Numerical Calculations of Shield Effectiveness of Different Materials due to an Incident TM Wave

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***Abstract*—In this paper, we consider an incident TM wave with frequency more than 10 THz falling on a thin sheet of different materials such as Mumetal, Aluminum, and Plumbum (Lead) "Pb". We calculate Shield Effectiveness (SE) for each of these materials, which is considered one of the most important parameter for radiation protection in nuclear reactor stations where the main purpose is to reduce the radiation exposure to persons and staff in the vicinity of radiation sources. Also, different polymer materials, such as Polytetrafluoroethylene (PTFE), can be used as the base material for design of shields for microwave frequencies (100 MH-10 GHz).**

***Index Terms*—Electromagnetic radiation, shielding effectiveness, nuclear power plants, gamma rays, PTFE**

I. Introduction

Electromagnetic shielding is frequently used to reduce emissions or completely avoid radiation from different sources to penetrate the outer surface to secure humans and the surrounding environment. Radiation protection is the science and practice of protecting people and the environment from the harmful effects of ionizing radiation. It is a important not only in nuclear reactor stations, but also in other industries such as medical centers. Radiation shielding usually consist of barriers of lead (Pb), concrete or water [1]. There are many many materials, which can be used for radiation shielding, but there are manifold situations in radiation protection. It highly depends on the type of radiation to be shielded, its energy and many other parameters. For example, even depleted Uranium can be used as a good protection from gamma radiation, but on the other hand uranium is absolutely inappropriate shielding of neutron radiation. Most commonly used neutron shielding in many sectors of the nuclear science and engineering is shield of concrete. Concrete is a hydrogen-containing material, but unlike water concrete have higher density (suitable for secondary gamma shielding) and does not need any maintenance. Because concrete is a mixture of several different materials its composition is not constant. Generally concrete are divided to "ordinary" concrete and "heavy" concrete. Heavy concrete uses heavy natural aggregates such as barites (barium sulfate) or magnetite or manufactured aggregates such as iron, steel balls, steel punch or other additives. As a result of these additives, heavy concrete have higher density than ordinary concrete (2300 kg/m3). Very heavy concrete can achieve density up to 5,900 kg/m3 with iron additives or up to 8900 kg/m3 with lead additives. Heavy concrete provide very effective protection against neutrons. [1]

Also, Carbon-fiber laminate woven materials are known to be used for shielding purposes [2], [3]. Lead aprons are used for personal protection of physicians and patients from X-ray (gamma) radiation during medical operations. It has been proposed in [4].

In this paper, we compare shield effectiveness of some materials, ... etc.

II. Shielding Effectiveness Theory

The shielding efficiency is generally measured in terms of reduction in magnitude of incident power/field upon transition across the shield. Mathematically shielding effectiveness SE_T can be expressed in logarithmic scale as per expressions:

$$\begin{aligned} SE_T(dB) &= SE_R + SE_A + SE_M = 10\log_{10}(\frac{P_T}{P_I}) \\ &= 20\log_{10}(\frac{E_T}{E_I}) = \log_{10}(\frac{H_T}{H_I}) \end{aligned} \tag{1}$$

where P_I (E_I or H_I) and P_T (E_T or H_T) are the power (electric or magnetic field intensity) of incident and transmitted EM waves respectively. As shown in Fig. II, three different mechanisms namely reflection (R), absorption (A) and multiple internal reflections (MIRs) contribute towards overall attenuation with SE_R, SE_A and SE_M as corresponding shielding effectiveness components due to reflection, absorption and multiple reflections respectively. According to [5], we can write total shield effectiveness as follow:

$$\begin{aligned} SE_T(dB) &= 20\log_{10}|p| + 20\log_{10}\left|e^{-\gamma d}\right| \\ &+ 20\log_{10}\left|(1-qe^{-2\gamma d})\right| \end{aligned} \tag{2}$$

where γ is the propagation constant, d is the thickness of the material, it is customary to define $\gamma = \alpha + j\beta = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)}$, $\omega = 2\pi f$ and f is the frequency.

$$p = p_H = \frac{4k}{(k+1)^2} \tag{3}$$

$$q = q_H = \frac{(k-1)^2}{(k+1)^2} \tag{4}$$

where, $k = \frac{Z_\omega}{\eta}$, Z_ω is the impedance of the incident wave $Z_\omega = 120\pi\Omega$ in free space, and η is the intrinsic impedance,

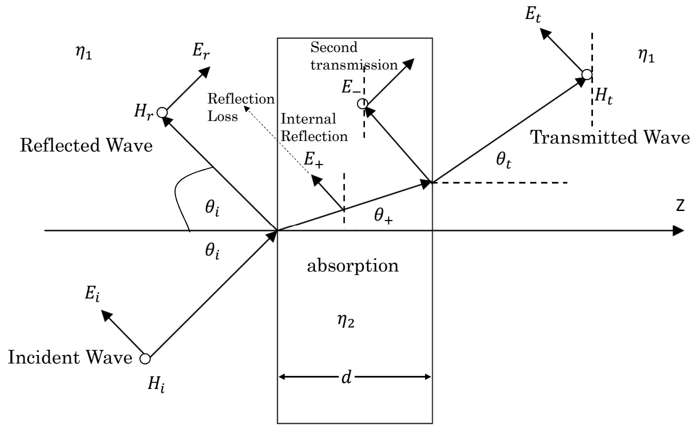

Fig. 1. Incident TM wave on a sheet.

$\eta = \sqrt{\frac{\mu}{\varepsilon}}$, μ is the permeability of the material, ε is the permittivity of the material.

$$Z = \eta \frac{Z(d)\cosh(\gamma d) + \eta \sinh(\gamma d)}{\eta \cosh(\gamma d) + Z(d)\sinh(\gamma d)} \tag{5}$$

where Z is the impedance of homogenous barrier of thickness d, $Z(0)$ is the impedance at interface 0 looking into the plane and $Z(d)$ is the impedance at interface d looking into the right of the plane at $z = d$. If $Z(d) \neq \eta$, reflection occurs at the boundary $z = d$.
The reflection q_H and transmission p_H coefficients can be written as follow:

$$\begin{aligned} q_H &= \frac{H^r}{H^i} = \frac{\eta - Z(d)}{\eta + Z(d)} \\ p_H &= \frac{H^t}{H^i} = \frac{2\eta}{\eta + Z(d)} = 1 + q_H \end{aligned} \tag{6}$$

Another solution of SE can be found in [6].

III. Simulations and Results

MATLAB simulations are performed to calculate SE of three materials which are, Mumetal ($\sigma_r = 0.0305$ and $\mu_r = 30000$), Aluminum ($\sigma_r = 0.58$ and $\mu_r = 1$), and Lead "Pb" ($\sigma_r = 0.0763$ and $\mu_r = 0.98$). Where σ_r is the relative conductivity, relative conductivity is defined with respect to Copper ($\sigma_{Copper} = 5.96 \times 10^7$), and μ_r is the relative permeability with respect to free space. Thickness of the sheet is 10 μm and it is on a distance of 30 cm from the source of radiation. The simulations also have shown that, the variation of incident angles will slightly change the total SE by a fraction of 1 dB which can be negligible.

From simulations

Theoretically a few hundreds dB SE can be reached at low frequencies even with a few micrometer thick shield against electrical interfering sources, but this may be as low as 0 dB for the magnetic sources as seen in Fig. 2. Starting from low frequencies, SE decreases with frequency for electrical shielding and increases with frequency for magnetic shielding.

In practice, depending on the critically of the problem under consideration, SE values of 30-60 are considered acceptable, whereas SE values in the range of 70-90 dB represent quite high shields. The shielding performance of a metal box with no holes, slots, joints, vents, windows, or other discontinuities, the SE can only be as good as allowed by such shielding imperfections [7].

We can notice these results:

- Shielding mostly occurs because of reflections and absorption at low and high frequencies respectively.
- High conductivity is good for both reflection and absorption while high permeability causes high absorptions but low reflections.

In brief, SE performance of a sheet depends on the material permeability μ, conductivity σ, sheet thickness d, distance from source of radiation, and frequency of the incident wave.

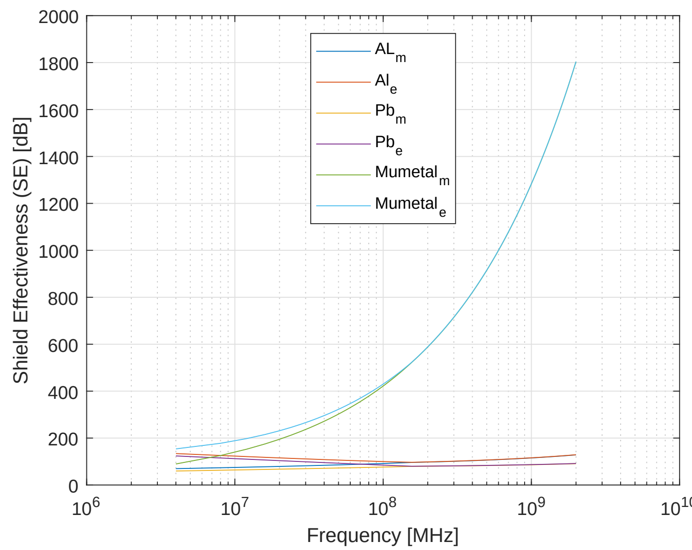

Fig. 2. Shield Effectiveness vs. frequency of different metals.

IV. Detection and Shielding of Gamma Radiation

In nuclear power plants there are several methods that are used for fast neutron detection. In [8], they used Teflon (PTFE) to detect fast neutrons with energies $E_n > 3$ MeV.

Effective shielding of gamma radiation is in most cases based on use of materials with two following material properties: (a) high-density of material, and (b) high atomic number of material (high Z materials). However, low-density materials and low Z materials can be compensated with increased thickness, which is as significant as density and atomic number in shielding applications.

A lead (Pb) is widely used as a gamma shield. Major advantage of lead shield is in its compactness due to its higher density. On the other hand depleted Uranium 235 is much more effective due to its higher Z. Depleted Uranium 235 is used for shielding in portable gamma ray sources.

V. Polytetrafluoroethylene (Teflon)

Polytetrafluoroethylene (PTFE), also known as Teflon, is a commonly used material in a spacecraft design, automotive and semiconductor industry. Reported applications are associated to the fact that PTFE has excellent chemical inertness, high thermal stability and low frictional coefficient [9], [10]. Therefore, it is broadly used in a range of industrial sectors where severe conditions as radiation, high temperature or lack of protection atmosphere occurs [11]. Materials subjected to aforementioned conditions are of great importance when it comes to safety assurance in nuclear facilities.

Also, different polymer materials, such as Teflon or thermoplasts, can be used as the base material for design of shields for microwave frequencies (100 MH-10 GHz). Teflon is almost non-dispersive in the frequency range of interest, and its loss factor can be neglected. The dielectric constant of the Teflon is taken as 2.2.

Over a wide range of frequencies, Teflon coatings have a high dielectric strength, low dissipation factor, and high surface resistivity. Dielectric strength is the highest voltage that the coating can withstand before it breaks down. The dissipation factor is the percentage of electrical energy absorbed and lost when current is applied to the coating. A low dissipation factor means that the absorbed energy dissipated as heat is low. Adding fillers to certain coatings can make them electro-conductive enough to be used as an anti-static coating. In addition, it can be used for shielding [12].

VI. Conclusion

We have studied the shield effectiveness of some materials which can be used to cover any nuclear power plants in order to provide secure for the surroundings. Mumetal seems to be the best solution as it provide the highest SE in high frequencies. We have also discussed the importance of PTFE and its future work in nuclear power plants.

Acknowledgment

We would like to thank all members of Electrical Engineering Department at Alexandria University for their for help in the initial stages of this work.

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