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NON-HERO MICROWAVE HAZARDS TO MUNITIONS

Matthew Ferran

Munitions Safety Information Analysis Center (MSIAC)

NATO HQ, Brussels

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ABSTRACT

Accidental initiation of munitions via the heating of bridgewires by radiofrequency (RF) radiation (i.e. HERO) is well understood; far less work has been undertaken to determine how bulk energetic materials (cased or uncased) directly respond to exposure to RF radiation. It is important to understand this phenomenon, particularly in the context of the ever increasing power of military transmitters.

A review of the factors influencing microwave heating of energetic materials was undertaken, at both the material and munition level. Experimental data from the literature was used to determine the likely response of munitions to a microwave environment representative of that experienced in-service with NATO armed forces.

Under the right conditions, it is possible that certain energetic materials may be heated to the point of initiation by the in-service microwave environment in a short timescale (e.g. minutes).

In order to provide a more comprehensive understanding of the non-HERO microwave hazards to munitions, further work is required to characterise the dielectric properties of a variety of energetic materials over representative temperature and frequency ranges; this must be supplemented by a better understanding of the response of non-energetic munition components to the same environment, including their effect in ameliorating the microwave environment.

Keywords:

Microwave; heating; complex permittivity; dielectric properties; hazards

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ABBREVIATIONS

ECM	Electronic Countermeasures
EED	Electro-explosive Device
EMC	Electromagnetic Compatibility
EME	Electromagnetic Environment
HERO	Hazards of Electromagnetic Radiation to Ordnance
PBX	Polymer Bonded Explosive
RF	Radiofrequency
S3	Safety and Suitability for Service

INTRODUCTION

In accordance with NATO principles, the Safety and Suitability for Service (S3) of a munition system is evaluated prior to military use. Such an evaluation typically considers the effects on the munition of detrimental climatic, mechanical and electromagnetic environments. These can be either natural or induced.

The effect of the expected in-service Electromagnetic Environment (EME) on a munition system is considered extensively, and typically includes an assessment of electrostatic discharge; atmospheric electricity and lightning strike; interaction of electromagnetic radiation with the correct functioning of electronic equipment (i.e. Electromagnetic Compatibility or EMC); electromagnetic pulse (nuclear or otherwise); magnetic fields; and accidental initiation of a munition via the heating of bridgewires by radiofrequency (RF) radiation (i.e. Hazards of Electromagnetic Radiation to Ordnance or HERO).

However, at present no consideration is given to the response of energetic materials to direct exposure to electromagnetic radiation, particular in the radiofrequency range. This is despite the near constant exposure of munition systems to this environment during operational use.

It is the intent of this paper to review the interaction of the NATO RF EME with energetic materials, specifically in the microwave region, and to consider the hazards this may pose to a munition system other than those presently considered by an S3 evaluation.

1 THE MILITARY RADIO FREQUENCY ELECTROMAGNETIC ENVIRONMENT

1.1 OVERVIEW OF THE MILITARY RADIO FREQUENCY ELECTROMAGNETIC ENVIRONMENT

Deliberately generated RF emissions are a ubiquitous threat to munition systems. These generally originate from communication and radar transmitters on land, sea and air platforms, as well as civilian and military fixed installations. Other sources such as electronic countermeasures (ECM) must also be considered. The nature of these RF sources is ever changing due to technology advancements, proliferation of more powerful emitters and expanded use of the electromagnetic spectrum worldwide (usually at higher frequencies).

1.2 DEFINITION OF THE ELECTROMAGNETIC ENVIRONMENT

The actual RF EME that will be encountered by a munition system is dependent on many factors, including the operational environment (e.g. land, sea or air); the platform or platforms from which it is operated; the proximity to transmitters at various points in its life cycle; etc.

The NATO standard AECTP-250 addresses the RF EME likely to be encountered by materiel of any service during NATO operations. The “NATO Worst Case EME”, reproduced below in Table 1, is a compilation of the maximum field strength levels from the land, sea and air environments, and is used for safety related evaluations such as HERO susceptibility and intra-system Electromagnetic Compatibility (EMC). Values for both average and peak field strength are provided for a range of frequency bands: this is because pulse-modulated signals (such as from a radar) have differences between the peak and average power density (and hence field strength), with the average power density determined by the ratio of time-on to time-off over an interval (i.e. the duty cycle of the transmitter); for a continuous wave signal, such as from a communications system, the duty cycle equals unity, and therefore peak and average power are the same. [1]

Table 1: NATO Worst-Case Operational EME Field Strength Levels [1]

Frequency Range / MHz			Average Field Strength / $V.m^{-1}$	Peak Field Strength / $V.m^{-1}$
0.01	-	**2**	200	200
2	-	**30**	200	200
30	-	**150**	200	200
150	-	**225**	200	200
225	-	**400**	200	1500
400	-	**700**	270	1860
700	-	**790**	240	1500
790	-	**1000**	480	2530
1000	-	**2000**	600	7000
2000	-	**2700**	490	6000
2700	-	**3600**	2620	21050
3600	-	**4000**	490	8550
4000	-	**5400**	400	7200
5400	-	**5900**	400	7200
5900	-	**6000**	400	7200
6000	-	**7900**	400	2500
7900	-	**8000**	400	2500
8000	-	**8400**	750	5000
8400	-	**8500**	400	5000
8500	-	**11000**	1940	10000
11000	-	**14000**	680	3630
14000	-	**18000**	680	6000
18000	-	**40000**	420	3640
40000	-	**45000**	580	580

2 INTERACTION OF ELECTROMAGNETIC RADIATION WITH MATTER

The theory of interaction of electromagnetic radiation with matter is covered in detail in many texts (including [2]), and will not be repeated here; however, it is necessary to provide a brief summary of the key concepts and those factors important to energetic materials and munition systems.

Upon exposure to microwaves, the interaction between the electric and magnetic field components of microwaves and materials can result in dielectric and magnetic losses, leading to heating of the material. Dielectric losses have been studied extensively and can be attributed to the redistribution of charges or polarization under the influence of an alternating external electric field. Heating arises due to the ability of the electric field to polarize the charges in the material and the inability of the polarization to keep up with the rapidly changing electric field. In materials with high conductivity, such as metals, heating depends on conduction losses. In magnetic materials, magnetic losses such as hysteresis, eddy currents, domain wall and electron spin resonance contribute to the heating.

Accordingly, knowledge of a material's dielectric and magnetic properties is crucial in determining the response of the material to microwaves. The dielectric properties of a material are affected by many factors such as purity, chemical state and manufacturing process, and also vary with temperature and frequency.

2.1 PERMITTIVITY

Permittivity (ε'), also known as the **dielectric constant**, describes the response of a material to an electric field and is determined by the ability of a material to polarize in response to the applied electric field.

The **complex permittivity (ε*)** is introduced to describe the response of a material exposed to sinusoidal fields and to account for losses. It is a measure of the ability of a material to absorb and store electrical potential energy, with ε' representing the penetration of microwaves into the material and the **dielectric loss factor (ε")** representing the ability of the material to store energy. It can be expressed as follows:

$$\varepsilon^{*}=\varepsilon'-j\varepsilon'' \qquad (1)$$

where $j = (-1)^{0.5}$. Values for permittivity are usually expressed as the dimensionless **relative permittivity (ε_r)**, which is a ratio of the absolute permittivity and the **vacuum permittivity (ε_0; $8.85.10^{-12}$ F.m^{-1})**. Note that the subscript 'r' is often omitted when referring to values of relative permittivity; all values quoted in this report are of the dimensionless relative permittivity.

In the microwave heating of dielectric materials, it is assumed that the magnetic field does not contribute to microwave absorption and heating occurs entirely due to the electric field. The power per unit volume dissipated into or absorbed by the material by the conversion of the electric field component of electromagnetic energy into heat can be expressed by:

$$P = 2 \cdot \pi \cdot f \cdot \varepsilon''_{eff} \cdot \varepsilon_0 \cdot E^2_{rms} \quad (2)$$

where **P** represents power density (W.m^{-3}) in the material at position (x, y, z); **f** is the frequency of the incident radiation (hz); $\boldsymbol{\varepsilon_{eff}''}$ is the effective dielectric loss factor, this being the summation of losses from polarization and conduction; and $\mathbf{E_{rms}}$ refers to the root mean square of the electric field (V.m^{-1}).

The rate of increase of temperature of a material subject to electric field heating can be expressed as:

$$\frac{\Delta T}{\Delta t} = \frac{2 \cdot \pi \cdot f \cdot \varepsilon''_{eff} \cdot \varepsilon_0 \cdot E^2_{rms}}{\rho \cdot c_p} \quad (3)$$

where **T** is temperature (K); **t** is time (s); **ρ** is the density of the material (kg.m^{-3}); and $\mathbf{c_p}$ is the specific heat capacity of the material (J.kg^{-1}.K^{-1}).

It should be noted that these equations represent basic approximations, and do not take into account factors such as the change in a material's complex permittivity with temperature.

2.2 PENETRATION DEPTH

The **penetration depth** of radiation into a material is characterised by a parameter, **d**, which is defined as the distance from the surface at which the magnitude of the field strength drops to e^{-1} (=0.368) of its value at the surface. Penetration depth decreases with the increase of the frequency and dielectric loss factor (ε"); it is therefore also dependent on temperature. In some cases, materials with extremely low dielectric loss factors can be almost transparent to microwaves.

For low loss materials (e.g. those with (ε"/ ε') << 1) magnetic losses can be ignored, and penetration depth of the electric field can be calculated as follows:

$$d = \frac{\lambda_0 \cdot (\varepsilon')^{0.5}}{\pi \cdot \varepsilon''_{eff}} \quad (4)$$

where $\boldsymbol{\lambda_0}$ is the free space wavelength (m). Penetration depth is also proportional to resistivity: e.g. for a perfect conductor, resistivity is zero, and therefore the penetration depth is zero. However, in most metals, total reflection of microwaves is

impossible because of the limited resistance in the material due to the presence of defects. In general, the penetration depths for a variety of metals are limited to a few microns at the frequency range of microwaves, as is shown in Table 2.

Table 2: Electric field penetration depth of selected metals at different microwave frequencies [2]

	Penetration Depth (μm)	
Metal	**915MHz**	**2.45GHz**
Aluminium	2.7	1.7
Copper	3.9	2.4
Iron	5.2	3.2
Tungsten	3.9	2.4

2.3 MICROWAVES AND METALS

Metals, being conductors, cannot be heated significantly using microwaves because of limited penetration depths of only a few microns (Table 2) for most metals at common microwave frequencies. As such bulk metals will reflect most of the microwaves incident upon them.

However, when in the form of powders or small particles, metals can absorb microwaves and be heated significantly. This fact can be used advantageously e.g. to use microwaves to sinter powdered metals.

The interaction of microwaves with metal powders is complex and poorly understood, and cannot at present be adequately explained by existing theories. Gupta and Leong provide an overview of some initial models attempting to describe this phenomena, and some examples from the literature of sintering processes for different metals. There are some experimental indications that metal particle size plays an important role, with direct coupling of microwaves occurring when the particle size is less than or equal to the penetration depth. [2]

3 DIELECTRIC PROPERTIES OF ENERGETIC MATERIALS

3.1 MEASUREMENT OF DIELECTRIC PROPERTIES

The dielectric properties of materials can be measured in a number of different ways. A common technique for energetic materials is the Cavity Perturbation Method, wherein the complex permittivity at a specific frequency can be calculated from changes in the resonant frequency and quality factor of a cavity on introduction of a sample. [3]

3.2 SELECTED AMBIENT DIELECTRIC PROPERTIES OF ENERGETIC MATERIALS

A number of researchers have reported values for the ambient condition complex permittivity of energetic materials at frequencies within the range of military interest; some of these are summarised below in Table 3. Much of this work has been limited in scope due to the frequency and temperature dependence of dielectric properties, that is to say a comprehensive body of knowledge of the dielectric properties of energetic materials at varying temperatures and frequencies does not exist.

When comparing these figures, it should be remembered that factors such as temperature, experimental method, material density, material purity etc. have not been taken into account; accordingly, this data is merely intended to provide an overview of the likely orders of magnitude involved, and should not be taken as definitive.

Table 3: Selected ambient dielectric properties of energetic materials

Material	*~2.5GHz*		*10GHz*		*13.25GHz*	
	ε'	*ε"*	*ε'*	*ε"*	*ε'*	*ε"*
RDX **[4] [5]**	3.62	0.02	3.523	0.0029	3.5	<0.01
HMX **[4] [5]**	3.4	0.02	3.482	0.0026	3.4	<0.01
PETN **[4] [5]**	3.0	0.02	3.015	0.0098	3.2	0.01
TNT **[4] [5]**	3.0	0.01	3.017	0.0033	3.0	0.02
Comp. B **[4] [5]**	3.4	0.01	3.292	0.0048	3.6	<0.01
Octol **[4] [5]**	3.4	0.02	3.419	0.0045	3.6	<0.01
PBXN-5 **[5]**	3.6	0.02	-	-	3.6	<0.01
PBXN-7 **[5]**	4.1	0.02	-	-	4.2	0.01
PBXN-14 **[5]**	4.1	0.02	-	-	4.1	0.01
PBX-9404 **[5]**	3.7	0.03	-	-	4.0	0.05
PBX-9501 **[5]**	3.7	0.04	-	-	4.0	0.03
Composite Propellant (Coarse AP) **[6]**	5.83	0.228	-	-	-	-
Composite Propellant (Bimodal AP) **[6]**	5.87	0.266	-	-	-	-
JA2 Propellant **[7]**	4.1	0.75	-	-	-	-

As can be seen, a variety of experimental techniques result in the reporting of values to varying degrees of accuracy. In addition, the reported values for ε' for Comp. B and Octol at 13.25GHz appear to be greater than those of either of their major constituents (i.e. RDX/TNT and HMX/TNT respectively). Nevertheless, the following general observations can be made:

- The loss factor (ε") is very low for all molecular explosives and formulations thereof (e.g. Comp. B and Octol). They may therefore be expected to display low energy absorption and low heating rates in a microwave electric field.

- The loss factor is susceptible to a very slight increase by addition of fairly low proportions of binder (e.g. ~7% in PBX-9501) in polymer bonded explosives (PBXs), although the loss factor is still very low and these materials may also be expected to display low energy absorption.

- Composite propellants show a greatly increased loss factor compared to the molecular explosives, by a factor of 10.

- Of all the materials considered, JA2 propellant possessed the highest loss factor, and may be expected to absorb microwave energy quite efficiently. This may be attributable to the inclusion of graphite in the formulation: carbon is well known to be a strong absorber of microwave radiation, and is commonly

used as a microwave receptor to allow heating of materials that are otherwise microwave transparent.

A limited amount of work has been done to determine how the dielectric properties of energetic materials vary with temperature:

- The loss factor for JA2 propellant has been observed to increase by a factor of ~2 when heated from room temperature to 80°C. [8]

- The loss factor for TNT and TNT based explosives increases slowly as temperature approaches the melting point, but then increases dramatically to ~0.5 once the melting point is reached. It then decreases slowly again as temperature increases above the melting point, with the rate of decrease frequency dependent. [9]

4 IMPLICATIONS FOR MUNITION SYSTEMS

4.1 HEATING OF ENERGETIC MATERIALS

Despite the relatively low values of loss factor, the literature shows that it is possible to heat neat energetic materials to the point of initiation by application of microwave frequency radiation of sufficiently high electric field strength. Initiation can be realised in timescales in the order of minutes. [10] [11]

In addition, modelling has shown that application of field strengths of 10^5-10^6 $V.m^{-1}$ can heat neat energetic materials to 100°C in the order of milliseconds. [4]

It is worth mentioning that there are some examples in the literature of the deliberate microwave heating of energetic materials. Applications include initiation of an explosives train [12], pre-heating of gun propellant to improve performance [7] and the demilitarisation of munitions by “melting-out” low-melting explosives based on TNT. [13]

4.2 EFFECT OF MILITARY ELECTROMAGNETIC ENVIRONMENT ON ENERGETIC MATERIALS

The above examples of deliberate heating of energetic materials are not representative of the military electromagnetic environment described in AECTP-250, specifically in terms of electric field strength employed. It has not been possible to locate any examples of research considering the exposure of energetic materials to microwave radiation of frequency and field strength representative of the military service environment.

In lieu of such examples, an estimate of the microwave heating rate for in-service energetic materials may be made using the following:

- Equation (3) for rate of temperature increase
- Values for dielectric and physical properties taken from the literature
- Average field strength values derived from AECTP-250 [1]

Table 4 shows the time taken to heat a number of bare explosives starting at ambient temperature by 100K calculated by this method. It should be noted that this is a very simplistic model, and neglects factors such as the temperature dependence of complex permittivity and other material properties, and thermal transport within the energetic material or munition system as a whole.

Table 4: Time to heat selected bare explosives by 100K @ 2.5GHz, starting at ambient temperature

Explosive	*ε"*	*E / V.m^{-1}*	*ρ / kg.m^{-3}*	*C_P / J.kg^{-1}.K^{-1}*	*Time / s*
PETN	0.02	490	1780	1090	290643 (80 hr)
TNT	0.01	490	1590	1125	535913 (149 hr)
Comp. B	0.01	490	1730	1065	552001 (153 hr)
PBX-9404	0.03	490	1844	1130	208095 (58 hr)
JA2	0.75	490	1500	1260	7549 (2 hr)
***JA2 @ 50°C* [8]**	1.00	490	1500	1260	5662 (1.5 hr)
JA2 @ 3GHz	0.50*	2620	1500	1260	330 (~5.5 min)

* This value for ε" was not taken from the literature but is an estimate used to demonstrate the effect of the worst-case electric field strength on heating rates.

As can be seen from the table, the time to heat low dielectric loss materials (e.g. neat explosives and PBXs) by 100K when exposed to the average electric field strength experienced at 2.5GHz is in the order of days. However, for a material with a much higher dielectric loss such as JA2, this time is reduced to just 2 hours. Making the reasonable assumption that the starting temperature of the JA2 is 50°C, the time to heat by 100K is further reduced to 1.5 hours.

If we further assume that the value of loss factor for JA2 is slightly less at 3GHz than at 2.5GHz, we can then demonstrate the effect of the highest average electric field strength likely to be experienced in the military environment: the time taken to heat JA2 by 100K at 3GHz is then reduced to just 5.5 minutes. This does not take into account the increase of loss factor that JA2 experiences on heating, which is likely to reduce the time even further.

4.3 ENERGETIC MATERIALS CONTAINING POWDERED METALS

As discussed above, metal powders are capable of strongly absorbing microwave radiation, although the exact mechanism by which this occurs is not understood.

There are implications for those energetic materials which contain powdered metals to a greater or lesser degree, for instance composite propellants which may contain up to 20% by weight of powdered aluminium (µm), and flare compositions which may contain up to 60% by weight of powdered magnesium (µm).

Although it has not been possible to identify research that considers the microwave heating rates of such energetic materials, some research has been conducted into the rate of temperature increase on microwave heating of pure powdered metals [14]. Selected average heating rates for metal powders (unspecified particle size) in a 1kW 2.45GHz commercial microwave oven are shown below in Table 5.

Table 5: Selected microwave heating rates for powdered metals [14]

Metal Powder	***Heating Rate / °C.min^{-1}***
Aluminium	96
Magnesium	17
Iron	109

The estimated electric field strength inside a microwave oven is in the region of 3000 V.m^{-1} [15]. As comparable electric field strengths may be experienced in the NATO EME, it is reasonable to conclude that powdered metals have the potential to contribute significantly to microwave heating of energetic materials such as composite propellants and pyrotechnics.

4.4 INFLUENCE OF MUNITION SYSTEM DESIGN AND USE

There are two main ameliorating factors which will reduce the effect of microwave heating of energetic materials as employed in military service:

- The vast majority of munitions have a metal case of some description, be it the body of the munition or a metal logistic container. As discussed above, the microwave penetration depth of metals is in the order of microns, and so such enclosures may provide effective shielding from electromagnetic radiation, noting that RF radiation may still penetrate the munition through discontinuities such as seams, ports, vents, rocket motor nozzles, RF transparent seeker windows etc. In addition, the microwave irradiation of metals with sharp edges or tips can pose an additional threat of electrical discharge in the form of arcing or sparking.

- The period of exposure to high intensity electromagnetic radiation is generally insufficient to allow for heating. This is of course scenario dependent, but consider:

    - A ship-launched guided missile flying through the main beam of the ship's radar will be exposed to a very high electric field, but only for a very brief period of time.

    - For munitions on e.g. the flight deck of a ship, the exposure could be prolonged – but guidance given in AECP-02 *NATO Naval Radio and Radar Radiation Hazards Manual* recommends that the radar is sector blanked, put into low power mode or switched off. [16]

- At locations where munitions are stored for long periods of time, electric field strengths are usually very low either by design (e.g. in a ship's magazine) or circumstance (e.g. an isolated munitions depot with no significant nearby transmitters). In addition, at such locations munitions are generally stored in logistic packaging which can potentially provide additional protection against electromagnetic radiation.

Composite materials are increasingly being used in munition systems, particularly in rocket motors where the reduction in mass penalty can improve performance.

Unlike metals, composite materials are generally insulating materials, and thus absorb microwave radiation to some extent. Reported values of dielectric loss factor for composite materials at 10GHz range from ε"=0.70 (for a glass fibre composite) to ε"= 13.1 (for a carbon fibre composite), with penetration depths of up to 23 mm (cf. a typical rocket motor case thickness of 5-10mm) [17]. This shows that composite materials are potentially very strong absorbers of microwave radiation, and may also allow microwave radiation to penetrate into the underlying energetic material.

It is therefore important to note that assumptions regarding the protective nature of munition casings may not always be valid. It has not been possible to find information related to microwave heating of composite rocket motor casings in the open literature.

4.5 KNOWN INCIDENTS

Regardless of any ameliorating factors, taking the worst case of energetic material (i.e. highest dielectric loss factor), munition design (i.e. no metal casing) and electromagnetic environment (i.e. highest field strength at a high frequency), without appropriate procedures in place it is entirely possible that a munition system may be exposed to an electromagnetic environment sufficient to heat the energetic materials inside to the point of initiation in a short timescale (i.e. within minutes).

As most contemporary munition systems contain an electro explosive device (EED) of some description, it may be difficult to identify incidents where the direct interaction of RF radiation with an energetic material is the cause, rather than interaction with the EED (i.e. HERO). However, in 2013 an incident was recorded where non-electric signal flares and smokes caught fire after being irradiated by the radar of a USN DDG class destroyer during a replenishment activity [18]. According to the incident report, the radar was not sectored or put into low power mode during the activity, leading to the irradiation of a lifeboat on the adjacent supply ship. No flames were seen, only a thick black smoke followed by orange signal smoke. The remains of the affected items are shown in Figure 1.

Figure 1: Remains of non-electric signal flares and smokes after exposure to a DDG radar during replenishment [18]

Basic information on the energetic materials contained within these stores can be obtained from the product Safety Data Sheets found on the manufacturer's website.[1] Ingredients include the powdered metals aluminium and magnesium, and an unspecified rocket propellant.

[1] https://www.painswessex.com/products/solas/

CONCLUSIONS

Heating of energetic materials by microwave radiation is a credible hazard; however, the scope of the associated safety risk is dependent on factors including the dielectric properties of the energetic material, the design of the munition system and the electromagnetic environment to which the munition system will be exposed.

A small amount of research exists in the open literature regarding the dielectric properties of energetic materials at a limited number of microwave frequencies; however, this mostly considers neat explosives rather than formulations and gives no consideration to the temperature dependence of dielectric properties. Molecular explosives such as RDX and TNT appear to have low susceptibility to microwave heating, whereas composite propellants and materials containing graphite display moderate to high susceptibility. In addition, energetic formulations containing powdered metals are also likely to be susceptible to microwave heating, although the mechanism is not understood.

The design of a munition system may provide some inherent protection to energetic materials from electromagnetic radiation. However, such protection should not be assumed, particularly due to the increased use of composite materials in munition systems which allow the penetration of microwaves and may themselves be susceptible to microwave heating.

Taking the worst combination of energetic material (i.e. high dielectric loss factor and / or containing powdered metal), munition design (i.e. no metal casing) and electromagnetic environment (i.e. high field strength at a high frequency), without appropriate procedures in place it is entirely possible that such a munition system may be exposed to an electromagnetic environment sufficient to heat the energetic materials inside to the point of initiation in a short timescale (i.e. within minutes). There is at least one recorded incident where this is strongly suspected to have occurred.

An assessment of munition susceptibility to microwave heating should be made as part of the introduction into service of new munition systems. For metal cased munitions containing molecular explosives and subject to a benign EME, the assessment is likely to be straightforward; for munitions without metal cases, those containing graphite or powdered metals, or those subject to a severe EME, a more extensive assessment may be required. This may include measurement of energetic material dielectric properties at temperatures, field strengths and frequencies of interest, or exposure of entire munitions to microwave radiation to directly measure heating rates or time to initiation.

Without such an assessment, it is necessary to rely solely on administrative measures such as NATO operational guidance to manage the risk.

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