{dv}{2} \quad (18)$$

where m and n represent the number of apertures in length and width of the array, respectively.

$$V_1 = \frac{(V_0 * Zah^1)}{(Z_0 + Zah^1)} \quad (19)$$

$$Z_1 = \frac{(Z_0 * Zah^1)}{(Z_0 + Zah^1)} \quad (20)$$

The SE is:

$$\text{SE} = -20 \log_{10}|2V_Q/V_0| \quad (21)$$

C. Honeycomb Structure

The attenuation constant for the wave guide is given below [15]. The attenuation constant is used for the calculation of the SE value of the wave guide:

$$\alpha = w(\mu \in)^{\frac{1}{2}}\sqrt{\frac{f_c}{f} - 1} \quad (22)$$

where fc is the cutoff frequency of the waveguide. The attenuation constant of the waveguide in dB can be calculated by placing the cutoff frequency value in (22). The SE value for a single hexagon cell (honeycomb structure) is calculated by using (23):

$$\text{SE}_{\text{dB}} = 17.5\frac{d}{g}\sqrt{1-\left(\frac{g_f}{96654}\right)^2} \quad (23)$$

In [16], an infinite array of parallel-plate waveguides is analyzed by the Wiener-Hopf method. The resulting equation is shown below. The first part gives the SE of the unit cell of a hexagon waveguide, while the second term is the SE of an infinite array of parallel-plate waveguides [24].

$$\text{SE}_{\text{dB}} = 17.5\frac{d}{g}\sqrt{1-\left(\frac{g_f}{96654}\right)^2} - 20\log_{10}\frac{2k_g}{\pi}\cos\varphi \quad (24)$$

where k is the wave number, g is a transverse dimension of the waveguide, and φ is the angle of an incident wave.

The SE equation for a hexagon structure has been modified by adding a third term to (24), so the performance of the hexagon structure at lower frequency is increased. The normalized frequency during the design of the honeycomb structure should be greater than 5 times the radius of the cell of the honeycomb structure. SE value does not depend on the number of hexagon cells in the honeycomb structure, but on the size and the length of a single cell.

$$SE_{dB} = 17.5\frac{d}{g}\sqrt{1-\left(\frac{g_f}{96654}\right)^2} -20\log_{10}\frac{2k_g}{\pi}\cos\varphi - 20\log_{10}\frac{2R_g}{f} \quad (25)$$

IV. SIMULATIONS

A. Shielded Room with a Single Point of Entry

A shielded room with a size of 2m×2m×2m with a single PoE of size 0.075m×0.0375m is shown in Figure 5. The probe was placed at the center of the shielded room. The position of the probe varied inside the room to find the fields inside the room with an EMP signal transmitted continuously to the shielded room. The material used in the design of the shielded room is Perfect Electrical Conductor (PEC). The thickness of the shielded material is 2mm.

SE value varies with the size of the PoE. A PoE of size 10cm×5cm is considered and the SE value is 255dB. If the size of the aperture is decreased, the SE value is increased as shown in Table II. The size of the PoE depends on the frequency of the EMP signal. Figure 6 shows the SE value for 4 apertures.

TABLE II. SE VALUES FOR DIFFERENT POINTS OF ENTRY

PoE	*a* (m)	*b* (m)	SE (dB)
P1	0.1	0.05	290
P2	0.075	0.0375	310
P3	0.06	0.03	320
P4	0.05	0.025	330

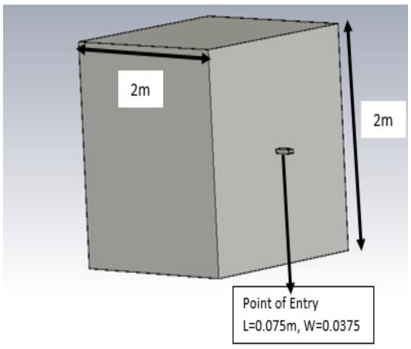

Fig. 5. Shielded room with a single PoE.

B. Shielded Room with Multiple Points of Entry

The shielded room with different entries was designed in CST simulation tool as shown in Figure 6. The SE value for an individual PoE is shown in Figure 7.

Let us consider shielded rooms with 4 PoE with different dimensions. The dimensions of an entry depend on its cutoff frequency. The cutoff frequency should be greater than the frequency of the EMP signal. In this condition the SE value meets the military standards MIL-STD-188-125-1 and 2. Figure 8 shows the total SE value of 4 different dimensions. The SE value decreases with the frequency of operation, which is below the resonant frequency. The resonant frequency of the shielded room was calculated by considering the room dimensions along with mode of propagation. The electric field probe is considered at the center of the shielded room, so that maximum SE value is obtained at that point. The SE value for 4 different PoE is 250dB.

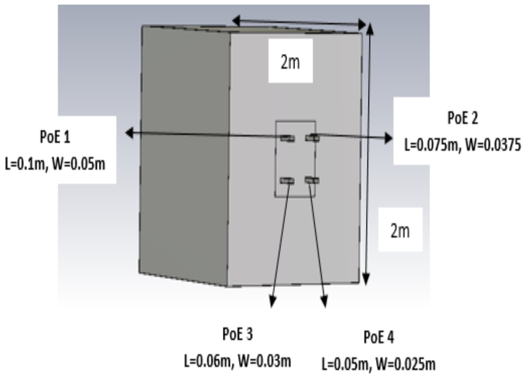

Fig. 6. Shielded room with 4 PoE with different sizes.

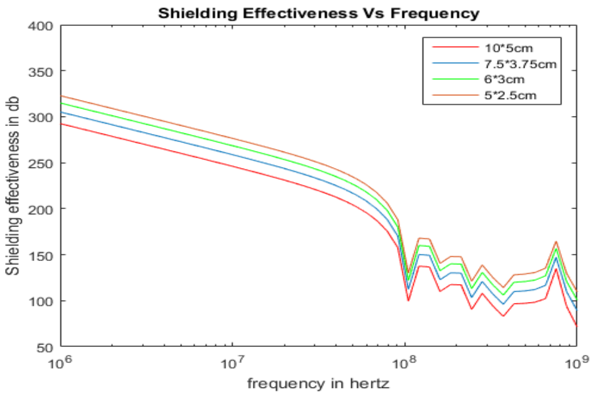

Fig. 7. SE value for different PoE sizes when an EMP signal is given as input.

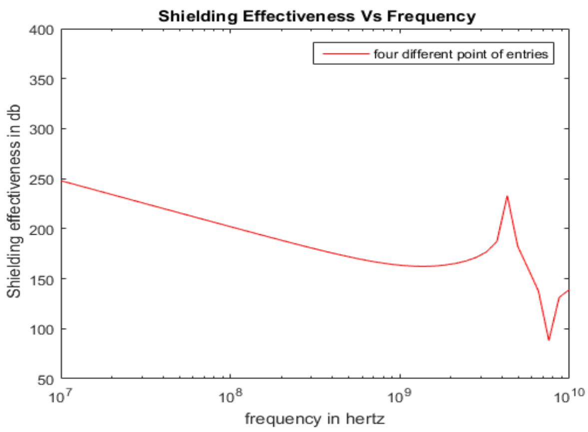

Fig. 8. Effect of SE when an EMP is applied to multiple PoE.

C. Shielded Room with Honeycomb Structures

The shielded room was designed with honeycomb structures used for ventilation, placed at the top of the room. The honeycomb structures were designed such that no external signal would enter the shielded room. Figure 9 shows the honeycomb structure. The honeycomb structures placed on the shielded room are shown in Figure 10. The SE value is calculated when the EMP signal is applied to the room.

(a)

(b)

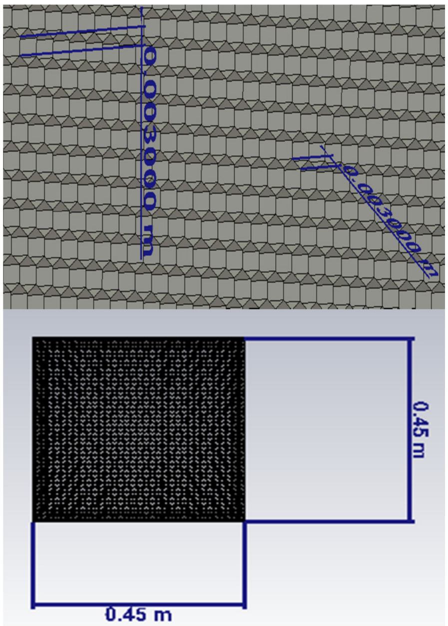

Fig. 9. Cell dimension details of the honeycomb structure, (b) total honeycomb structure.

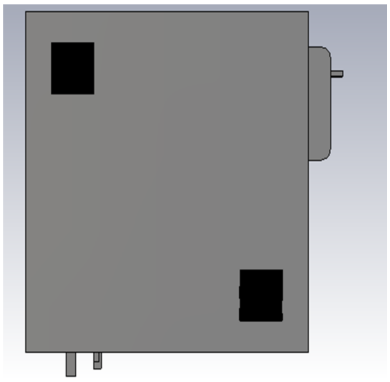

Fig. 10. Shielded room with 2 honeycomb structures.

D. Shielded Room with Points of Entry and Honeycomb Structure

The shielded room was designed with 4 PoE and 2 honeycomb structures, as shown in Figure 11. The EMP signal is incident on the shielded room with a voltage of 55kv. The SE value is calculated by placing the field probe at the center of the room. The total shielded room SE value is given in Figure 12.

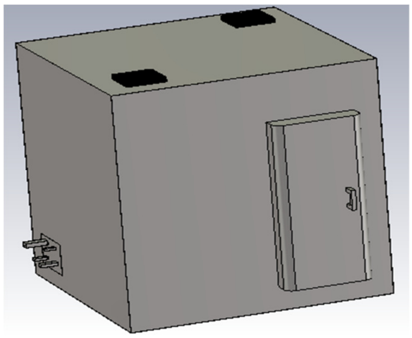

Fig. 11. Shielded room with 4 PoE and 2 honeycomb structures.

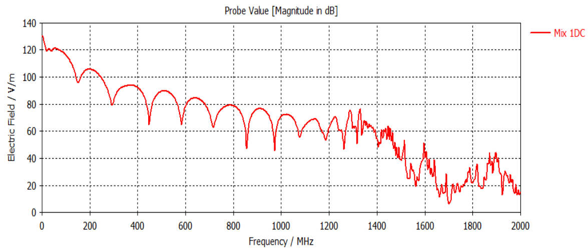

Fig. 12. The electric field value for a totally shielded room with 4 PoE and 2 honeycomb structures.

Total SE is calculated by taking the difference between the electric field with and without shield.

E. Effect of Varying Field Probe

The EMP signal is incident directly to the shielded room, which has dimensions of 2m×2m×2m with a single PoE. The EMP signal is parallel to the shielded enclosure. In this case the polarization type is fixed, so the field probe inside the enclosure is varied so that the SE value varies with changes in the position of the probe. The field probe gives the position of the equipment so that maximum SE is noted. The shielded room with a single PoE is shown in Figure 4. The change in the value of SE with the position of the field probe is shown in Figure 8. Consider a point Q at a different distances x1, x2, x3 from the front panel of the shielded room. The SE value increases when the position of the probe is near the wall of the shielded room as clearly observed in Figure 13.

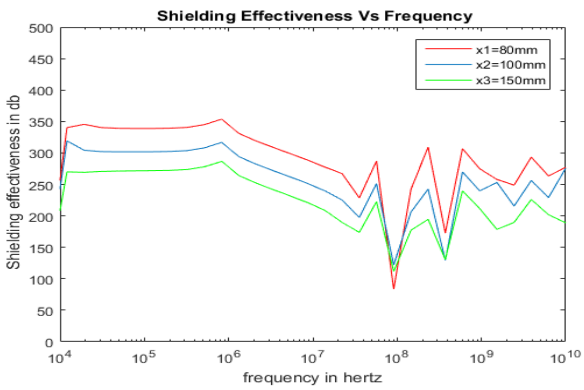

Fig. 13. Varying position of the field probe in the shielded room when the EMP is applied.

By observing the graph of Figure 13, we note that the SE value increases when the position of the probe is to the shielded room front wall and at the center of the room, and decreases when the probe is near to the back wall of the shielded room.

V. CONCLUSION

Theoretical calculations and simulation analysis were conducted in this paper for a shielded room against EMP signals. The transmission line method was used in the theoretical calculations of the shielded room with 4 different PoE dimensions. The smallest PoE with 0.05m length and 0.025m width has better SE value of 330dB than a PoE with greater size, with 0.1m length and 0.05m width, where the SE value decreases to 250dB. Simulation analysis is done with 3DEM CST modeling tool to verify the combined effect of multiple PoE and honeycomb structures. The total SE value for a shielded room with 4 PoE and 2 honeycomb structures is 140dB.

The novelty of this paper is that it was conducted as per MIL-STD-188-125-1/2 to protect the equipment from external EMP signals. This design of shielded room is useful for RF engineers that need to estimate the interference levels in sensitive equipment due to EMP signals.

REFERENCES

[1] J. Chen and J. Wang, "A Three-Dimensional Semi-Implicit FDTD Scheme for Calculation of Shielding Effectiveness of Enclosure With Thin Slots," *IEEE Transactions on Electromagnetic Compatibility*, vol. 49, no. 2, pp. 354–360, Feb. 2007, https://doi.org/10.1109/TEMC.2007.893329.

[2] A. Rabat, P. Bonnet, K. E. K. Drissi, and S. Girard, "Analytical Formulation for Shielding Effectiveness of a Lossy Enclosure Containing Apertures," *IEEE Transactions on Electromagnetic Compatibility*, vol. 60, no. 5, pp. 1384–1392, Jul. 2018, https://doi.org/10.1109/TEMC.2017.2764327.

[3] F. G. K. Abdulla and R. Abdulla, "A Comparative Application for Evaluating Composite Fabrics Used in Electromagnetic Shielding," *Engineering, Technology & Applied Science Research*, vol. 7, no. 6, pp. 2156–2159, Dec. 2017, https://doi.org/10.48084/etasr.1480.

[4] A. Khodadadi, M. H. Nazari, and S. H. Hosseinian, "Designing an Optimal Lightning Protection Scheme for Substations Using Shielding Wires," *Engineering, Technology & Applied Science Research*, vol. 7, no. 3, pp. 1595–1599, Jun. 2017, https://doi.org/10.48084/etasr.1175.

[5] Q. Xu, Y. Huang, X. Zhu, L. Xing, Z. Tian, and C. Song, "Shielding Effectiveness Measurement of an Electrically Large Enclosure Using One Antenna," *IEEE Transactions on Electromagnetic Compatibility*, vol. 57, no. 6, pp. 1466–1471, Sep. 2015, https://doi.org/10.1109/TEMC.2015.2477455.

[6] S. C. A. Bikkina and P. V. Y. Jayasree, "Development of a Wire Mesh Composite Material for Aerospace Applications," *Engineering, Technology & Applied Science Research*, vol. 12, no. 5, pp. 9310–9315, Oct. 2022, https://doi.org/10.48084/etasr.5201.

[7] S. S. Pudipeddi, P. V. Y. Jayasree, and S. G. Chintala, "Polarization Effect Assessment of Sub-6 GHz Frequencies on Adult and Child Four-Layered Head Models," *Engineering, Technology & Applied Science Research*, vol. 12, no. 4, pp. 8954–8959, Aug. 2022, https://doi.org/10.48084/etasr.5096.

[8] P. Dehkhoda, A. Tavakoli, and R. Moini, "An Efficient and Reliable Shielding Effectiveness Evaluation of a Rectangular Enclosure With Numerous Apertures," *IEEE Transactions on Electromagnetic Compatibility*, vol. 50, no. 1, pp. 208–212, Oct. 2008, https://doi.org/10.1109/TEMC.2007.911922.

[9] T. Martin, M. Backstrom, and J. Loren, "Semi-empirical modeling of apertures for shielding effectiveness simulations," *IEEE Transactions on Electromagnetic Compatibility*, vol. 45, no. 2, pp. 229–237, Feb. 2003, https://doi.org/10.1109/TEMC.2003.810818.

[10] M. Edrisi and A. Khodabakhshian, "Simple Methodology for Electric and Magnetic Shielding Effectiveness Computation of Enclosures for Electromagnetic Compatibility use," *Journal of Electromagnetic Waves and Applications*, vol. 20, no. 8, pp. 1051–1060, Jan. 2006, https://doi.org/10.1163/156939306776930312.

[11] "IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures," *IEEE Std 299-2006 (Revision of IEEE Std 299-1997)*, pp. 1–52, Oct. 2007, https://doi.org/10.1109/IEEESTD.2007.323387.

[12] A. Wraight, W. D. Prather, and F. Sabath, "Developments in Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) Test Methods," *IEEE Transactions on Electromagnetic Compatibility*, vol. 55, no. 3, pp. 492–499, Jun. 2013, https://doi.org/10.1109/TEMC.2013.2241442.

[13] M. P. Robinson *et al.*, "Analytical formulation for the shielding effectiveness of enclosures with apertures," *IEEE Transactions on Electromagnetic Compatibility*, vol. 40, no. 3, pp. 240–248, Dec. 1998, https://doi.org/10.1109/15.709422.

[14] *MIL-STD-188-125-2: High-altitude Electromagnetic Pulse (Hemp) Protection For Ground-based C4I Facilities Performing Critical, Time-urgent Missions, Part 2: Transportable Systems*. Washington DC, USA: Department of Defence, 1999.

[15] H.-R. Im, I.-K. Jung, J.-G. Yook, and H.-R. Song, "Analysis of EMP Penetration into an Enclosure with Electromagnetic Shielding Material," in *2018 USNC-URSI Radio Science Meeting (Joint with AP-S Symposium)*, Boston, MA, USA, Jul. 2018, pp. 31–32, https://doi.org/10.1109/USNC-URSI.2018.8602763.

[16] W. A. Bereuter and D. C. Chang, "Shielding Effectiveness of Metallic Honeycombs," *IEEE Transactions on Electromagnetic Compatibility*, vol. EMC-24, no. 1, pp. 58–61, Oct. 1982, https://doi.org/10.1109/TEMC.1982.304013.