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Electromagnetic Fields: Principles of Exposure Mitigation

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*Basic principles of reducing exposure to electromagnetic fields are reviewed in this article. Measures to reduce exposure can be divided into organisational/administrative and technical/engineering actions. Both strategies are briefly analysed and the basic principles of the theory of shielding are presented. A definition of shielding effectiveness (*SE*) is given, and the results from the general Transmission Lines Theory are presented. Practical situations of shielding static and time-varying electric and magnetic fields are discussed on the basis of the physical properties of the fields and of the shield.*

EMF (electromagnetic fields) mitigation shielding

1. PRINCIPLES OF MITIGATING EXPOSURE TO ELECTROMAGNETIC FIELDS

Measures to reduce occupational exposure to electromagnetic fields can be addressed to protect the workers from direct effects and comply with exposure standards (a typical case when dealing with high power sources able to generate particularly strong fields), or to prevent electromagnetic interference with electronic devices, especially medical implants. In the latter case, even low fields could have an influence on the operating modes and the reliability of electric and electronic equipment, and they could produce risk conditions, so the requirements of shielding can be completely different than in the former case.

Measures to reduce exposure can be divided into two categories:

- organisational/administrative actions, concerning the work area and/or workers' exposure;
- technical/engineering actions (e.g., actions on the source, shielding, grounding).

1.1. Administrative Measures

Administrative measures are feasible through work area reorganisation, workers' education and training, and optimisation of work-shifts. Factors that influence exposure levels may include high density of source devices inside small areas, improper positioning of sources, improper positioning of electric cables (power feeding or radio frequency [RF] connections), metallic objects or surfaces in the work environment (re-radiation or contact currents risk), installation not compliant with manufacturers' recommendations especially in the case of high power industrial equipment like RF heaters.

It is a protective measure, also established by Directive 2004/40/EC [1] for high exposure levels, to indicate the risk area with appropriate signs and to use barriers and/or alarms in order to avoid access of non-authorised personnel. Such measures are

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particularly useful in preventing indirect effects on implantable medical devices. A substantial mitigation of exposure can often be achieved by re-organising the work area, moving the source far away from the workers, introducing remote controls, or automating workers' operations [2]. In the case of protection from the heating effects of RF, it is also possible to organise proper shifts for the workers, in order to keep exposure levels compliant with 6-min average limit values. Regular maintenance of equipment is also an aspect of great concern. In some cases obsolete devices can produce high exposure levels due to power supply control being out of order. Malfunctions can also lead to additional risks related to electrical safety.

Organisational/administrative measures can be generally implemented at moderate cost. Their effectiveness is strengthened by guidelines on equipment management, and by suitable personnel education and training.

1.2. Engineering Measures

Technical/engineering measures can be implemented a priori at the equipment design level by including specific requirements to reduce unnecessary emission. They can also be applied a posteriori on operating devices. After publication of Council Recommendation 1999/519/EC [3], the European Committee for Electrotechnical Standardization (CENELEC) issued several product standards referring to the limitation of human exposure to electromagnetic fields, in order to include in the design phase of products (or product families) compliance with exposure limits established in the Recommendation. As a matter of fact, mitigation measures adopted at the design phase are more effective and less expensive than a posteriori interventions. To avoid hazards of contact currents, engineering measures should also consider proper grounding of metal objects located in the workplace.

2. SHIELDING

The use of shielding can be considered when the adoption of other measures has not been successful or is not applicable. Shields are employed to reduce field levels at the source or on the "victim" device (this is the most common application in electromagnetic compatibility [EMC]). They can also be used to mitigate an electromagnetic disturbance introduced into the environment from the outside. The performance of shielding depends on different factors, such as geometric characteristics and physical properties of the material (electrical conductivity σ and magnetic permeability μ), properties of incident radiation, and shield–source distance compared with the wavelength of disturbance [4, 5, 6].

Shields are generally made of materials with high electrical conductivity. It is also possible to use natural or synthetic fabrics with the addition of a material with high conductivity (e.g., graphite, metal filaments). Transparent shields can be performed by inserting a metal grid between two layers of glass or transparent plastic material, or by applying a thin conductor layer (e.g., gold) over a glass or plastic support.

Shielding effectiveness (*SE*) is the ratio between electric/magnetic field amplitude in the same point of measurement, before (E_i, H_i) and after (E_t, H_t) the insertion of the shield:

$$SE_E = E_i/E_t \qquad \text{in dB:} \quad SE_E = 20 \log E_i/E_t$$
$$SE_H = H_i/H_t \qquad \qquad \quad SE_H = 20 \log H_i/H_t$$

2.1. Shielding Static Fields

Static electric fields can be shielded by means of conductor materials. Extremely thin metal sheets can be used to make very high performing shields. Nettings of conductors also have good shielding properties in electrostatic fields, and good attenuation is produced by building materials, such as reinforced concrete, and by vegetation. The presence of holes in a shield does not generally excessively reduce the quality of its performances, if no conductive object is placed close to the hole.

Otherwise, static magnetic fields are very difficult to shield. They can be mitigated with ferromagnetic materials, which are able to change the path of magnetic strength-lines and concentrate the field inside the shield; non-ferromagnetic metals, like aluminium, are completely transparent to static magnetic fields. Examples of ferromagnetic materials at room temperature

TABLE 1. Conductivity (σ) and Relative Permeability (μ) of Selected Materials [4]

Material	σ (S/m)	μ_r
Selenium	83×10^6	1
Silver	62×10^6	1
Copper	58×10^6	1
Gold	41×10^6	1
Aluminium	38×10^6	1
Chromium	38×10^6	1
Brass (66% Cu, 34% Zn)	26×10^6	1
Tungsten	18×10^6	1
Zinc	17×10^6	1
Nickel	14×10^6	max 600
Cobalt	10×10^6	max 250
Platinum	9.5×10^6	1
Lead	4.6×10^6	1
μ-Metal (Ni, Fe, Cu, Cr)	$2 \times 10^6 - 4 \times 10^6$	max 10^5
Supermalloy (Ni, Fe, Mo)	1.7×10^6	max 10^6
Stainless steel	1.1×10^6	1
Mercury	1.0×10^6	1
Graphite	71×10^3	1
Seawater	3	1

are iron, nickel and cobalt, as well as their alloys and oxides. Ferromagnetic alloys can also contain certain amounts of non-ferromagnetic metals, such as manganese, copper, and aluminium. Since the value of magnetic permeability of ferromagnetic materials changes with magnetic field strength, the choice of the material is critical. Materials such as μ-metal and supermalloy have high permeability for relatively low magnetic field strength, but they rapidly reach saturation, with consequent decay of permeability, as magnetic field strength increases. Table 1 shows conductivity and relative permeability of selected materials.

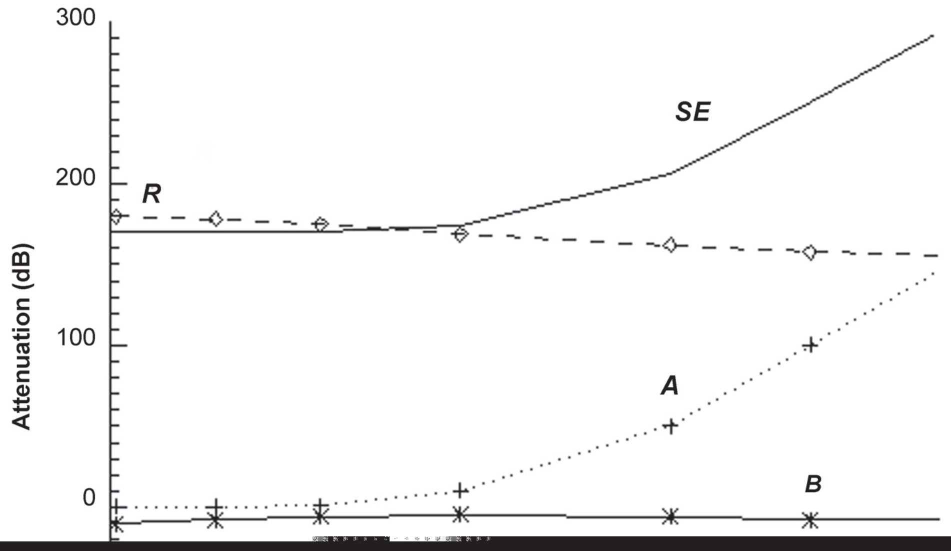
2.2. Shielding Time-Varying Fields

Time-varying fields induce eddy currents in conductive shields. These currents increase *SE* as they produce electric and magnetic fields in opposition to incident ones. The calculation of *SE* is generically based on numerical (complex shape analysis) or analytical methods (simple shape analysis). The configuration of eddy currents is very complex, and in order to understand the shielding mechanism it is common to employ analytical methods to solve Maxwell equations in simple geometrical shapes (e.g., a plane wave incident on an infinite metal plane of finite thickness). In this case, the wave propagation inside the shield is similar to tension and current waves inside a transmission line. On the basis of this concept, it is possible to analyse shield performance by exploiting the general Transmission Lines Theory; for a metal plane shield it can be obtained that *SE*, in dB, is given by the sum of three coefficients:

$$SE_{\mathrm{dB}} = R_{\mathrm{dB}} + A_{\mathrm{dB}} + B_{\mathrm{dB}}.$$

R_{dB} is associated with wave reflection at the two discontinuity surfaces (air/shield in entrance and shield/air in exit); A_{dB} is associated with absorption loss inside the shield; B_{dB} is associated with multiple reflections between the two sides of the shield. This last coefficient gives a negative contribution to *SE*.

The absorption loss depends on the properties of the material (μ, σ, penetration depth) and on the thickness of the shield [7]. The reflection loss depends on the characteristic impedance of the shield and on the impedance of the incident wave: the greater the difference between shield and wave impedances, the greater the reflection loss.



[redacted]

Figure 1. ***SE = R + A + B*** **(dB) as a function of frequency for an infinite copper plane of finite thickness for a normal incident plane wave condition.** *Notes. SE*—shielding effectiveness.

The contribution of multiple reflections can often be neglected, especially in the case of electrically thick shields.

In a plane wave condition (or far field in practice) and the same medium, *SE* is the same for the electric and magnetic fields ($SE_E = SE_H$). In that condition, the prevailing mechanisms are reflection, predominant at lower frequencies, and energy loss predominant at higher frequencies (Figure 1).

In near or reactive field conditions (i.e., at a distance from the source shorter than λ) electric and magnetic fields are uncoupled, so that SE_E and SE_H are different and must be treated separately, especially in reactive field conditions (a distance from the source shorter than λ/2π).

In the case of an electric field, reflection losses prevail in the near-field condition as well, and SE_E can reach high values, even at the frequency of 50 Hz. That is the reason why electric fields are easy to shield at all frequencies from ELF (extremely low frequency) to MW (microwave) range. On the other hand, in the case of a magnetic field, reflection losses in the near field are much lower than in the far field, and the condition at the air–shield interface is more similar to matching rather than reflection. Moreover, the negative contribution due to multiple reflections is not negligible, especially at lower frequencies, including 50 Hz, at which SE_H is mostly due to absorption losses. Absorption loss depends on the thickness and magnetic permeability of the shield. That is why just two solutions are effective to shield low frequency magnetic fields: improving the thickness of the shield (mostly impractical and expensive), or using magnetic materials. Proper combinations of two methods have also shown to be helpful.

It must be remarked that the magnetic permeability of materials varies with frequency, as shown in Table 2, and at frequencies higher

TABLE 2. Frequency Dependence of Relative Permeability (μ) of Selected Materials [9]

	Frequency		
Material	**1 kHz**	**10 kHz**	**100 kHz**
Steel	180	60	5
Iron	200	100	10
Iron (4% Si)	500	150	10
Permalloy	2500	800	50
Hypernyk	4500	1400	95
μ-Metal	20000	6000	400
Supermalloy	100000	30000	2000

than 1 MHz the relative magnetic permeability for most materials approaches the value of 1.

Active shields can be made of properly positioned loops able to generate, for the induction law of Faraday-Neumann, a magnetic field in opposition to the main one in the place where mitigation is needed (the field is necessarily enhanced in other regions of space). This solution has been proposed to mitigate 50-Hz magnetic fields of power lines. In this case a significant reduction in magnetic fields can be also obtained by a proper geometry of wires and phases.

As magnetic permeability varies considerably when the material is close to saturation, materials of high conductivity can be effectively used in order to shield very strong magnetic fields at low frequencies. In this case shielding performance can be improved either by increasing absorption losses through increasing the thickness of the shield, or by increasing reflection losses through increasing the distance between the shield and the source.

As frequency increases, the reactive field condition occurs only at a short distance from the source, and at frequencies greater than a few megahertz any metal can be used to effectively reduce magnetic fields in most real-life situations.

In practice it is impossible to make closed shields that completely separate the source of the disturbance from the potential victim; there is a need for openings for power feeding, connections, ventilation, maintenance, and so on. The apertures modify the eddy current path and degrade the shielding performance in unpredictable ways. In order to maintain acceptable shielding performance, a practical rule is to make apertures that are smaller than λ/50. If doors or windows are necessary (like in anechoic chambers) very good electrical continuity must be guaranteed, and a general rule it is to perform electric contacts (e.g., welding) in steps of at least λ/20. When a closed shield is required, it is a good solution to use netting, provided that the mesh step is suitable in relation to the wavelength of the disturbance.

3. PERSONAL PROTECTION EQUIPMENT

Personal protection equipment, such as shielding garments, gloves and safety shoes, is available [8]. Safety glasses have been proposed for protection from RF, although their effectiveness has not been proved yet. The use of shielding garments is limited over particular frequency ranges, and should be invoked when engineering and administrative measures have been insufficient (e.g., workers climbing radio/TV towers). Insulating gloves are helpful in preventing shocks and burns from contact currents, and safety shoes can be used to ensure compliance with the local Specific Absorption Rate (*SAR*) in the limbs through mitigation of foot current.

4. DISCUSSION

A review of measures and actions for mitigation of exposure to electromagnetic fields has been presented. As far as protection against direct effects is concerned, mitigation requirements are often not very severe, as addressed to ensure compliance with exposure standards, and in many practical situations organisational or administrative measures are sufficient for such a scope. The requested level of mitigation is generally not very severe even for 50-Hz magnetic fields, for which several magnetic materials—with high shielding performance—are commercially available. The design of shielding (shape, thickness, orientation, etc.) must however be performed by a skilled person or service, as it could completely fail even if based on proper materials. The most critical situations concern industrial heaters, where an adequate reduction of exposure may often require very complex and expensive engineering measures.

As far as protection against electromagnetic interference effect on implanted medical devices is concerned, as stated in Directive 2004/40/CE [1], adherence to exposure limits and action values may not necessarily eliminate interference problems and appropriate precautions should be undertaken, mostly based on signs and proper workers–source distance. Strong mitigation actions can be however necessary when low immunity electronic equipment must be placed in critical areas or close to strong field sources.

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