Radiative and reactive coupling of lightning to electro-explosive devices in storage

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Abstract

We theoretically study the absorption of radiative and reactive electromagnetic fields by electro-explosive devices (EEDs) in a munition storage struck by lightning. We find that reactive coupling in the near-field dominates for high resistance EEDs, while radiative coupling in the far-field from the strike location dominates for low resistance EEDs. Surprisingly, both couplings are substantially weaker than previously estimated. This is because the strike duration is long compared to typical electromagnetic response times. This lowers reactive absorption due to saturation of the electro-explosive device capacitance, while radiative absorption is low because the strike mostly emits low frequency modes with wavelengths longer than the dimensions of the munition storage.

Keywords: electro-explosive devices; lightning protection; HERO; munition storage

1 Introduction

Preventing unintended detonations by lightning strikes is a critical aspect for safe munition storage. Lightning strikes can not only initiate detonation by a direct strike on munition or sparking of poorly shielded conductors in the storage location, but there is also the possibility that detonation is initiated by the coupling of electromagnetic (EM) fields to electro-explosive devices (EEDs). While this non-conductive coupling of EM fields is very inefficient, the large energy content of a lightning strike (~1 GJ [1]) compared to typical firing energies of EEDs (~1 mJ [2], [3]) ensures that even for very weak couplings (>-120 dB) a risk of unintentional detonation remains. This risk has been widely recognized since at least the 1960s when EM pulses from high altitude nuclear explosions were recognized to be sufficiently strong to enable unwanted detonation [3]. Since then, the Hazards of EM Radiation to Ordnance (HERO) program has developed several standards for the maximum tolerable amplitudes of EM radiation near munition [3]–[5]. Similarly, military [5], [6] and industry standards [7] describe the requirements for effective lightning protection of storage buildings. For the Dutch MoD the lightning safety of munition storages was assessed along the lines of Ref. [7] by TNO and DNV [8], [9]. This assessment requires the analysis of non-conductive EM risks and while a large amount of literature exists on the modelling of HERO risks, these usually assume the EM sources are located several wavelengths from the EED in the far-field. As the emission of EM radiation occurs within several meters from an EED during a lightning strike on a storage this requires novel analysis taking into account reactive near-field couplings.

Here we will improve upon the previous worst-case estimate [8] of power and energy absorption of an EED in a storage struck by lightning by studying an explicit model of the reactive and radiative EM energy transfer. This idealized model considers the power P and energy U injected into an open circuit EED by a time dependent electric $\mathbf{E}(t)$ and magnetic field $\mathbf{B}(t)$. Previous work [8] estimated this power as the conductive Ohmic power (P_*) and energy (U_*)

$$P_* = \frac{E_0^2 \ell^2}{R}, \tag{1a}$$

$$U_* = \frac{E_0^2 \ell^2 \tau_1}{R}. \tag{1b}$$

by the EED with resistance R, length ℓ along the maximum electric field E_0 during the strike duration with decay time τ_1. However, this equation does not consider that for radiative absorption the EED can act as an antenna with a characteristic length much longer than the physical size ℓ thereby absorbing substantially more energy. Similarly, for reactive absorption of a static electric field with $\tau_1 \to \infty$ the predicted absorbed energy Eq. (1b) grows to infinity while in reality it should decay to zero. In this work we aim to clarify these limitations of Eqs. (1a)-(1b) by constructing explicit models for radiative and reactive absorption of EM fields by an EED in a munition storage struck by lightning.

As depicted in Fig. 1, we consider an idealized model where the lightning impact on a munition storage is considered to act as an emitter of an EM field with perpendicular electric and magnetic fields. The EED is oriented in such a way as to maximize the power absorption of the EM fields in an otherwise empty munition storage. The EED acts as an antenna when absorbing far-field EM components with wavelengths λ much shorter than the storage length $2L$ [3], [10]. In contrast, for large wavelength EM components $\lambda \gg 2L$ in the near-field power transfer occurs through reactive (capacitive and inductive) coupling of the EED to the munition storage [11]. Our aim is to find whether Eqs. (1a)-(1b) over- or under-estimate the power transferred to the EED load compared to radiative and reactive coupling. While we will find that the estimates Eqs. (1a)-(1b) generally underestimate the transferred power, we will show that this sensitively depends on the lightning rise time τ_2 being very long compared to the natural EM timescales of an EED in a munition storage. The presented analysis should be interpreted as a worst-case order of magnitude estimate, as several features such as electronic hardening, load mismatch and suboptimal EED orientation [10] are neglected and simultaneously a simplified representation for the EM characteristics of the munition storage is used. Furthermore, our analysis only considers non-conductive couplings and hence does not consider other HERO risks such as for example sparking, flash-over or stray currents.

We consider the single, initial, lightning strike on the munition storage to have a double exponential time envelope [12] which overestimates the initial rise time [13] and hence constitutes a worst case estimate

$$I(t) = \theta(t)\, I_o \left(e^{-t/\tau_1} - e^{-t/\tau_2}\right), \tag{2}$$

with $\theta(t)$ the Heaviside stepfunction and the lightning decay time $\tau_1 \simeq 10^{-5}$ s much larger than the lightning rise time $\tau_2 \simeq 10^{-6}$ s. The lightning strike gives rise to an electric field $E(t)$, with perpendicular magnetic field $B(t)$ and potential difference $V(t) = E(t)(2L + \ell)$ over the storage, where L is separation between EED and wall and ℓ is the EED load length along the electric field. In accordance with separation distance guidelines for munition storage we assume $L \gg \ell$. The EED is centered in the storage, as we will show later that centering of the EED maximizes reactive coupling. The expression for the potential difference $V(t)$ is valid for homogeneous EM fields $E(t)$ and $B(t)$, which we show to be a good approximation for strikes with $\tau_2 \geq 10^{-6}$ s. We assume the electric field $E(t) = E_0\, I(t)/I_0$ and magnetic field $B(t) = B_0\, I(t)/I_0$ have similar time envelopes as the lightning current $I(t)$. This assumption is not supported by Digital Twin models of storage complexes struck by lightning as shown in Ref. [8], which show oscillating modes with frequencies on the order of τ_1^{-1}. However, we will show that both radiative and capactive coupling are dominated by the shortest timescale, the lightning rise time τ_2, and thus oscillations on the order of τ_1^{-1} are neglected in this analysis. Finally, we do not explicitly account for heat transfer inside the EED and shielding, for which suitable models are available in the literature [3], [8], [10], [14], [15].

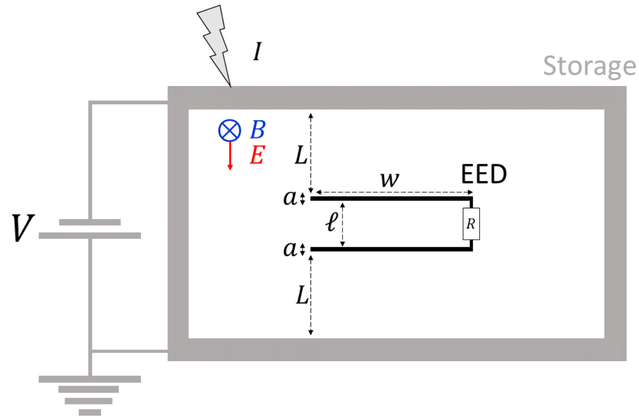


Figure 1. Schematic depiction of a lightning strike on the roof of a storage location (grey) with an (open circuit) electro-explosive (EED, black) device inside. The time dependent lightning current $I(t)$ creates a magnetic field (blue) $B(t)$ and electric field (red) $E(t)$ which are assumed to be perpendicular. As the characteristic wavelength of the EM field is much longer than the storage length $2L$ the EM fields can be considered to be homogeneous, and the voltage difference between ground and strike location $V(t) = E(t)(2L + \ell)$. Here the EED load has resistance R and length $\ell \ll L$ oriented parallel to the electric field, whereas the wires perpendicular to the load with width w are oriented such that the open $w\ell$ plane is normal to the magnetic field. The wires have a constant radius a and are positioned a distance L from all walls.

2 Radiative coupling

Most HERO analysis considers the metallic components of an EED to act as an antenna, which can efficiently transfer energy from the large wavelength (λ) components of an EM field to an EED. This radiative power transfer is not accounted for in Eqs. (1a)-(1b) and to assess whether the neglect of radiative coupling results in an underestimate of U_* and P_* a more thorough evaluation is needed. As the effective antenna area A of a small dipole antenna scales as $A \propto \lambda^2$ [16], [17] it follows that the transferred energy grows very quickly or even diverges for large wavelength components of the EM field. However, this relation for the collection area A is only valid in the far-field when emitter and absorber are several wavelengths apart $\lambda \gg 2L$ [16]. Hence, for radiative power transfer we only consider EM components with $\lambda \leq 2L$, as depicted in Fig. 2.

In the far-field the EM field has decayed to its purely radiative components, and the Poynting vector for a plane wave $|\mathbf{S}(t)| = \mu|\mathbf{E}(t) \times \mathbf{H}(t)| = |E^2(t)|/\eta$ [16], with $\eta = \sqrt{\mu/\epsilon} \simeq 377\ \Omega$ the vacuum impedance and μ and ϵ the magnetic permeability and electric permittivity in vacuum, respectively. The total energy U in the EM spectrum that can be transferred to an EED load far from the emitter then becomes

$$U = \int_{-\infty}^{\infty} \frac{|\hat{E}^2(\omega)|}{\eta} A(\omega) e(\omega) \mathrm{d}\omega\,, \tag{3}$$

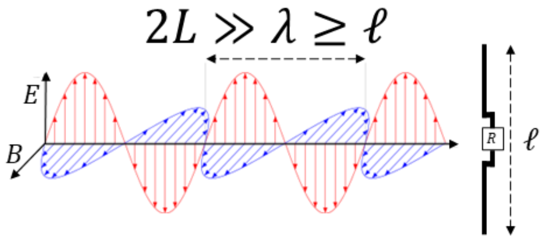


Figure 2. Schematic depiction of an EED (thick black line) acting as a receiver for an EM wave, with perpendicular electric (red) and magnetic (blue) fields. The EM wave is a plane wave with wavelength λ and the EED is far from the emitter $\lambda \leq 2L$, small comparable to the wavelength $\lambda \gg \ell$ and oriented normal to the incoming wave.

where $\hat{E}(\omega)$ is the Fourier transform of $E(t)$ and $A(\omega) = \gamma\lambda^2 = \gamma c^2/\omega^2$ is the frequency dependent absorption area, with the velocity of light $c = 3 \cdot 10^8$ m/s. For now, we assume perfect power transmission efficiency from the EM field to the EED load for all wavelengths $e(\omega) = 1$, which is not physically realisable for real antennas where $e(\omega) < 1$. Finally, the gain equals $4\pi\gamma \simeq 1.5$ for small Hertzian antennas with $\ell \ll \lambda$ [16]. As noted, before, Eq. (3) diverges for low frequencies of ω and is only valid in the far-field for large frequencies $\omega \gg \tau_s^{-1}$, with $\tau_s = 2L/c$ the time it takes for light (at speed c) to travel over the munition storage. The EM energy transferred radiatively to an EED load from a lightning strike then becomes

$$U_\mathrm{A} = 2\int_{\tau_s^{-1}}^{\infty} \frac{E_0^2}{2\pi\eta} \frac{c^2\gamma(\tau_1-\tau_2)^2}{(\omega+\omega^3\tau_1^2)(\omega+\omega^3\tau_2^2)} \mathrm{d}\omega \overset{\tau_2 \gg \tau_s}{\simeq} \frac{4\gamma}{5\pi} \frac{E_0^2 L^2}{\eta} \left(\frac{\tau_s}{\tau_2}\right)^3 \tau_2 \tag{4}$$

where the time envelope $I(t)$ (Eq. (2)) introduces the τ_i dependency through $\left|\hat{E}^2(\omega)\right|$ and the factor 2 before the integral results from the even symmetry of the integrand. The simplification is valid when $\tau_1 \gg \tau_2$ and the light travel time is much smaller than the lightning rise time $\tau_2 \gg \tau_s$, which is the case for munition storages smaller than 300 m.

As there is no straightforward method for deriving the time dependent power density $P(t)$ received by the antenna, we estimate the average antenna power as $P_A = U_A/\tau_1$. Comparing the energy and power U_A and P_A absorbed by an antenna to the initial worst case assumption of EED energy (U_*) and power (P_*) absorption we find

$$\frac{P_*}{P_A} = \frac{5\pi}{4\gamma}\frac{\eta}{R}\left(\frac{\ell}{L}\right)^2\left(\frac{\tau_2}{\tau_s}\right)^3 \gg 10^5\left[\frac{\Omega}{\mathrm{m}^2}\right]\left(\frac{\ell^2}{R}\right), \tag{5a}$$

$$\frac{U_*}{U_A} = \frac{5\pi}{4\gamma}\frac{\tau_1}{\tau_2}\frac{\eta}{R}\left(\frac{\ell}{L}\right)^2\left(\frac{\tau_2}{\tau_s}\right)^3 \gg 10^6\left[\frac{\Omega}{\mathrm{m}^2}\right]\left(\frac{\ell^2}{R}\right). \tag{5b}$$

For most EEDs the ratio $R/\ell^2 \ll 10^5$ [Ω/m^2] and thus Eqs. (1a)-(1b) considerably overestimate the energy transfer from a lightning strike by EM fields. Interestingly, for small EEDs with $\ell < 10^{-2}$ m and/or large resistances $R > 10^2\ \Omega$ the worst case energy U_* and power P_* transfer in first instance seems to imply that radiative energy transfer is underestimated by Eqs. (1a)-(1b). However, this result follows from our assumption of an antenna that can harvest energy from all wavelengths at a perfect efficiency $e(\omega) = 1$, which as previously noted is unphysical. Rather, the real energy transfer depends on the load-matching from antenna (metallic wires) to the load (bridge wire). When the imaginary part of the load and antenna impedance are matched, the efficiency for the largest wavelengths in the small antenna large resistance limit equals $e \simeq 4(\ell^2/R)(\eta/L^2) \ll 10^{-5}$ [16] and hence the energy ratio becomes $U_*/U_A \simeq (\tau_1/\gamma\tau_2)\,(\tau_2/\tau_s)^3$ while the power ratio becomes $P_*/P_A \simeq \gamma^{-1}(\tau_2/\tau_s)^3$ which both are much greater than 10^3. Thus, even in the small EED/large resistance limit the radiative power transfer efficiency $e(\omega)$ vanishes and the worst-case assumptions P_* and U_* remain orders of magnitude larger than the radiative power and energy transfer within a munition storage.

Summarizing, we find that U_* and P_* from Eqs. (1a)-(1b) overestimate energy transfer for EEDs in the idealized setting we considered in Fig. 1. Our Eqs. (5a)-(5b) show that the validity of the worst case estimate U_* and P_* sensitively depend on the ratio of lightning rise time to travel time of light, which is typically small $\tau_s/\tau_2 \ll 10^{-1}$. While this suggests that munition becomes sensitive in extremely large munition storages (> 300 m), for such storages the decay of EM radiation from the strike location must be considered which dramatically lowers EM energy transfer. Therefore, the only free parameter in τ_s/τ_2 is the rise time τ_2 which for initial lightning strikes has 10^{-6} s as a lower bound. Only for EM pulses (EMP) from high altitude nuclear blasts τ_2 are sufficiently low (10^{-8} s [3]) to invalidate Eqs. (1a)-(1b) as a worst-case estimate.

3 Reactive coupling

As shown in the previous section the radiative coupling of EM fields to EEDs in munition storage is inefficient as most of the energy is transferred by EM fields with wavelengths much longer than the munition storage $\lambda \gg 2L$. For such waves a far-field analysis based on antenna receiver equations is not appropriate [16]. Rather, here the coupling is reactive and is achieved by mutually capacitive and inductive elements shared by "emitter" and "absorber" [18]–[20]. For such coupling the EED and munition storage can be considered to act as a single circuit, like shown in Fig. 3. The circuit in Fig. 3 is suitable when the charge from the lightning strike is primarily distributed over the roof and ground as depicted in Fig. 1, in which case the storage and EED reduce to a (modified) 4-plate capacitor [18], [20].

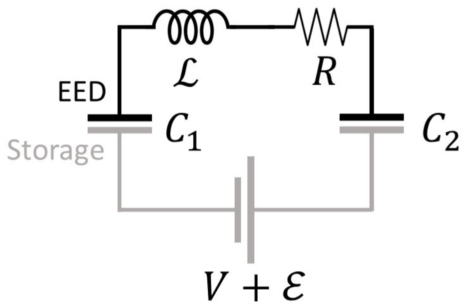


Figure 3. Effective circuit where the EED (black) and storage (gray) are capacitively coupled through capacitor C_1 and C_2. The EED circuit consists of a self-inductance $\mathcal{L}$ and a resistance R. We only consider the resistance of the load of the EED, such as a bridge wire, neglecting all other EED resistances.

For the circuit the potential drop over the entire circuit should equal the sum of potential drops ψ_i over the individual elements

$$V + \mathcal{E} = \psi_1 + \psi_{\mathcal{L}} + \psi_R + \psi_2. \tag{6}$$

Here $\mathcal{E}$ is the electromotive force induced by a changing magnetic field in the open circuit loop, which is at most equal to the electromotive force of the closed loop $\mathcal{E}(t) = w\ell\,\dot{B}(t)$, with $\dot{B}$ the time derivative of the magnetic field. The electromotive force $\mathcal{E}$ is achieved through a mutual inductance between munition storage and EED, which could be calculated explicitly with a more detailed model of the storage location. For the large wavelengths components of $E(t)$ considered in this section the electric field must be nearly constant over the length of an empty munition storage, in which case the voltage $V(t) = (2L + \ell)\,E(t)$. The magnetic and electric fields are assumed to be oriented such that $V(t)$ and $B(t)$ add constructively, rather than destructively.

The potential drops over capacitors C_1 and C_2, resistor R and inductor $\mathcal{L}$ are given by

$$\psi_1 = LE(t) + \frac{Q}{C_1} \tag{7a}$$

$$\psi_2 = LE(t) + \frac{Q}{C_2} \tag{7b}$$

$$\psi_{\mathcal{L}} = \mathcal{L}\ddot{Q} \tag{7c}$$

$$\psi_R = R\dot{Q} \tag{7d}$$

where $2Q$ is the charge difference over R and $\dot{Q}$ is the current through R. The capacitive potential drops ψ_1 and ψ_2 carry a charge independent term $LE(t)$ accounting for the charge at the strike and ground locations. This ensures that the effective circuit obeys the Laplace equation for the electric potential when no net charge is present in the munition storage.

Combining the expressions for the driving forces $V(t)$, $\mathcal{E}(t)$ together with $E(t) = E_0\,I(t)/I_0$, $B(t) = B_0\,I(t)/I_0$ and Eqs. (7a)-(7d) we find that the charge obeys the differential equation for an RLC circuit (dampened oscillator)

$$I(t)/I_0\,(i_E + i_B) \simeq Q/\tau_{RC} + \dot{Q} + \tau_{LR}\ddot{Q} \tag{8}$$

where the typical electric and magnetic field induced currents are given respectively by $i_E = E_0\ell/R$ and $i_B = B_0\ell w/(\tau_2 R)$, when $\tau_1 \gg \tau_2$.. The capacitive RC time and self-inductive LR time for two wires parallel to a wall and to themselves are given by $\tau_{RC} = 4\pi\epsilon w R/\cosh^{-1}(L/a)$ and $\tau_{LR} = \mu w/(\pi R\,\cosh^{-1}(\ell/a)$ [21].To maximize τ_{RC} we have here set the separation of the EED to ground and strike location equal, such that $C_1 = C_2$ which maximizes the total capacitance $(C_1^{-1} + C_2^{-1})^{-1}$ when C_i monotonically decreases with separation L. As we will show that reactive power transfer $P_C \propto \tau_{RC}^2$, this surprisingly means that reactive power transfer is maximized for an EED centered in the storage.

For typical separations $L = 0.5$ m, dimension $w = 10^{-1}$ m, $a = 10^{-3}$ m and EED resistances $R < 10^6\,\Omega$ we find that the capacitive RC time is short $\tau_{RC} \ll \tau_2 \simeq 10^{-6}$ s. When we take the Laplace transform in this limit ($\tau_{RC} \ll \tau_2$) and back transform we find that, with boundary conditions $Q = \dot{Q} = 0$ at $t = 0$, the charge on the capacitors is given by

$$Q(t) = \tau_{RC}\frac{(i_E + i_B)}{I_0}\,I(t). \tag{9}$$

Here the circuit behaves quasi-statically as the small EED capacitance is nearly instantaneously charge saturated over a time τ_{RC}. The power transferred to the circuit load during the lightning strike can be found as $P_C = R\dot{Q}^2$ and energy $U_C = \int P_C(t)\mathrm{d}t$. When the self-inductance of the storage is small this means that the magnetically induced current of the storage is similarly small $i_B \ll i_E$, in which case we can compare the near-field circuit power P_C and energy U_C to the initial assumption of the peak power P_* and U_*, finding

$$\frac{P_*}{P_C} = \left(\frac{\tau_2}{\tau_{RC}}\right)^2 \gg 10^1, \tag{10a}$$

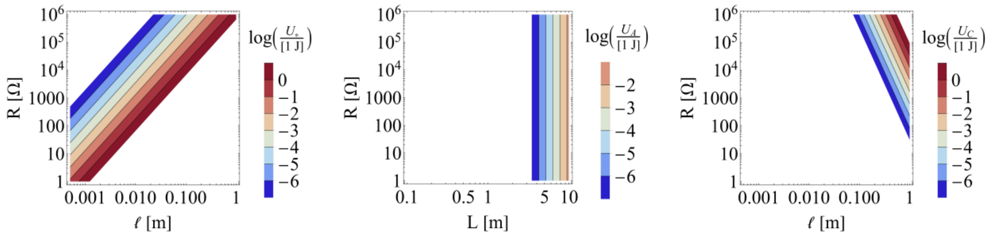
$$\frac{U_*}{U_C} = \frac{2\tau_1\tau_2}{\tau_{\mathrm{RC}}^2} \gg 10^2, \tag{10b}$$

which is valid when $\tau_1 \gg \tau_2 \gg \tau_{RC}$. From Eqs. (10a)-(10b) it becomes clear again that the original Eqs.(1a)-(1b) for P_* and U_* significantly overestimate the sensitivity of EEDs to EM fields generated by lightning strikes, again due to the lightning strike being slow compared to the EM timescales of the EED, $\tau_2 \gg \tau_{RC}$. If the response time of the circuit τ_{RC} would be similar to the lightning rise time τ_2 (as is the case for repeat strikes with short rise times) a more advanced analysis is needed. While the energy U_C is unlikely to exceed U_* in this case, the maximum power P_C has the possibility to exceed P_* for under dampened circuits with $\tau_{RC} < 4\tau_{LR}$. However, even in this case it is unlikely that the circuit resonance modes at $(\tau_{RC}\tau_{LR})^{-1/2} \propto c/w \gg 1\ \mathrm{GHz}$ are excited, as they occur at frequencies which are unreasonably large for lightning strikes.

4 Discussion and conclusion

In Fig.4(a),(b) and (c) we respectively show the EM energy transferred to an EED load as estimated by Eq. (1b), Eq. (5b) and Eq. (10b), for a large electric field $E_0 = 3 \cdot 10^5\ \mathrm{V/m}$. It can be seen in Fig. 4(a) that for EEDs with moderate resistance $R \simeq 10^2\ \Omega$ and moderate sizes $\ell \simeq 10^{-2}$ m the estimated energy $U_* \simeq 10^{-1}\ \mathrm{J}$ is already sufficient for a substantial chance of detonation. However, the radiatively absorbed energy for such an EED acting as an antenna is many orders of magnitude smaller $U_A \ll 10^{-6}$ J. Similarly, for an EED absorbing EM energy through a capacitive coupling the absorbed energy is also much smaller $U_C \ll 10^{-6}\ \mathrm{J}$. Interestingly, we also find that the resistance dependence is very different for the different absorption mechanisms: in Fig. 4(a) we find $U_* \propto R^{-1}$, while in Fig. 4(b) we find $U_A \propto R^0$ and in Fig.4(c) $U_C \propto R^1$. The reactive coupling increases with resistance as the current is limited by the small EED capacitance instead of the resistance, and for a fixed current a large resistance will maximize energy dissipation. The difference in resistance scaling ensures that radiative absorption dominates for low resistance EEDs, while reactive absorption dominates for large resistance EEDs. For all coupling modes the absorption is largest for large EEDs and munition storages. Most importantly, Fig. 4 shows that the estimate for U_* in (a) is much larger than those for U_A and U_C in (b) and (c) over almost the entire domain.

In conclusion, we considered an idealized model for radiative and reactive electromagnetic (EM) energy transfer from a lightning strike on a munition magazine to an electro explosive device (EED). We found that both radiative and reactive energy transfer is less efficient than previously estimated. This low efficiency is due to the rise time of the strike ($\sim 10^{-6}$ s) being long compared to the characteristic timescales of both radiative and reactive absorption by the EED. For radiative power transfer the characteristic timescale is the time required for light to traverse the storage ($\ll 10^{-7}$ s) and for reactive power transfer the characteristic timescale is the EED/storage RC-time ($\ll 10^{-6}$ s). Only when the typical lightning rise time is more than an order of magnitude faster $\tau_2 \ll 10^{-7}$ s will the simple expressions Eqs. (1a)-(1b) for U^* become insufficient to estimate the worst case EM field coupling to EEDs. Surprisingly, for such fast EM pulses the risk is largest for EEDs with large resistance, instead of EEDs with small resistance.



(a) (b) (c)

Figure 4. Logarithmic plot of the logarithmic energy $\log(U_i/[1\ \mathrm{J}]) \in (-7, 1)$ transmitted to the load of an EED by an EM field with $E_0 = 3 \cdot 10^5\ \mathrm{V/m}$. The previous estimated energy (U_*), far-field radiative energy (U_A) and near-field reactive energy (U_C) are shown in respectively (a), (b) and (c) for τ_1=10^{-5} s, τ_2=10^{-6} s, $a = 10^{-3}$ m, and $w = \ell$. In (a) and (c) the energy is plotted as function of the EED resistance R and length ℓ for $2L = 1$ m, while in (b) the energy is shown for varying munition storage length L.

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