Australian Government
Department of Defence
Guided Weapons and
Explosive Ordnance Group

Electromagnetic Heating of Energetic Compositions in Electro-explosive Devices and Explosive Ordnance

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Introduction

- Hazards of Electromagnetic Radiation to Ordnance (HERO) are commonly associated with electro-explosive devices (EEDs) and the heating that occurs at the ‘bridge’.
- The bridge heating effect is potentially of less concern as frequency increases.
- Concerns have been raised about the bulk heating of energetic materials.
- At certain frequencies the bulk heating effect becomes a greater concern potentially, when compared to bridge heating effects in EEDs.

Interoperability

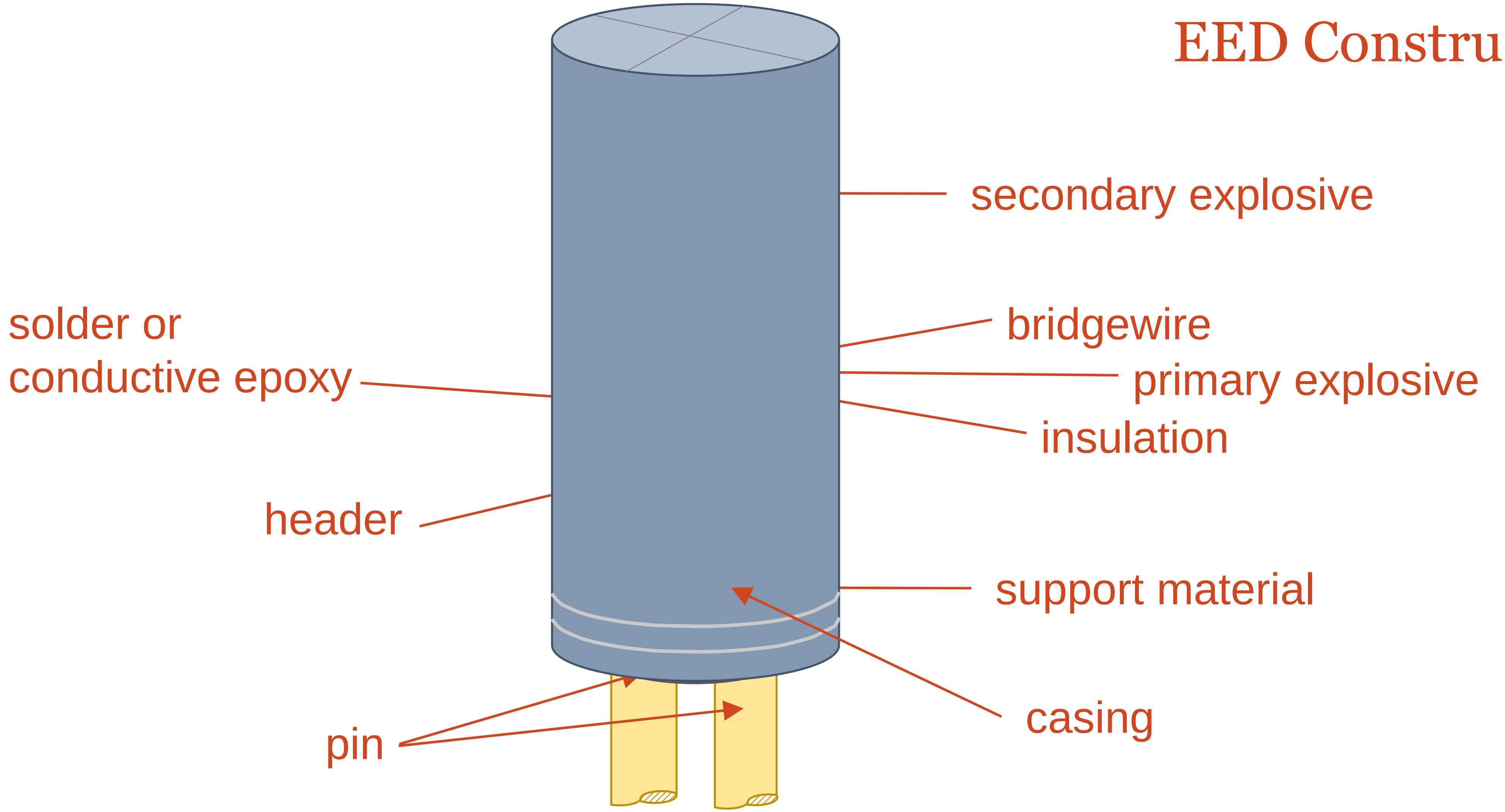
- Definition: *"…the ability to routinely act together coherently, effectively and efficiently to achieve tactical, operational and strategic objectives."*

Interoperability Activities: *"…defined as any initiative, forum, agreement, or operation that improves the ability to operate effectively and efficiently as a component of the joint force and as a member or leader of an alliance or coalition across the range of military operations."*

- Inadvertent initiation of an EED, or bulk energetic materials will inevitably have consequences that will affect the ADF's interoperability objective.

Reference: https://www.army.mil/article/231653/interoperability_embrace_it_or_fail

EED Construction



secondary explosive

solder or
conductive epoxy

bridgewire

primary explosive

insulation

header

support material

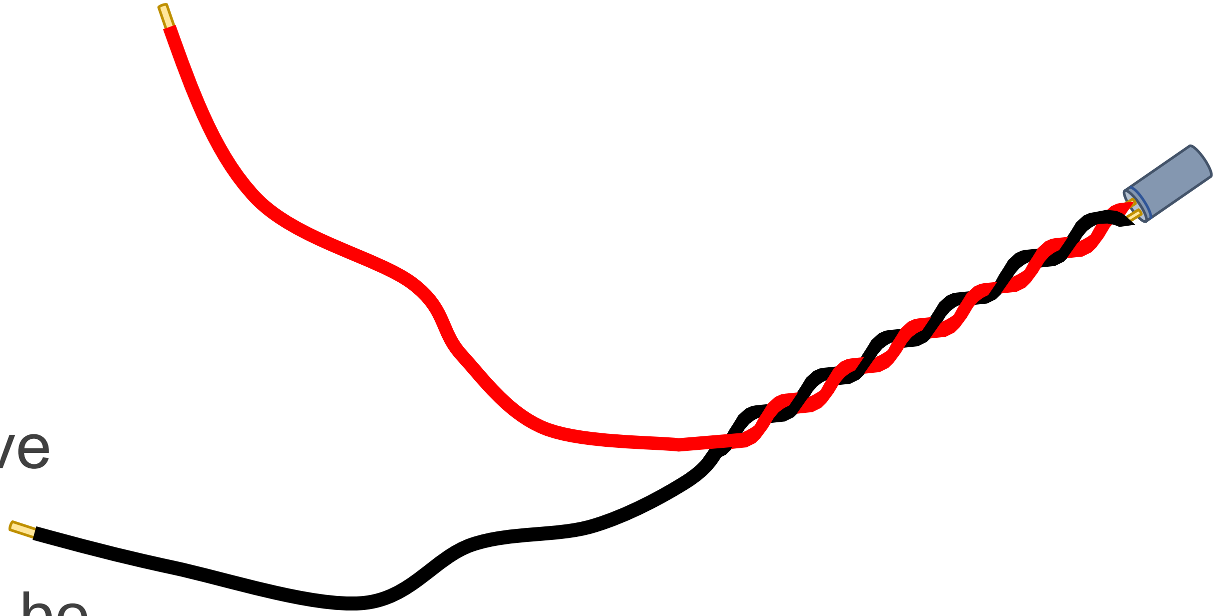
casing

pin

Worst-case RF 'Pick-up' Trace

- The antenna effective area (A_e) can be written in terms of the antenna's gain factor (G) and the wavelength (λ) of the incident signal as follows:

$$A_e = \frac{\lambda^2}{4\pi} G$$



- A_e represents the area of the incident wavefront that is 'captured' by the receive antenna.
- The power received by the antenna can be expressed in terms of the incident power flux density (S) as follows:

$$S = P_{received} \left(\frac{4\pi}{G\lambda^2} \right) \Longrightarrow P_{received} = S(A_e)$$

Worst-case RF Pick-up Trace (with $P_{\text{received}} = 1$ W)

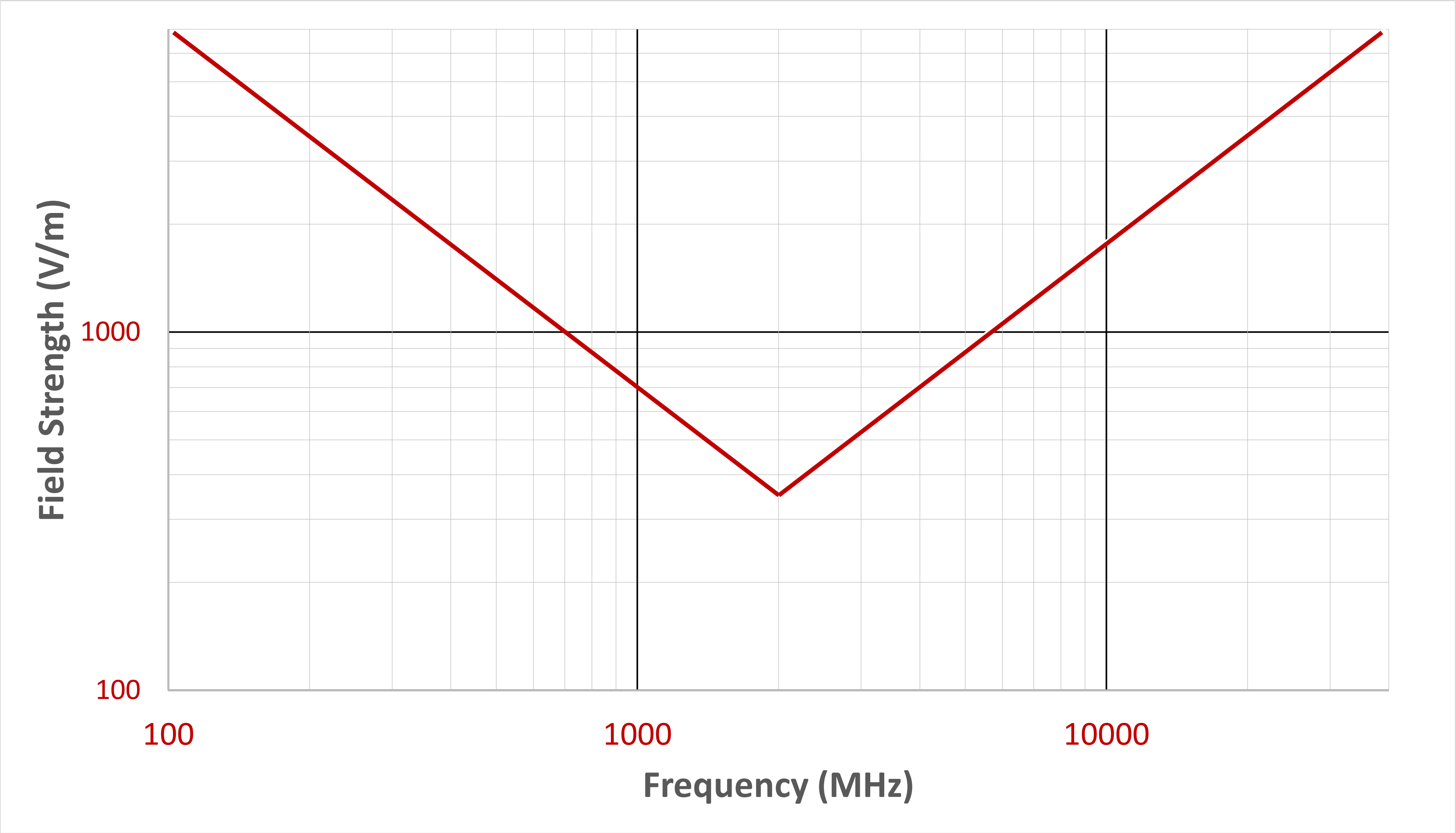
- For a dipole that is resonant at 2GHz, $\lambda = 0.15$m.
- For $P_{received} = 1$W and the antenna gain equal to 1.64 (for a dipole), the power density needs to be:

$$S = P_{received}\left(\frac{4\pi}{G\lambda^2}\right)$$
$$= (1)\left(\frac{4\pi}{1.64(0.15)^2}\right)$$
$$= 340.55\mathrm{W}/m^2$$

- The field strength of the incident EM wave is:

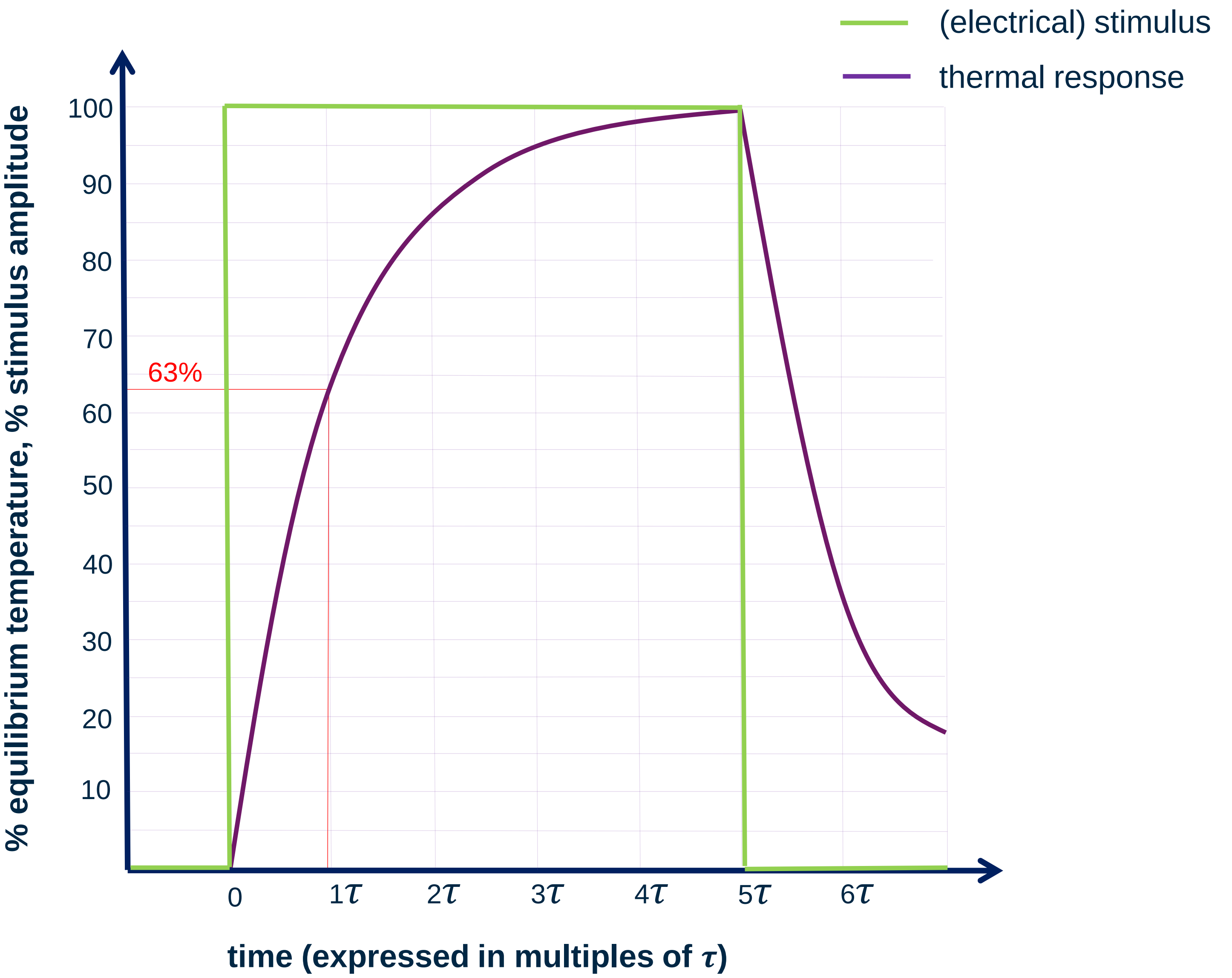
$$E_{incident} = \sqrt{S \times 377}$$
$$= \sqrt{(340.55)(377)}$$
$$= 358.31V/m$$

RF Susceptibility Trace of 2 GHz, λ/2 dipole | $P_{received}$ = 1W (0dB margin)



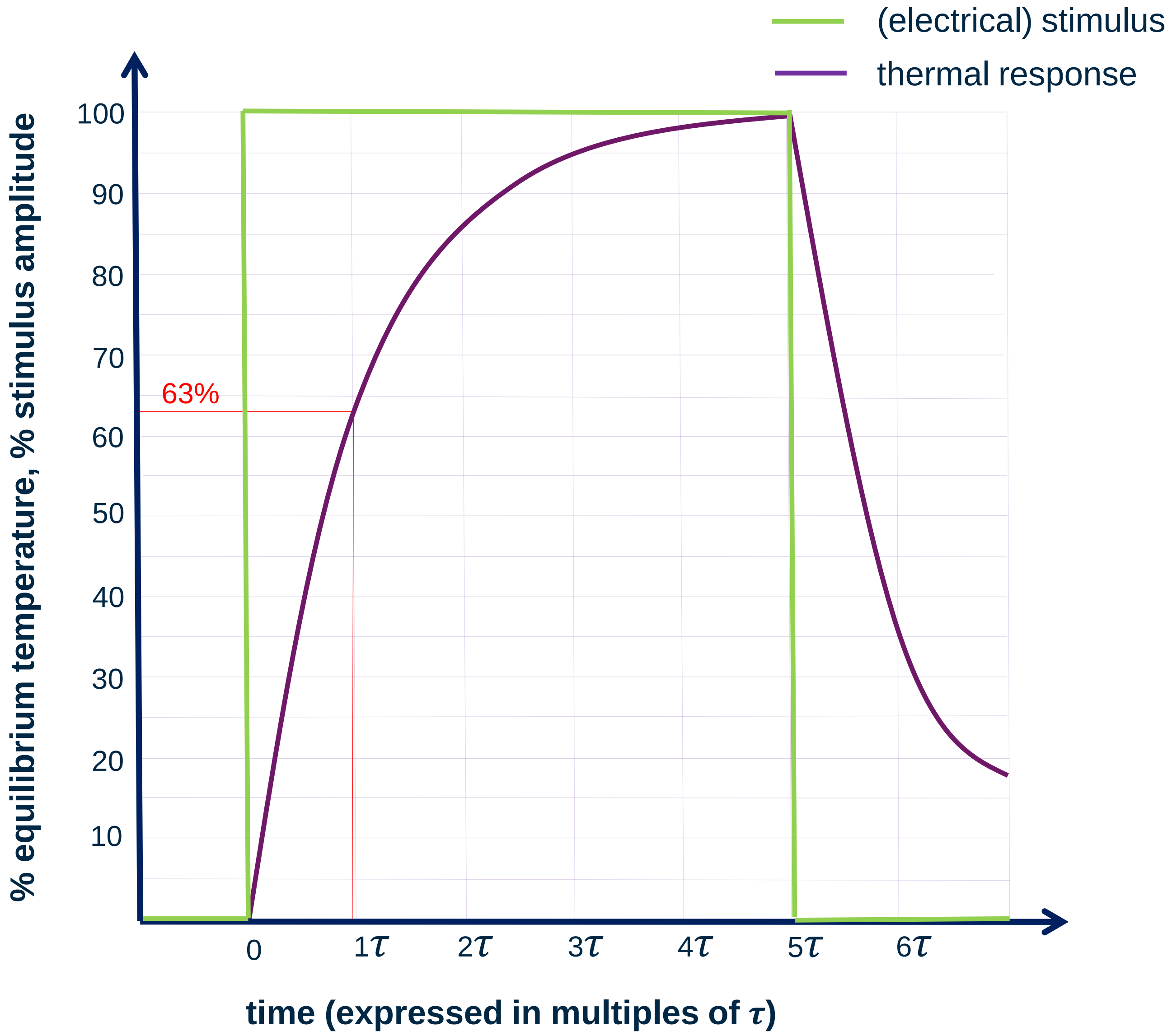
The Thermal Time Constant

- The response of a bridgewire (BW) EED to a step input (i.e. electrical stimulus) is characterised by an exponential rise in temperature.
- The thermal time constant (τ) is the time it takes for the BW EED to reach 63% of its equilibrium temperature.
- If the stimulus pulse width is long enough (5τ, in this case), the EED has the potential to reach the temperature equilibrium.



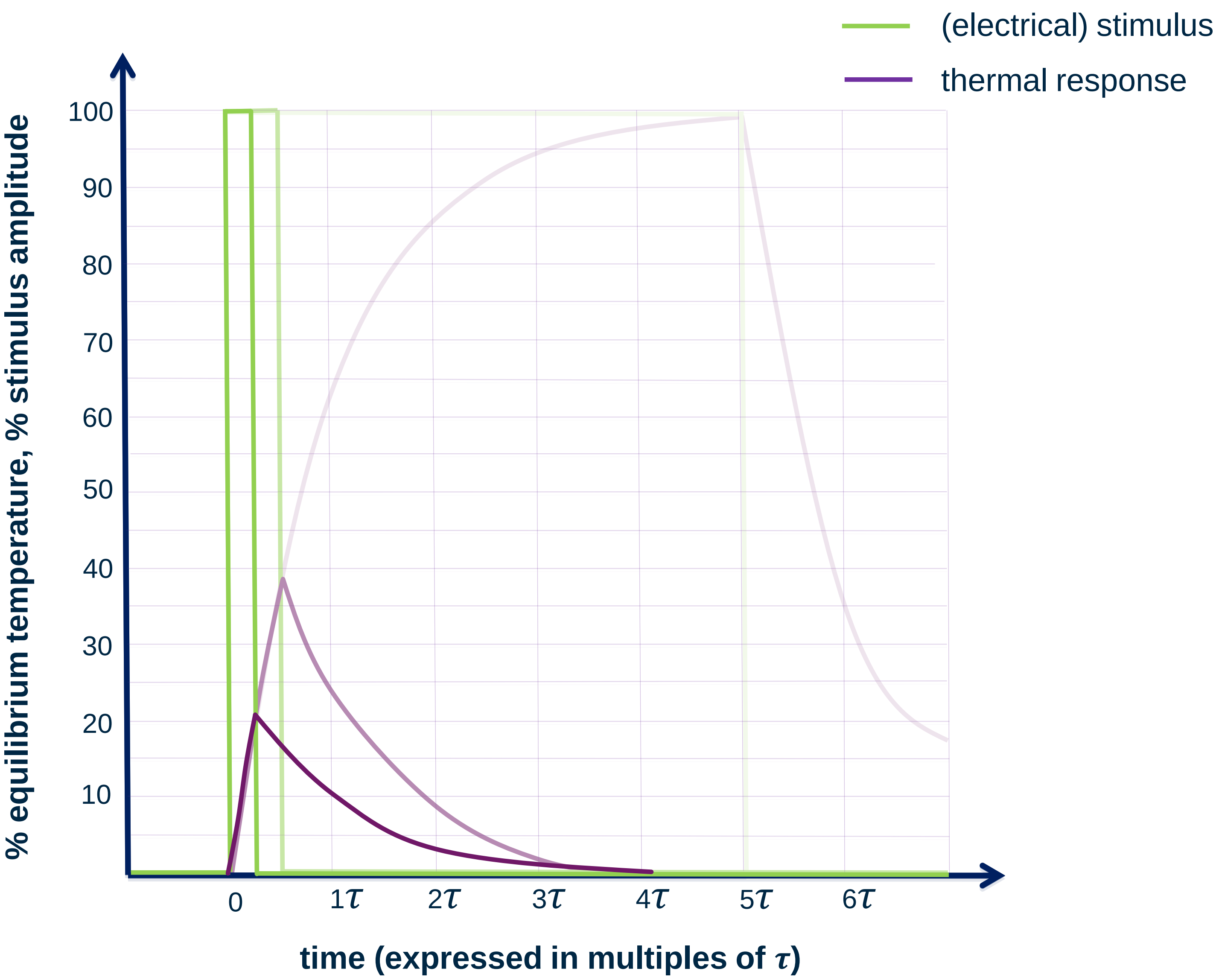
Thermal Time Constant - Continued

- If the stimulus amplitude is high enough, initiation of the EED will occur as the temperature equilibrium is approached (or some time after).



Thermal Time Constant - Continued

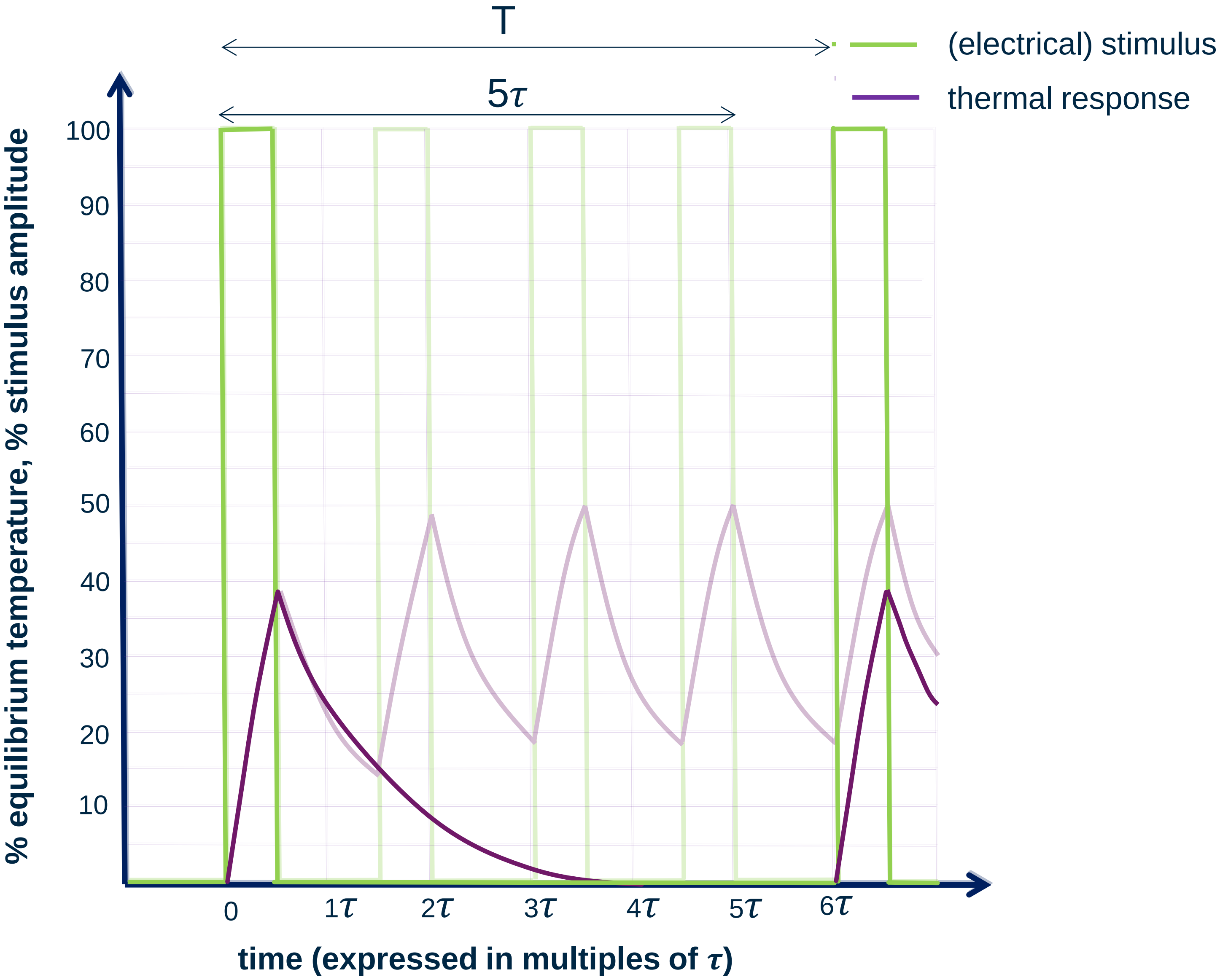
What happens when the pulse width is below τ ?



Thermal Stacking

- A bridgewire’s temperature may increase incrementally (or ‘stack’) when there is insufficient time between stimulus (i.e. radar) pulses for the bridgewire to cool down.

- If, however, T >> 5τ thermal stacking will not occur *(Source: Survey of Electro-explosive devices, Clarkson College of Technology, January 1977)*



Thermal Stacking

- Assume that a bridge temperature θ_1 is reached after the first pulse. The bridge temperature θ_N, after N pulses is as follows:

$$\theta_N = \theta_1 \left(\frac{1 - e^{\frac{-NT}{\tau}}}{1 - e^{\frac{-T}{\tau}}} \right) \qquad (1)$$

T is the pulse period and τ is the EED’s thermal time constant.

- Eq. (1) can be rewritten as follows to determine N:

$$N = -\frac{\tau}{T} ln \left[1 + \frac{\theta_N}{\theta_1} \left(e^{\frac{-T}{\tau}} - 1 \right) \right] \qquad (2)$$

Reference: Franklin Applied Physics EED Course, 31 Jul 2014

Example

- Common primer mixes, such as NOL-130, are made up of 40% basic lead styphnate, 20% lead azide, 20% barium nitrate, 15% antimony sulphide and 5% tetrazene. Its temperature of ignition is reported to occur at 240ºC.
- With τ = 1ms, T = 0.5ms, θ_1 = 95ºC and the ignition temperature of NOL-130 being 240ºC:

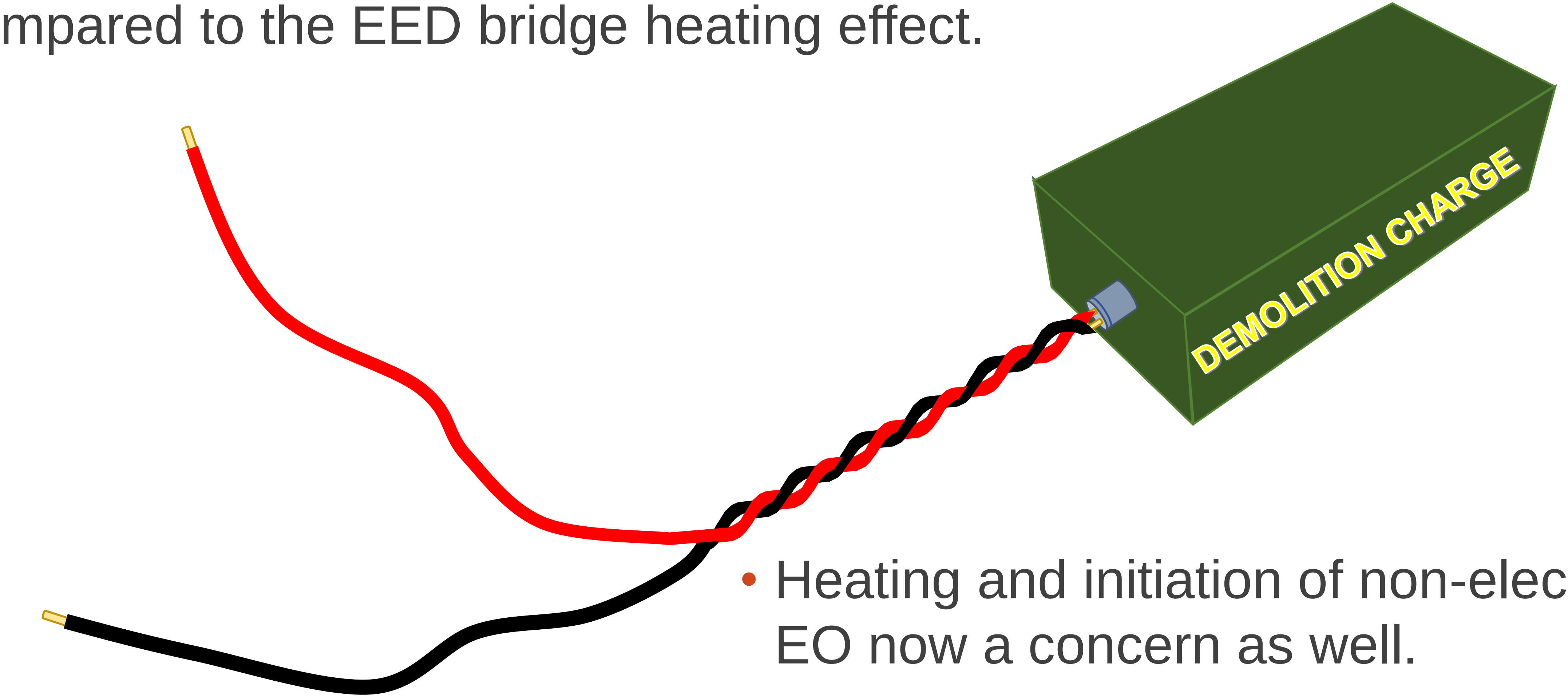
$$N = -\frac{\tau}{T} ln\left[1 + \frac{\theta_N}{\theta_1}\left(e^{\frac{-T}{\tau}} - 1\right)\right] = \frac{-1}{0.5} ln\left[1 + \frac{240}{95}\left(e^{\frac{-0.5}{1}} - 1\right)\right] = 10.24 \rightarrow 11 \text{ pulses}$$

Notice that the pulse period T is < τ

References: (1) M. Maksacheff, D.J. Whelan, DSTO Report MRL-R-1000, Thermochemistry of Normal and Basic Lead Styphnates using Differential Scanning Calorimetry of May 86, (2) A. Gash Et. Al., Environmentally Benign Stab Detonators, UCRL-TR-201628 of 29 Dec 03

A Newly Identified Issue

- At some frequencies, the bulk heating of energetic materials may be of greater concern when compared to the EED bridge heating effect.



- Heating and initiation of non-electric EO now a concern as well.

HERO Incident – Non-electric Pyrotechnic Devices

- 2013 incident involving the radar of a USN DDG Destroyer.
- Non-electric signal flares and distress signal devices were initiated during a replenishment activity.
- The radar was not sector-blanked, nor was it set to low-power mode, when it radiated the items on a Rigid-Hulled Inflatable Boat (RHIB) on the adjacent supply ship.

Reference: *C. Denham, HERO Capability Gap within NATO, MSIAC Steering Committee Presentation of Oct 17*

Bulk Heating of Energetic Materials

- Microwave heating – a common industry application.
- What influences energetic heating in the presence of strong electromagnetic fields?
- Fine metal powders are susceptible to aggressive heating under the right circumstances.
- Case materials influence the penetration of said microwave emissions into materials.
- Of particular concern is the scenario where bulk energetic materials are not effectively shielded by a conductive enclosure.

Bulk Heating of Energetic Materials - continued

$$P = 2\pi f(\varepsilon_{eff}\varepsilon_o)E_{rms}^2 \xcancel{+ 2\pi f \mu_0 \mu'' H_{rms}^2}$$

- Microwave heating in the material can be represented in the general form.

$$P = 2\pi f(\varepsilon_{eff}\varepsilon_o)E_{rms}^2$$

- Considering generally non-conductive materials, the equation can be simplified. This assumption holds part of the time, but is a safe assumption for particular high-explosive compositions.

$$\frac{dT}{dt} = \frac{2\pi f(\varepsilon_{eff}\varepsilon_0)E_{rms}^2}{\rho C_p}$$

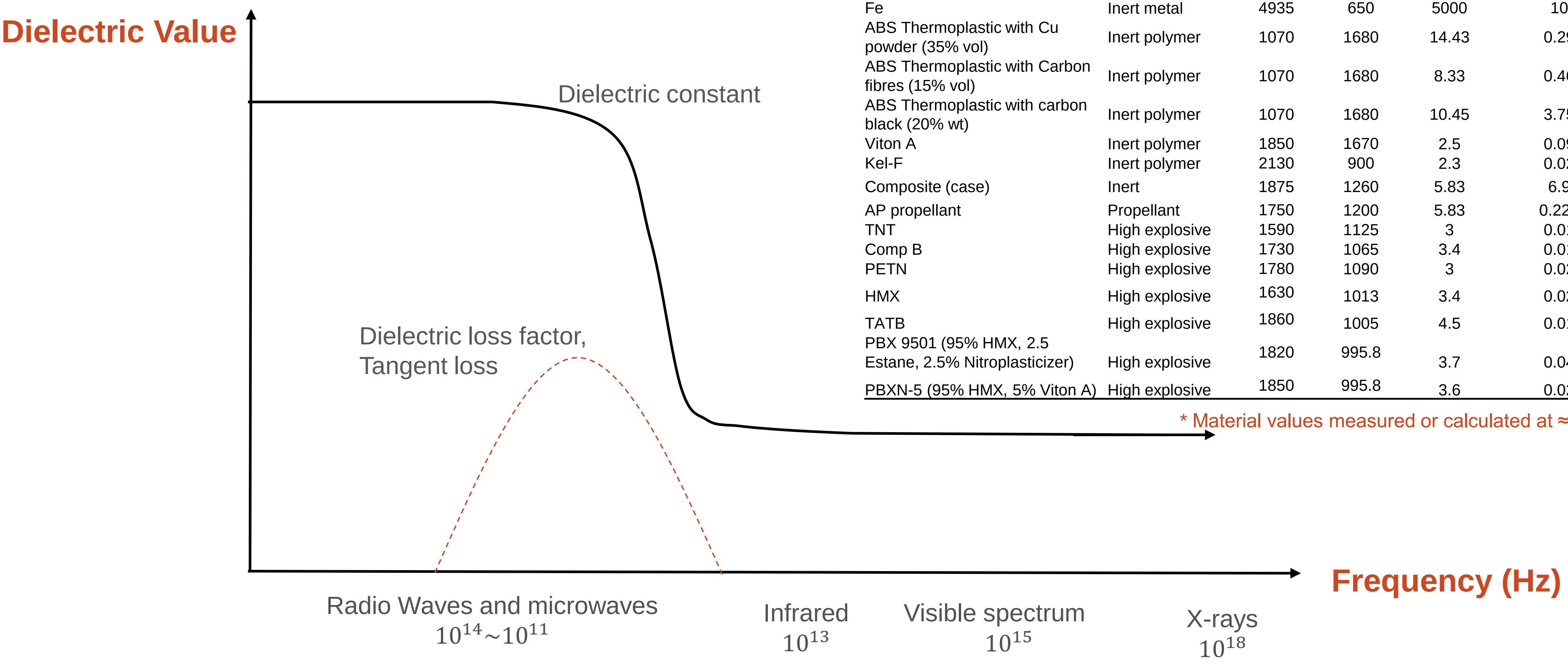
- Substitute power for material heating with $\mathrm{P} \sim \frac{\rho C_p dT}{dt}$, which assumes no heat loss from the material.
- This yields an equation that is intuitive to understand microwave heating in a material.

(Energetic) Material Properties

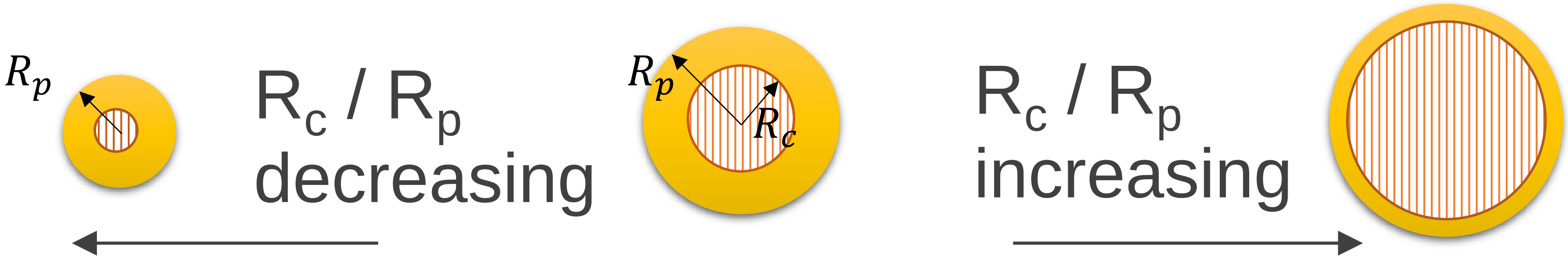
Dielectric values of materials are dependent on the frequency of incident microwave frequency.

Material	Type	Density [kg/m^3]	Heating Capacity [J/kg.k]	Permittivity e'	Dielectric loss factor e"
Al	Inert metal	2941	900	1	2.78
Fe	Inert metal	4935	650	5000	10
ABS Thermoplastic with Cu powder (35% vol)	Inert polymer	1070	1680	14.43	0.29
ABS Thermoplastic with Carbon fibres (15% vol)	Inert polymer	1070	1680	8.33	0.46
ABS Thermoplastic with carbon black (20% wt)	Inert polymer	1070	1680	10.45	3.75
Viton A	Inert polymer	1850	1670	2.5	0.09
Kel-F	Inert polymer	2130	900	2.3	0.02
Composite (case)	Inert	1875	1260	5.83	6.9
AP propellant	Propellant	1750	1200	5.83	0.228
TNT	High explosive	1590	1125	3	0.01
Comp B	High explosive	1730	1065	3.4	0.01
PETN	High explosive	1780	1090	3	0.02
HMX	High explosive	1630	1013	3.4	0.02
TATB	High explosive	1860	1005	4.5	0.01
PBX 9501 (95% HMX, 2.5 Estane, 2.5% Nitroplasticizer)	High explosive	1820	995.8	3.7	0.04
PBXN-5 (95% HMX, 5% Viton A)	High explosive	1850	995.8	3.6	0.02

* Material values measured or calculated at ≈ 2.5GHz



Metallic Powders

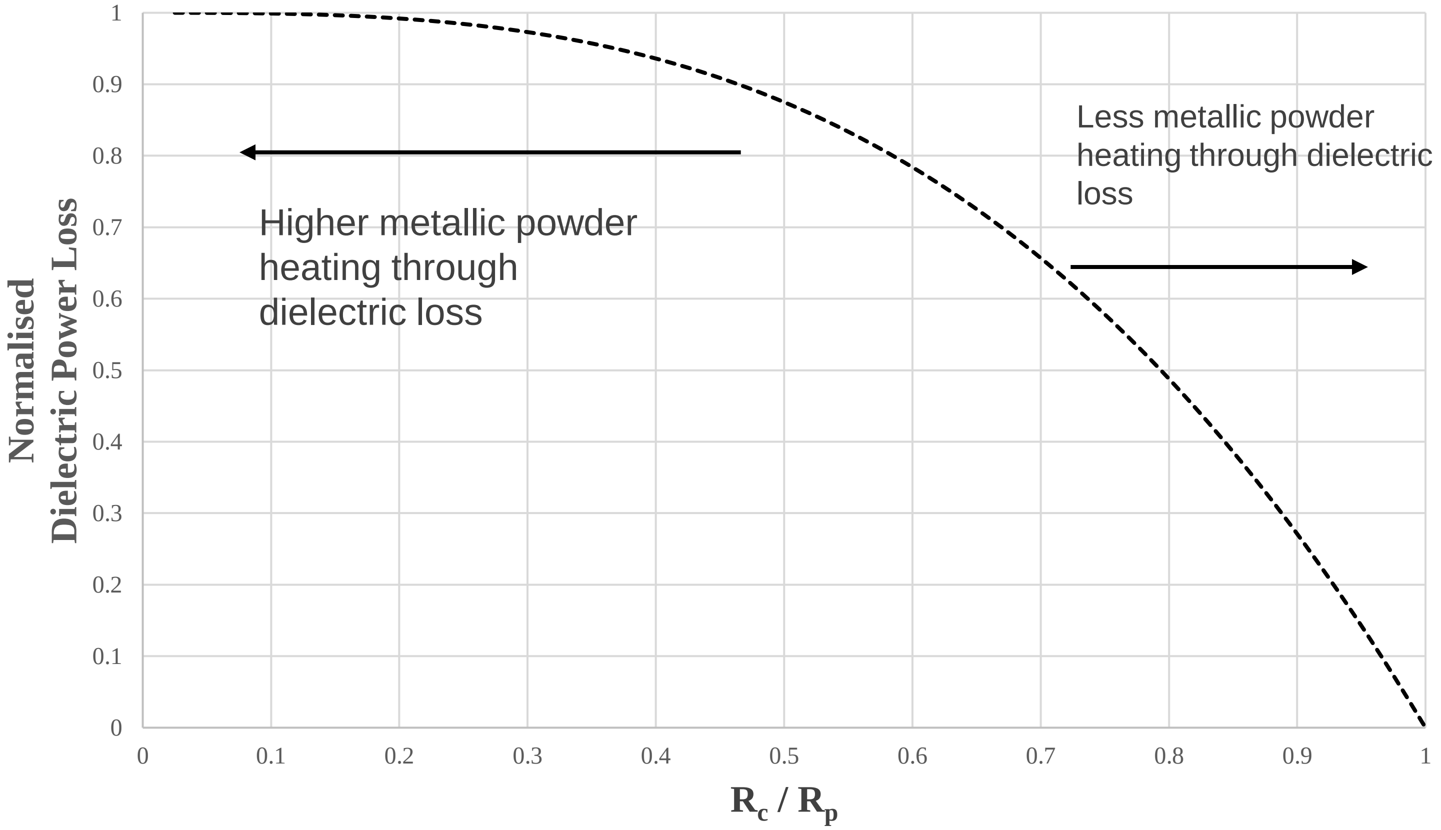


R_c / R_p decreasing

R_c / R_p increasing

Decreasing oxide layer relative to particle.

Increasing oxide layer relative to particle.

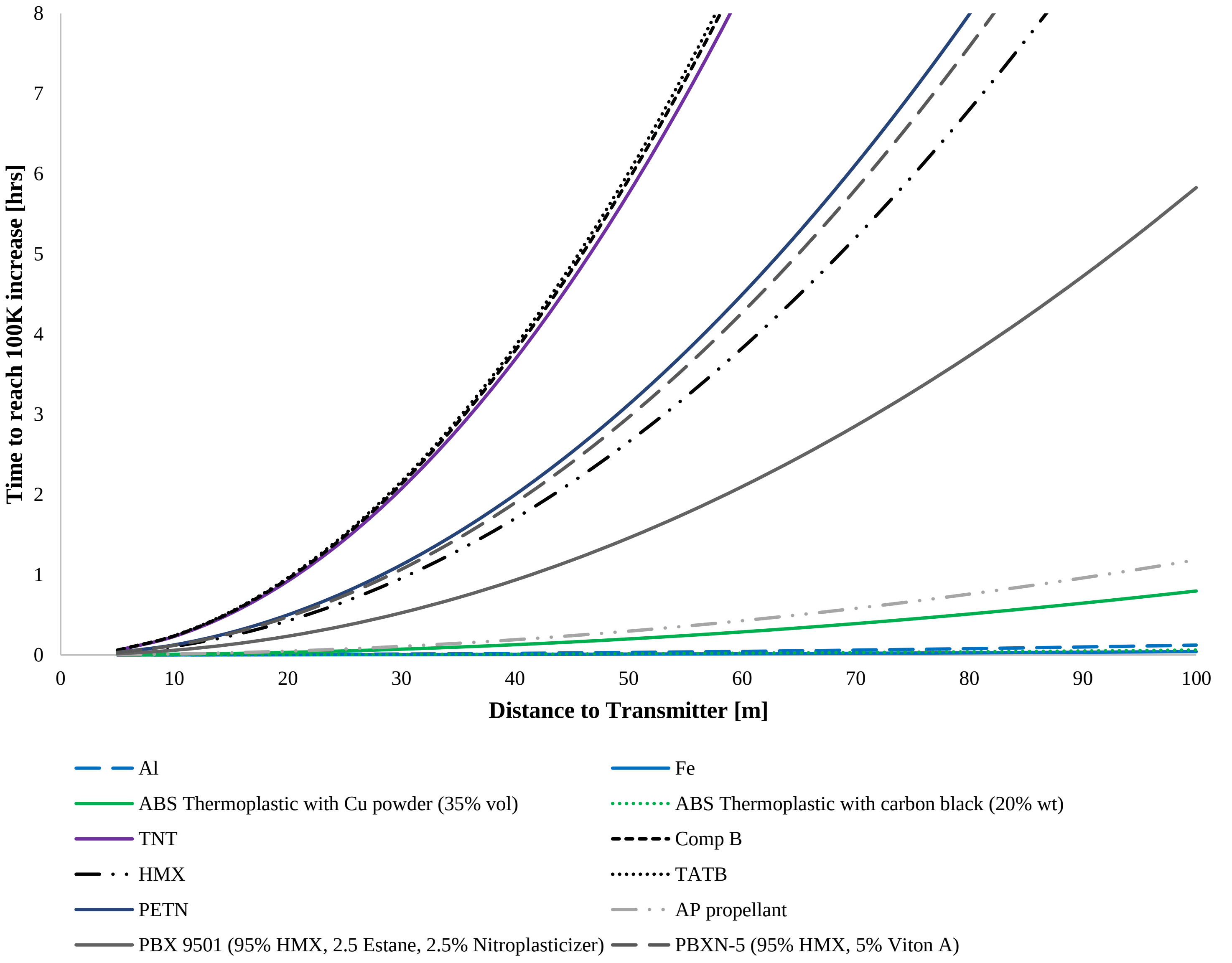


Higher metallic powder heating through dielectric loss

Less metallic powder heating through dielectric loss

Heating Potential

- Using SPY-1 as example radar with $P_{average}$ = 58 kW, Gain Factor = 9300



$$\frac{dT}{dt} = \frac{2\pi f(\varepsilon_{eff}\varepsilon_0)E_{rms}^2}{\rho C_p}$$

Risk Factors

Pyrotechnics	Cast Composite Propellants	High Explosives
• Limited damage.	• Substantial damage	• Catastrophic damage.
• High susceptibility to microwave heating.	• Moderate susceptibility to microwave heating.	• Very low susceptibility to microwave heating.
• High powder metal content represents a risk.	• Composite cases with no metallic material embedded provides little to no shielding.	• Generally shielded with metallic cases in an all-up system.

Special Case: X-raying of EO

- X-raying of EO treated as a special case, mainly because of operating frequencies of 10^{16} - 10^{20} Hz, which well exceed the frequencies where HERO is commonly of concern.
- Queries surrounding the safety of EO X-raying procedures remain.
- NAVSEA OP 3565 Vol 2, Rev 19 of 7 Jul 17 presents evidence of X-ray survivability testing of EO.
- Alludes to the potential ‘damage’ of explosives, depending upon the material properties and given sufficient X-ray radiation exposure time.
- Allows for X-ray dose < 1,400rads/minute, total dose <100,000 rads.
- *“No HERO problems are expected and explosives should remain safe and reliable”.*

Summary

- The thermal behaviour of EEDs are generally well-understood.
- With the introduction of radars with longer pulse widths, even bridgewire EEDs may be considered as pulse sensitive. There is also an increased risk of ‘thermal stacking’.
- Necessitates the need for more detailed assessments to contextualise the risks presented by specific RF emitters.
- At certain frequencies the bulk heating of energetic materials may be of greater concern than the bridge heating effect in EEDs.
- Basic equations may aid in predicting the heating potential in energetic materials due to particular RF emitters.
- Of particular concern is the scenario where bulk energetic materials are not effectively shielded by a conductive enclosure.

Concluding Observations

- Joint Ordnance Test Procedure (JOTP)-062 covers personnel-borne and helicopter-borne electrostatic discharge testing, and already has an increased scope, which covers bare energetic materials and EO with or without EEDs.
- Similarly, the future scope of HERO testing will likely change – to include EO with or without EEDs.
- Further research on this topic is essential, especially because of its potential impacts on the ADF’s interoperability objective.

Questions?

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