The Safety of Ordnance in High Frequency Electromagnetic Fields

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Abstract: The threat imposed on ordnance containing Electro-Explosive-Devices (EED) by high frequency electromagnetic fields is investigated. As examples for the required immunity levels for ordnance MIL-STD 464 and STANAG 4234 are reviewed. For ordnance not fulfilling the requirements of the applicable document possibilities of shielding are investigated. As an example the MILAN FIELD OVERSOCK MK 4 which is currently used by the UK Armed Forces in Afghanistan is considered more closely.

Keywords: Ordnance, Electro-Explosive Devices, Shielding, Conductive Textiles, Standards

Introduction

In recent years there has been an increasing threat that military electronic equipment may be influenced or damaged by high frequency electromagnetic fields.

Some of the difficulties are originated in the way electronic equipment is introduced into military service. An increasing number of not hardened equipment is brought into service due to financial reasons. Since the EMC properties are seldom tested in a sufficient manner by the manufacturer, these devices may fail even at low field strength. It is up to the military laboratories to do the necessary tests.

Another reason especially valid for ordnance is the susceptibility of the systems due to their ever rising complexity. The performance of modern weapon systems is based on the extensive use of electronic devices covering the broad range from control systems containing microprocessors to electrically initiated devices (EID). An EID is defined as any component activated through electrical means and having an explosive, pyrotechnic or a mechanical output resulting from an explosive or pyrotechnic action. Examples include bridgewire Electro-Explosive-Devices (EED) on which this paper is focused and many other kinds of initiators and detonators. The unintentional activation of an EED nearly always has devastating consequences. Not only is the ordnance unable to serve its purpose afterwards, there is a high probability that members of the handling crew may be harmed. Therefore it is very important to ensure that such devices are unsusceptible to electromagnetic fields applied from the outside.

The third reason is that the electromagnetic environment in which the ordnance is supposed to operate has changed dramatically. Numerous electromagnetic fields have to be reckoned with, emitted either by own transmission equipment, enemy transmitters or by ambient radio signals. All of these signals may have adverse influences on military equipment in storage, in transit or in operation. Basically there are two kinds of fields: The equipment is threatened either by incidentally radiated fields, or by intentionally applied fields radiated from directed energy weapons. The real danger to ordnance emanating from different sources can be estimated by taking a look at the properties of the field, the way the energy couples to the ordnance and effects it may cause there.

Fields and the Threat to Ordnance

Effects caused by Electromagnetic Fields

In order to find out what harm can be done, the operational state of the ordnance when exposed to an electromagnetic field should be identified at first. Is it in operation, in transport or storage?

As an example a guided missile as it is used for many purposes is considered here. If the electromagnetic interference occurs in operation, that means after the missile is launched, any system that depends on electronic signals for its operation may be upset. The most likely scenario is that the missile deviates from its course due to falsified signals and will be destroyed without completing the mission. It is important to notice that no physical damage is done to the electronic systems of the missile at this point. It is a malfunction of control elements due to the fact that the electronic signals needed for the function of the missile are changed. The energy needed to cause this effect may be rather low. Nevertheless the result is a lost missile, an intact target and a possible counter operation.

Before looking at other possible effects it is necessary to make a few definitions. Normally when speaking about the “strength” of a field we think of the magnitude of the electric and magnetic field vectors. Most destructive effects however are due to heating and it seems more natural to speak in terms of energy. The power density in an electromagnetic field is given by the Pointing Vector

$$\vec{S} = \vec{E} \times \vec{H} \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \tag{1}$$

The fluence u or energy density is a measure of time-integrated power density expressed in energy per unit area. It is therefore the product of the magnitude of the time average pointing vector p_{avg} and the time interval Δt

$$u = p_{\mathrm{avg}}\,\Delta t \qquad \left[\frac{\mathrm{J}}{\mathrm{m}^2}\right] \tag{2}$$

This definition provides an upper limit for the energy components can pick up from the electromagnetic field in a certain time interval. Especially for directed energy weapons where short double-exponential pulses of only some nanoseconds length are emitted with high power densities the fluence taken over the pulse length contains a reference to the destructiveness of the pulse. Another important point is the rise time of the pulse because it determines the spectral energy density.

As described above microwaves can trigger spurious signals that might jam a device and debilitate it temporarily without destruction of any components. This is of interest only when the interference occurs in operation. At higher energy fluences semiconductor components can be burned out when absorbed microwave energy leads to excessive heating. This may happen not only in operation but also in storage or transport when the system is inactive. The main difference is that in an inactive state all of the energy that is deposited in the semiconductor comes from the external electromagnetic field while in the active state energy from the power source biasing the semiconductor can add to this amount. For this reason the destruction threshold may be slightly lower in the active state.

Very high energy fluences can affect the Electro-Explosive-Devices for example by heating up bridgewires. This might lead to the detonation of warheads, bombs or artillery shells.

Destruction Effects on Semiconductors

The destruction effects of semiconductors caused by the impact of different kinds of high amplitude electromagnetic pulses have been investigated recently [2].

The microscopic analysis of destructed semiconductor devices generally shows three different damaging effects (Fig. 1). At lower field strengths only electronic components like diodes or transistors on the chip, mostly as a result of flashover effects, were damaged (Fig. 1a). If the amplitude of the electromagnetic pulse increases by about 50 %, additional onchipwire destructions (this means smelting of pcb tracks without flashover effects) and multiple component destructions occured (Fig. 1b). Further increase of the amplitude leads to additional bondwire destructions (Fig. 1c) and multiple component- and onchipwire-destructions.

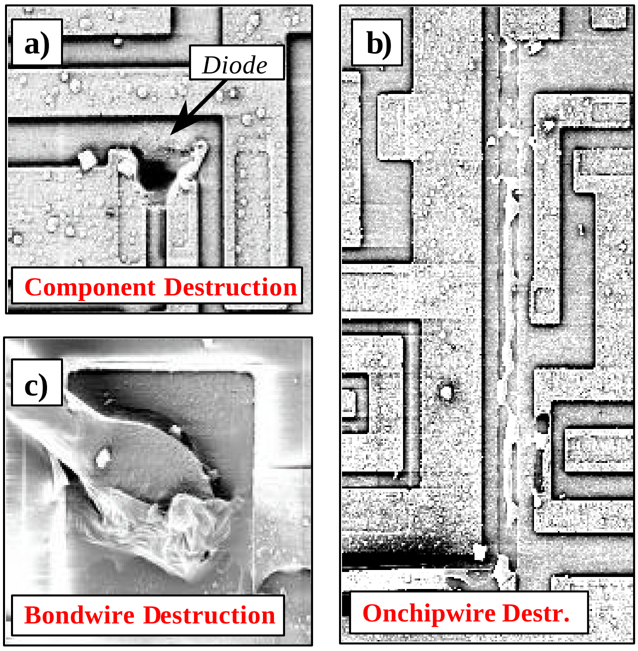


Figure 1. Destruction effects on chip level

The destructions were caused by the impact of an EMP with rise time $t_r = 7.5$ ns, and the full width half max value $t_{fwhm} = 180$ ns (fig. 2). The amplitude of the electrical field strength was about 1300 kV/m. The integrated circuit was contacted at the input pins by ribbon cable of ≈ 20 cm length. At the output pins ≈ 0 cm ribbon cable length was realized [2].

It has to be noticed that this measurements were done in a large guided wave EMP simulator. The field strength in a reasonable distance of 100 m – 1 km to a radiating source are considerably lower. Realistic peak values range from 10 to 100 kV/m. Combined with pulse length from 100 ns to 1 microsecond this leads to fluences from 0.01to 10 $\mathrm{J/m^2}$. The fluence decreases with increasing distance from the radiating source because of diffraction and attenuation. Higher fluences can be achieved by repetitive pulses.

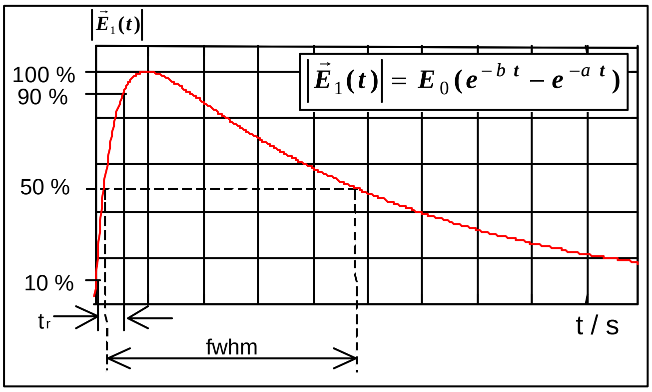


Figure 2. Pulsshape and definitions

Effects on Electro-Explosive-Devices

Electro-Explosive-Devices are extensively used in modern munitions to initiate explosives and pyrotechnics. Most EEDs employ a small resistive element called a bridgewire. When the EED is intentionally fired a current pulse is passed through the bridgewire, causing heating and resultant initiation of the explosive charge.

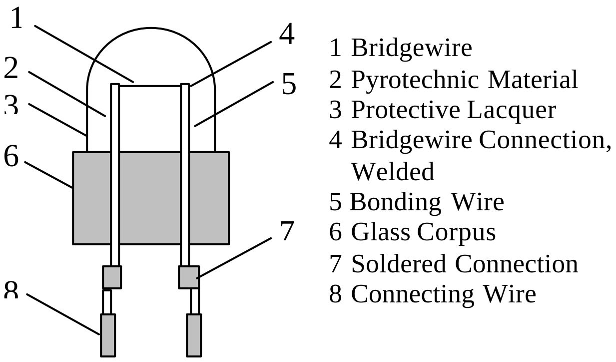


Figure 3. Construction of a Bridgewire EED

Unintentional firing of the EED may be caused by two effects. If the ordnance is in an active state RF energy may upset the firing circuits, causing unwanted current pulses to be sent to the EED. Secondly RF induced currents can cause bridgewire heating that that may fire the EED in active and inactive state of the ordnance. As can be imagined this requires substantially more energy than just upsetting the firing circuits.

An important parameter is the thermal time constant of the EED. The bridgewire responds to a current step with an increase in temperature that is an exponential function of time. The time constant is the point in time where 63% of the final temperature has been reached. Standard EEDs show a time constant between 1 and 20 milliseconds. The second important characteristic of an EED is the maximum no-fire-threshold (MNFT). It is defined as the level at which not more than 0.1% of the devices will fire at a 95% confidence level when the current is applied at least ten times the time constant. MNFTs are quite different due to the diversity of EEDs in use and cover the range from 100 mA to several Amperes.

Since it takes some time for the EED to heat up even if the induced current is above the MNFT short pulse are normally not considered to be a threat to ordnance. It has to be considered however that some RF sources like radar and some types of directed energy weapons radiate repetitive pulses. If applied to an EED each pulse causes a small amount of heating followed by a period where some cooling occurs. After several pulses the heating may be sufficient to initiate the EED. The amount of energy fed to a connected EED will depend upon several factors such as the physical and electrical parameters of the connecting wire relative to the wavelength, the polarisation of the incoming wave and the electrical impedances of the firing circuit. From several incidents especially on board of ships and measurements of a large number of ordnance it is well known however that sufficient energy to initiate certain types of EED can be picked up at lower field strengths than those likely to be encountered during military operations.

Treatment in Military Standards

The electromagnetic environment (EME) in which ordnance is required to be safely stored, handled and operated is defined for NATO purposes in STANAG 4234. The national German standards deduced from STANAG 4234 are VG 95378 and VG95379. Of international importance is especially MIL STD 464.

The current version of STANAG 4234 defines mean field intensities separately for Communications as well as radar and CW transmissions.

Table 1. Radio Frequency Environment (STANAG 4234)

Frequency Title	*Mean Field Intensities*	
	Field Strength V/m	Power Density W/m2
a) Communications Transmission		
200 kHz – 525 kHz	300	-
525 kHz – 32 MHz	200	-
32 MHz – 1 GHz	-	10
b) Radar and CW Transmissions		
150 MHz – 225 MHz	-	100
225 MHz – 790 MHz	-	50
790 MHz – 18 GHz	-	1000
18 GHz 40 GHz	-	100

The disadvantage of STANAG 4234 in the current version is that no statements concerning single and repetitive pulses are made. A new draft currently in preparation will include peak values for the field strength of pulsed CW signals as used for radar. Concerning double exponential pulses no statements are made. This is critical because short pulses can definitely damage electronic equipment as it was shown in the preceding section.

An international comparison shows that limits for pulsed fields are established in France, UK and the US. They are based however on specific national threats such as fields in the vicinity of aircraft carriers or the output levels of national available HPM sources and are not suitable for a standard NATO environment.

The probability that ordnance will be exposed to such specific environmental conditions has to be evaluated with respect to the special application. Then a baseline and a special severe environment can be defined. Otherwise non representative more severe requirements would be applied to all NATO ordnance. Especially for older ordnance this may lead to immense costs for additional hardening or shielding. The other solution would be constraints in the range of application due to safety reasons.

The US standard for electromagnetic environmental effects is MIL STD 464. A comparison of STANAG 4234 and MIL STD 464 shows that the discussion of possible threats is more comprehensive in the MIL STD. The applicable field strength for ordnance contains not only mean values as in the case of STANAG but additional peak values for pulsed CW fields. Furthermore lightning stroke pulses and double exponential pulses as well as multiple burst waveforms are considered. Table 2 shows that the values given for the peak field strength are extremely high for frequencies in the range of radar applications. This may be a results from incidents with ordnance onboard NAVY ships involving the inadvertent firing of rockets.

Table 2. Radio Frequency Environment (MIL STD 464)

Frequency (Hz) Title	Environment (V/m – rms)	
	Peak	Average
10 k – 150 M	200	200
150 M – 225 M	3120	270
225 M – 400 M	2830	240
400 M – 700 M	4000	750
700 M – 790 M	3500	240
790 M – 1000 M	3500	610
1 G – 2 G	5670	1000
2 G – 2.7 G	21270	850
2.7 G 3.6 G	27460	1230
3.6 G – 4 G	21270	850
4 G – 5.4 G	15000	610
5.4 G – 5.9 G	15000	1230
5.9 G – 6 G	15000	610
6 G – 7.9 G	12650	670
7.9 G – 8 G	12650	810
8 G – 14 G	21270	1270
14 G – 18 G	21270	614
18 G – 40 G	5000	750

The limits for average field strengths are also substantially higher for some frequencies as a direct comparison shows. For this purpose the values for power density given in STANAG 4234 have been translated to electrical field strengths under far field assumptions.

Table 3. Comparison between MIL STD 464 and STANAG

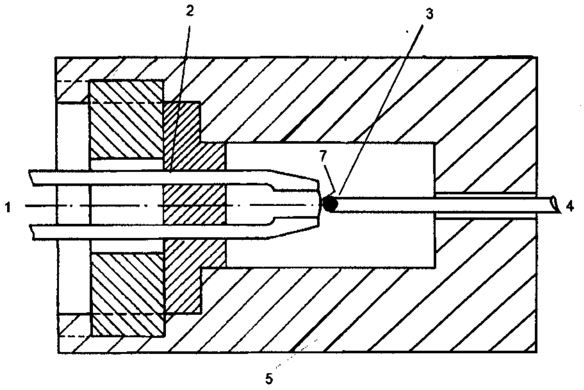
Frequency (Hz) Title	Environment (V/m – rms)		
	STANAG423		MIL STD 464
	Comm.	Radar	Average
10 k – 525 k	300	-	200
525 k – 32 M	200	-	200
32 M – 150 M	61.4	-	200
150 M – 225 M	61.4	194.2	270
225 M – 400 M	61.4	137.3	240
400 M – 700 M	61.4	137.3	750
700 M – 790 M	61.4	137.3	240
790 M – 1000 M	61.4	614	610
1 G – 2 G	-	614	1000
2 G – 2.7 G	-	614	850
2.7 G 3.6 G	-	614	1230
3.6 G – 4 G	-	614	850
4 G – 5.4 G	-	614	610
5.4 G – 5.9 G	-	614	1230
5.9 G – 6 G	-	614	610
6 G – 7.9 G	-	614	670
7.9 G – 8 G	-	614	810
8 G – 14 G	-	614	1270
14 G – 18 G	-	614	614
18 G – 40 G	-	194.2	750

The problem of overtesting becomes evident because it is not likely that ordnance is exposed to field strengths as high as given in MIL 464 during most NATO operations. Only on board of ships in the vicinity of antennas such fields are likely to be encountered. For equipment not used during shipboard operations the problem becomes evident only during transport onboard ships if it is stored on deck near the antennas. Another problem arises when looking at the extremely high peak field strengths given in table 2. Most EMC test facilities are not capable of generating such intense fields. For this reason it is barely possible to do adequate testing at reasonable costs.

Testing of EEDs

The field strengths given in the applicable standards have to be seen in connection with the safety margins required for ordnance. The margins distinguish between safety critical and other applications. Ordnance is required to have a margin of at least 17 dB of the MNFT for safety assurances and 6 dB for other applications.

To do adequate testing the EED has to instrumented using such techniques as thermocouple and fiber optic temperature sensors.



1. Interface to firing circuit
2. EED
3. Sensor
4. Optical fiber
5. Mechanical Adaption
6. IR sensible layer
7. Bridgewire

Figure 4. Fiber Optical EED Instrumentation

If the ordnance is exposed to an external field, the temperature of the bridgewire increases. From the temperature a value for the induced voltage or current is calculated. The relation of the MNFT and this value

$$a = 20\log\frac{\text{MNFT}}{\text{Induced Value}}$$

is the safety margin a in decibel. In order to demonstrate the required margins the field strengths given in the applicable document have to be generated if the capacity to generate these levels exist. When the available test levels are less than the specified levels the response may be extrapolated to the full environment for components with linear responses such as bridgewire EEDs. It should be noted however that non-bridgewire types of EED are being increasingly used. Their behavior differs considerably from bridgewire devices and they may exhibit nolinear response characteristics. For such components no extrapolation is permitted.

Methods of Shielding

If it becomes apparent that ordnance does not comply with the environmental conditions given in the standards as it is the case with some equipment that is in use in NATO countries for several years methods of shielding have to be considered. Examples are some types of guided missiles like MILAN which was developed more than thirty years ago and which has been shown to be sensitive to RF electromagnetic fields. For three decades the missile system has been the backbone of anti-tank defense in almost forty countries. Infantry forces will continue to rely on MILAN well beyond the year 2005. Considering the large number of MILAN in use it is nearly impossible to try to harden the missile itself and ensure safe operation in difficult RF environment. Mostly however this is not necessary because it seems unlikely that the ordnance is exposed to strong fields during the short time of operation. During storage and especially transport there exist possibilities of shielding. To shield the ordnance as long as possible the shield should be sturdy enough to be used in the field under all weather conditions to the point where the ordnance is made ready for use. It should be simple to handle to allow quick unpacking and should be available in camouflage pattern. These requirements limit the possible shielding materials to electrically conductive textiles that are light, flexible and sturdy enough to withstand harsh environmental conditions.

Conductive Textiles

In recent years a variety of electrically conductive textiles have been developed for different applications in EMC [3]. These include protective clothing for personnel exposed to high frequency electromagnetic fields and covers for the storage of electronic equipment which may be damaged either by electrostatic discharge or high frequency fields.

The fabrics can be divided in two main groups: Metal coated fabrics and metal interwoven fabrics. Despite their good shielding properties metal coated fabrics are not suitable for shielding covers because of their sensitivity to mechanical stress. The metal interwoven fabrics can be further divided. He yarn can contain a metal filament of infinite length and therefore be DC conductive. The filament is mostly lacquered or silver coated for protection. Coating is of advantage if the fabric has to be connected in any for as it is the case in the given application. The other possibility it a yarn containing fibers of a given length which are only statistically connected to each other. Such fabrics are not conductive for DC currents but can exhibit good RF shielding properties.

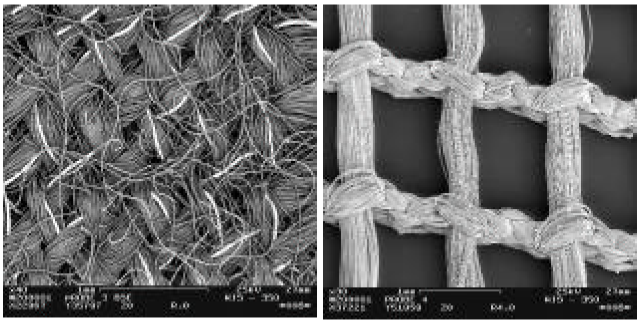


Figure 5. a) Interwoven Filament b) Metal Coated

For the construction of a shielding field cover for the MILAN missile two fabrics, one with an interwoven filament (PCCS 2131) and one with interwoven metal fibers (NAPTEX PM 30 FR) were used. A double layer of both fabrics was formed to achieve a high shielding effectiveness.

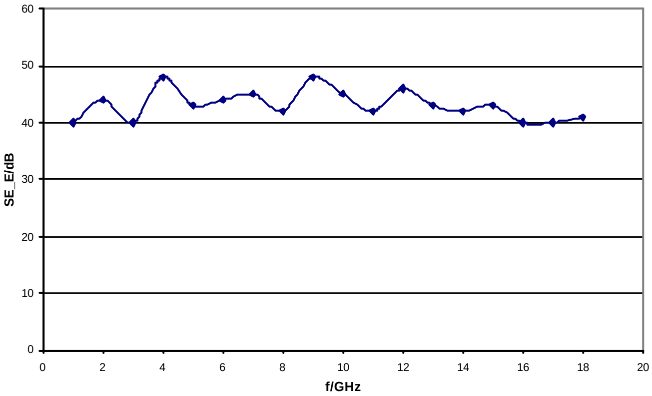


Figure 6. Shielding effectiveness of the Double Layer Shield

The electric shielding effectiveness was measured in a wide frequency range. From 300 MHz up to 18 GHz values between 40 and 50 dB can be achieved. . In practice however the measured shielding effectiveness of a shielding enclosure is considerably less for the following reasons:

- In most applications the shield forms a cavity resonator with internal resonances at certain frequencies where the measured shielding effectiveness breaks down. For this reason it is customary to do measurements with an appropriate filling of the enclosure.
- The shield consists of several textile parts which are connected by seams. Furthermore openings are needed for the stowage of equipment. They have to be closed by fasteners such as conductive zippers or velcro. The fasteners, even if closed, are potential inlets for the electromagnetic wave.

According to these considerations several factors have to be investigated separately when developing a textile shield. At first a fabric with a sufficient shielding effectiveness is needed. Highly conductive fasteners are needed. For the manufacturing of the shielding cover pouch conductive velcro was used .

The MILAN MK4 Cover

For the manufacturing of the MILAN cover the fabric of the inner layer (PCCS 2131) was coated with polyurethane on the inner side. This increases the resistibility against mechanical stress when the ordnance is packed or unpacked. A third layer of Camouflage material was added on the outside.

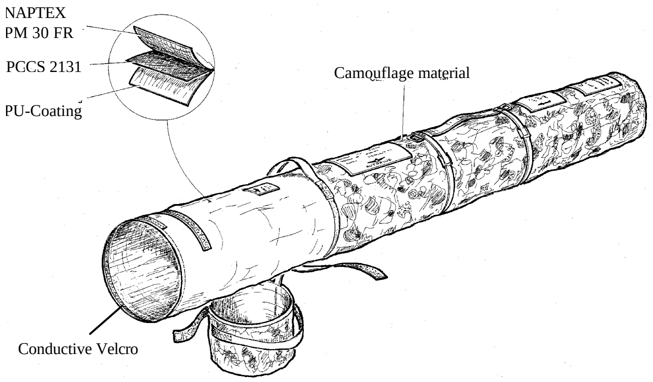


Figure 7. The MILAN Cover MK 4

Special attention has to be given to conductive velcro fastener. Even if a highly conductive silver coating is applied to the velcro it forms a potential inlet for the electromagnetic wave. For this reason the fastener was tested extensively in the test facility of the German Armed Forces WTD 81 in Greding.

Figure 8. The Velcro Fastener

It could be seen that the fastener despite the careful construction shows strong resonance effects at certain frequencies and acts as a slot antenna.

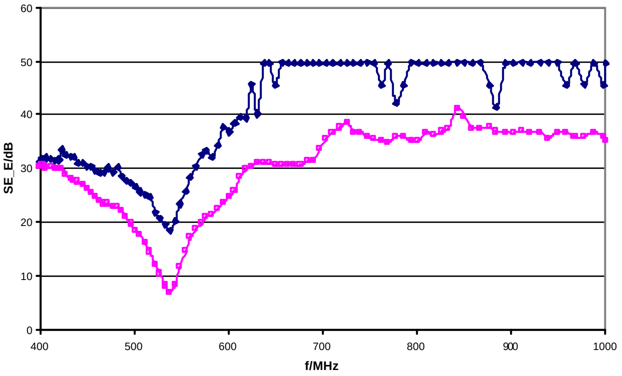


Figure 9. Shielding Effectiveness of the Velcro Fastener

For this reason the construction of the cover was slightly modified. The fastener has to be folded inwards and fixed with conventional velcro after closing. Then it is covered with an additional shielding cap.

Test Strategies for Closed Shields

There are several issues associated with the testing of closed shields. In some institutions it is common practice to place a sensor inside the empty cover and measure the electrical field strength. From the difference between the field strength at the measuring locale with and without the shield the electrical shielding effectiveness is calculated. This procedure suffers however from the internal resonances mentioned before. At resonance frequencies the electrical field shows maxima and minima dependent on the position inside the cover. Consequently the measured shielding effectiveness breaks down at some measuring locales and reaches a maximum at others.

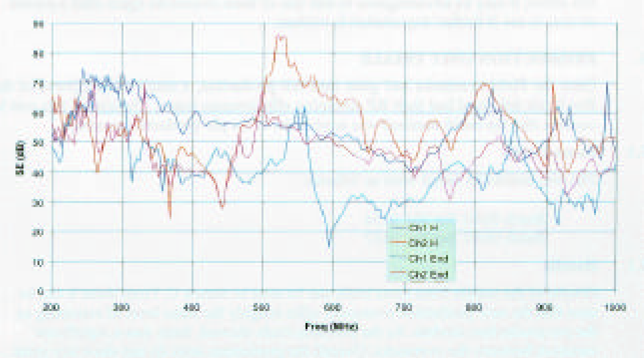


Figure 10. Shielding Effectiveness of the empty cover at different positions of the sensor

Certainly the mean value of the measured shielding effectiveness gives a hint to the protective properties but it has to be taken into account that the behavior is completely different when a filling like the MILAN is placed inside the cover.

Therefore tests as close as possible to the actual configuration are preferred over measurements of the shield alone. A MILAN dummy instrumented with the relevant EEDs has to be placed inside the cover for testing. The temperature of the EED has to be measured by and the safety margin calculated. This method provides a direct measure for the protective properties of the shield in the specific configuration. The disadvantage may be that results cannot easily be transferred to other systems.

Measurements with an instrumented MILAN were done at WTD 81 in Greding and confirmed that a safety margin of at least 20 dB can be achieved even in the electromagnetic environment according to MIL STD 464. In this case only the given average fields were considered. In addition to the measurements of the electrical properties standard military environmental test were done such as exposition to sea water, cooling and heating, and a field test. After all test were done some covers were measured again to assure that the shielding properties are not substantially degraded by these procedures. First covers were brought into service in UK in 2000. The covers are currently used by the UK Armed Forces during their peacekeeping mission in Afghanistan.

Figure 11. Shielded and unshielded MILAN Missiles

Conclusion

The threat imposed on ordnance containing Electro-Explosive-Devices (EED) by high frequency electromagnetic fields is of considerable importance now and in the future. Examples for the required immunity levels for ordnance are MIL-STD 464 and STANAG 4234. It was shown that for ordnance not fulfilling the requirements of the applicable document shielding with conductive textiles is possible even under harsh environmental conditions. This is especially important for ordnance that is in use for several years and not hardened sufficiently to fulfil the new requirements.

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(Has to be added in the final version)

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