Lightning Protection on a Munition Storage Compound – Method for Safety Risk Assessment

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Abstract

Munition storage structures are equipped with lightning protection systems in order to prevent accidental initiation of munition due to lightning flash strikes. The effect of lightning strikes on munition storage sites is being studied extensively by the Dutch MoD, DNV, and TNO, and comprises site reviews, risk assessments, and numerical modelling of the electromagnetic fields inside a munition storage structure induced by a lightning flash strike and the munition response. This paper focuses on one specific part of the study: a method for a safety risk assessment (SRA) in order to assess the effectiveness and safety level of lightning protection measures and systems on munition storage structures. The SRA-method is based on the international industry standard NEN-EN-IEC 62305 and can assess a wide variety of scenario's and protection measures. It assesses two types of risk: risk of loss of human life (i.e. people present inside the structure) and risk of loss of assets (i.e. loss of munitions and damage to the structure). For the loss of human life, the risk is expressed as a probability of lethality per year for an individual (individual risk, IR). For the loss of assets, a qualitative risk matrix is used for the assessment. The combined assessment of both risk types allows for a full view on the risks and identification of required (if any) mitigation measures.

1 Introduction

As part of explosives storage safety and risk management, munition storage structures are equipped with lightning protection systems, in order to prevent accidental ignition of munition or explosives due to lightning flash strikes on or near a storage structure. Such a lightning strike generates potentially large electromagnetic pulses and fields inside the structure, which can affect munitions with or without Electro Explosive Devices (EED). The resulting adverse effect could damage the munition, or in a worst case scenario lead to inadvertent ignition. For this reason, adequate lightning protection systems on munition storage structures are important.

Many nations have guidelines on the required lightning protection for munition storage structures [1-3], including the Netherlands [4]. Over the recent years, the Dutch MoD has changed its policy on lightning protection, where the intent is to adhere as much as possible to the international industry standard NEN-EN-IEC 62305 (in short: 62305) [5-8], instead of the older military standards. In light of this policy change, TNO and DNV have been tasked to investigate the applicability and effectivity of lightning protection systems (LPS) for munition storage structures. The research is aimed at the potential impact of lightning flash strikes on munitions, with and without an EED or fuse, inside a munition storage structure, and types of lightning protection systems and protection measures (as defined 62305) in particular.

For this investigation, various research efforts have been performed. TNO has developed a model to determine the munition sensitivity to electromagnetic

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effects of lightning strikes, in particular the EED or fuse in the munition [9]. DNV has developed Digital Twins, numerical models of the electromagnetic fields induced inside a structure during a lightning flash strike. These are not discussed in this paper. To be able to determine the effectiveness of an LPS, a safety risk assessment (SRA) method was developed, which combines the results of both models, with measurements on the structure(s) of interest, and various factors from the 62305. This paper describes the SRA-method, how the level of risk is determined and assessed, and what type of results and insights this method provides.

2 Risk assessment principles

In the developed SRA method several risk assessment principles are used to identify, quantify and assess the risks. Use is made of industry-wide methods like HAZID and ALARP, along with the international standard on lightning protection, and specific NATO guidelines on the storage of munitions and explosives.

2.1 HAZID

HAZID stands for Hazard Identification, which is a widely known method to clearly identify all hazards with the potential to an incident or (major) accident. HAZID is one of the best known methods to identify potential hazards, because it provides a structured approach to identify hazards, potential undesirable consequences and evaluate the severity and likelihood of what is identified [10]. In the SRA-method, use is made of HAZID to identify the particular hazards associated to lightning strikes on or near munition storage structures.

2.1.1 ALARP

ALARP means “as low as reasonably practicable”, and is a well-known way to assess risks and mitigation measures. This involves weighing a risk against the trouble, time and money needed to control it. Thus, ALARP describes the level to which it is expected to see workplace risks controlled. The UK HSE (Health and Safety Executive) has summarized the most important concepts for applying ALARP in assessing risks [11]. The ALARP principle is used to assess the mitigation measures for the lightning related risks identified and quantified with the SRA-method. In this way informed risk management decisions can be made for lightning protection of munition storage structures.

2.2 NEN-EN-IEC 62305

The lightning protection standard NEN-EN-IEC 62305 provides a comprehensive overview of all aspects related to lightning protection, risk analysis and installation aspects, for many types of structures and installations. For structures containing explosives, the 62305 leaves some important considerations and decisions up to the user, as the standard indicates that this requires specialist judgement and additional detailed analyses may be required.

For the SRA-method, the 62305, in particular Parts 2 and 3 [6,7], forms the basis of the risk analysis method. The SRA-method largely follows the risk management principles established in Part 2. The 62305 also provides the default input for many of the parameters required in the quantification of the risks. On several aspects, which are discussed in the current work, the SRA-method provides additional analyses as required by the 62305 for structures containing explosives. In essence, the SRA-method is a tailor-made, extended version of the 62305 Part 2 on risk management dedicated to munition storage structures.

2.3 NATO Guidelines

The NATO publication AASTP-1 gives guidelines on the safe storage of munitions by armed forces [12]. Furthermore, the AASTP-1 provides guidance on the design of munition storage structures, including lightning protection. Section IV of Part II gives some general considerations and advice. AASTP-1 states that all storage structures and workshops for munitions should be provided with lightning protection and LPL (lightning protection level) 2 or better should be achieved by the LPS, unless a detailed analysis has shown that a lesser (or no) LPL suffices. However, the information provided is insufficient for a detailed risk analysis. In essence, AASTP-1 provides nations with a minimum guideline and recommended LPL for the LPS of storage structures. Yet, it leaves the decisions on the exact LPS requirements and installation details up to national competent authority and/or involved experts.

3 Risk from lightning flash strikes

Lightning flashes affecting a (storage) structure are divided into flashes terminating on the structure (S1), near the structure (S2), on an incoming line (S3) and near an incoming line (S4). For each identified route, various types of damage can occur. The munition susceptibility to electromagnetic fields is vital in determining the risks for route S1. For each combination of a route (S*x*) and type of damage (D*x*), different types of loss can occur. In the end, the total risk is split into risk components ($R_{x,i}$) for each unique combination of lightning strike route, damage and loss type.

3.1 Types of damage

Due to a lightning strike three types of damage can occur: injury to living beings by electric shock (D1), physical damage (D2), failure of electrical and electronic systems (D3), see Table 1. For the SRA-method, only two combinations of strike routes, and types of damage and loss are relevant, see the highlighted cells in Table 1. D1 type damage (electric shock) is not considered here, as it does affect the munition inside the storage structure. The reason for D3 being irrelevant is addressed in section 4.4.

3.2 Type of loss

The 62305 distinguishes four types of loss, L1 – L4, namely loss of: human life (L1), service to public (L2), cultural heritage (L3), and economic value (L4). For munition storage structures, not all types of loss are relevant. Only the loss of human life (L1) and economic value (L4) are considered in the developed SRA-method. So, the SRA-method determines the risks to human life (R1) and loss of assets (R4).

For the loss of human life, the SRA-method specifically addresses the risk to people present in, or in the close vicinity of a munition storage structure. The risk to third parties is not part of the SRA-method, as that is covered in other national regulations. For the loss of assets, a relative assessment is made of the loss of the stored munitions and the storage structure itself, in case of an accident. This assessment does depend on hazard division of the stored munitions, where lower hazard divisions (HD), e.g. HD 1.4, lead to less potential (relative) loss.

Table 1 Risk components for different types of damage and lightning flash routes. Highlighted yellow cells are considered relevant to munition storage structures.

	Lightning flash route			
Type of damage	S1 Flash to structure	S2 flash near structure	S3 Flash to incoming line	S4 Flash near incoming line
D1 Injury to living beings by electric shock	R_A	-	R_U	-
D2 Physical damage	R_B	-	R_V	-
D3 Failure of electrical and electronic systems	R_C	R_M	R_W	R_Z

R_A = Risk component (Injury to living beings – flashes to a structure)
R_B = Risk component (physical damage to a structure – flashes to a structure)
R_C = Risk component (failure of internal systems – flashes to structure)
R_M = Risk component (failure of internal systems – flashes near structure)
R_U = Risk component (injury to living beings – flashes to connected line)
R_V = Risk component (physical damage to a structure – flashes to connected line)
R_W = Risk component (failure of internal systems – flashes to connected line)
R_Z = Risk component (failure of internal systems – flashes near connected line)

3.3 Munition sensitiveness to electromagnetic fields

When a lightning strike hits a munition storage structure, i.e. route S1, this induces electromagnetic fields (EM-fields) inside the structure [13]. This is especially relevant for munitions susceptible to electromagnetic pulses, and munitions containing electro explosive devices (EED). From the perspective of the munition item and its initiator, there are three potential coupling routes, which could lead to inadvertent ignition of the munition item [9]:

- Direct flashover, i.e an direct transfer of an electrical charge from the structure through the air to the munition. A necessary condition for direct flashover is that the electrical breakdown voltage of air is exceeded;
- Coupling of the electromagnetic energy to the munition packaging and casing due to current distribution created in metallic components (e.g. rebar) of the magazine via inductive or capacity coupling, which heats up the packing and casing itself;
- Coupling of an EM-field that radiates from current flowing in the magazine into an EED, which is assumed to be an antenna susceptible to both the electric and magnetic fields.

It is important to consider the shielding effect of the packaging and/or metallic casing of the munition. These aid to shield the EM-fields and reduce the effective EM-fields a munition and its EED are exposed to. TNO has developed a dedicated method to assess the susceptibility of munitions to EM-fields, including shielding effects [9]. This will not be further discussed in the current work.

3.4 Risks and their components

The SRA-method proposed here considers two types of risk, namely the risk of loss of human life (R1) and the loss of assets (R4). Each risk type is split up into various risk components. Each risk component R_x is expressed by the general equation:

$$R_x = N_x \cdot P_x \cdot L_x \quad (1)$$

Here N_x is the number of annual dangerous events, P_x is the probability of damage occurring causing loss and L_x is the (relative) loss. Table 1 shows which risk components apply to the combinations of strike routes and damage types. The total risk to human life R1 is:

$$\mathrm{R1} = \mathrm{R}_{B,1} + \mathrm{R}_{C,1} + \mathrm{R}_{\mathrm{M},1} + \mathrm{R}_{\mathrm{V},1} + \mathrm{R}_{\mathrm{W},1} + \mathrm{R}_{\mathrm{Z},1} \quad (2)$$

For the risk of loss of assets, a matrix is used to assess the semi-quantitative level of risk for each applicable combination of strike route and damage type, see section 4.5.2. This matrix uses the expected annual frequency of damage due to lightning flashes f_X and the relative amount of loss of assets $L_{X,4}$, see Table 4.

For each risk component, the SRA-method and 62305 provide the required input parameters to determine the total level of risk.

4 Safety risk assessment method

To calculate the total risk R1 and risk matrix for R4, many parameters and factors have to be determined either by using the 62305, or by additional expert analyses. As stated earlier, the SRA-method largely follows the risk analysis method set out in the 62305 Part 2. So most default values for parameters will be obtained from the 62305. However, some do require additional attention, like the lightning strike density, probability of accidental ignition due to a lightning strike and the probability of damage occurring. Also to assess the loss of assets, a dedicated matrix is used, instead of the method proposed in the 62305 Part 2. Below, an overview is given of the most important parameters, and how they can be determined. Also the risk assessment itself is discussed.

4.1 Number of lightning strikes

The average annual number of dangerous events N_x due to lightning flashes depends on the thunderstorm activity of the region where a structure is located and on the structure's physical characteristics. The lightning strike ground density N_G is the number of strikes to ground per km^2 per year. For the design of an LPS this is often based on long term weather observations of the region and includes a safety margin [14, 15]. In the Netherlands, a national guideline states that $N_G = 2.5/\text{km}^2/\text{yr}$ should be used [16]. The total annual number of flashes to consider also depends on the collection area and other (environmental) factors. For each strike route (S1 – S4), the 62305 gives the equations needed, the general form is:

$$N_x = N_G \cdot A_x \cdot C_i \quad (3)$$

Here N_x is the annual number of dangerous events for the strike route considered (S1 – S4), A_x is the relevant collection area and C_i represents one or multiple constants accounting for the environment type, line type etc.

An example of the collection area for a strike to structure A_D is given in Figure 1. Careful consideration should be given to the collection areas, as the default eqns. presented in the 62305 may be (over)conservative. The standard itself already indicates options to determine the collection areas more accurately. Also, currently any overlap of the collection areas of multiple structures (and lines) is not considered.

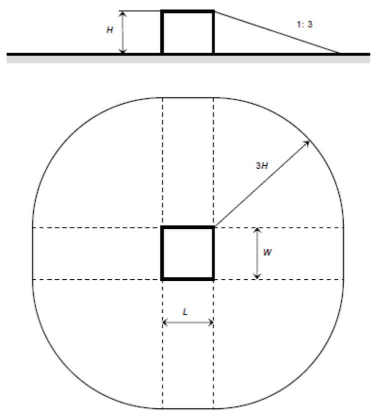

Figure 1 Collection area to structure A_D of an isolated structure [6].

4.2 *Probability of accidental ignition*

For a lightning strike impacting a storage structure (S1), extra consideration must be made for the lightning induced EM-fields. For the other strike routes (S2 – S4), the probability of accidental ignition is taken equal to the probability of failure of the LPS itself. The maximum probability of accidental ignition due to the lightning induced EM-fields, R_i^*, is assessed either:

A. Qualitatively: With expert judgement, classifying the susceptibility of a particular munition/fuse/EED, and comparing that to the qualitative estimate of the lightning induced EM-fields inside the storage structure. The maximum value of R_i for the three coupling routes, see section 3.3, should be used. Or;
B. Quantitatively: Calculating the actual lightning induced EM-fields, including the (packaging) shielding effects, the munition/fuse/EED is exposed to, and comparing that to the ignition thresholds of the particular fuse/EED for each of the three coupling routes. Again, the maximum value of R_i of those three should be used.

In the qualitative assessment, a simple severity matrix can be used, as shown in Table 2, to determine R_i^*. This should be done for each coupling route. For the quantitative assessment, use is made of the Digital Twin models to calculate the EM-fields inside the storage structure. With use of the newly developed munition sensitivity models, R_i^* can be calculated for all three coupling routes [9].

The maximum value of R_i for each of the coupling routes is the value to be used for R_i^*. This ensures a safe estimate of the risks. Next, for both the qualitative and quantitative assessments, it is assumed that if direct flashover can occur, ignition is to be expected for the stored munitions, hence $R_i = 1$, thus $R_i^* = 1$.

Table 2 Qualitative assessment of probability of ignition due to lightning induced EM-fields.

		Lightning induced energy level at munition/fuse/EED			
		High	*Medium*	*Low*	*No / very low*
Munition sensitiveness to EM-fields	*No / very low*			***R_i = 0.001***	
	Low				
	Medium		***R_i = 0.5***		
	High	***R_i = 1***			

4.3 *Probability of damage*

Based on 62305, the probability of failure for the LPS is obtained for each flash route S1 – S4. For route S1, the total probability of physical damage P_B^* is adjusted to consider the lightning induced EM-fields:

$$P_B{}^* = P_B \cdot r_{f,P} + (1 - P_B) \cdot R_i{}^* \cdot r_{f,i} \tag{4}$$

Here P_B is the probability that a flash to structure will cause physical damage, which depends on the LPL. Next, $r_{f,P}$ (applicable to the failure of the LPS) and $r_{f,i}$ (applicable to the EM-fields induced potential ignition) are two loss reducing factors depending on the risk of fire or on the risk of explosion of the structure. The values for P_B, $r_{f,P}$ and $r_{f,i}$ are based on the 62305 Part 2.

For route S3, the probability that a flash to a line will cause physical damage, P_V, is used as the probability of damage in the SRA. The value of P_V is determined based on the 62305. Routes S2 and S4 are not considered, see section 3.1.

4.4 *Loss factors*

Based on 62305, for each risk component R_X several loss (reducing) factors L_X are determined, in order to assess the potential loss in case of ignition of munition. There are notable differences between the loss factors applicable to R1 and R4.

4.4.1 Loss of human life

For R1, the loss factors take into account the time t_Z (in hours) that people are present in a munition storage structure. For the SRA, it is assumed one person is present in a storage structure 8 hours per day, 5 days per week, i.e. 2,086 hours annually. Also, an important loss factor is $L_{F,1}$. This determines the relative amount of loss of life, i.e. the probability of lethality λ, and can be varied depending on the hazard (sub)division of munition stored. λ applies only to people inside the storage structure or in the close vicinity of the structure. It must be noted the 62305 maximum value of $L_{F,1}$ for a structure with a risk of explosion is 0.1, which may be unconservative. The total loss factor for $R_{B,1}$ and $R_{V,1}$ is a multiplication of all relevant loss (reducing) factors:

$$L_{B,1} = L_{V,1} = r_p \cdot r_f \cdot h_z \cdot L_{F,1} \cdot n_i \frac{t_z}{8760} \tag{5}$$

Here:

- r_p is the loss reducing factor due to physical damage depending on the provisions taken to reduce the consequences of fire;
- r_f is the loss reducing factor due to physical damage depending on the risk of fire or on the risk of explosion of the structure;
- h_z is a factor increasing the loss due to physical damage when a special hazard is present. For munition storage a default value of h_z = 1 applies;
- n_i is the number of persons in the structure;
- A year is equal to 8760 hours (24*365);
- Subscript *1* refers to the loss of human life.

For D3, the loss factor L_O is set to zero, meaning that the resulting risk components R_X also become zero. Analyses have shown that D3 is not considered relevant for the ignition of munitions, and therefore not to loss of life. It must be stated that failure of electric systems, e.g. security or humidity control, may still be expected. Yet, that is considered out of scope for the SRA-method, which focuses only on the lightning induced accidental ignition of munitions. This is on the precondition that proper surge protection has been provided on all incoming lines and electric systems.

4.4.2 Loss of assets

For R4, effectively only one loss factor is used, namely the relative amount of loss $L_{F,4}$ (applicable to both S1 and S3), which depends on the hazard division of the stored munitions, varying between 1 for HD 1.1 and 0 for some HD 1.4 munitions, see Table 3. Here, subscript *4* refers to the loss of assets.

Table 3 Value for loss factor $L_{F,4}$ depending on the expected loss of assets.

Loss of assets	$L_{F,4}$
None	0
No / slight damage to contents and/or structure	0.1
Contents of one structure	0.5
One structure with contents	1

Again, the loss factor L_O is set to zero, thus the resulting risks for D3 are also zero. This means that $L_{F,4}$ is the only non-zero loss factor for R4.

4.5 Risk assessment and acceptance

Two different ways are used to assess the risk of loss of human life and assets. For the loss of human life, R1, this is done by comparing the total risk to a predefined threshold value for individual risk. For the loss of assets a semi-qualitative risk matrix is used, where the risk is assessed according to the ALARP principles.

The results for R1 and R4 can form the basis of risk acceptance for lightning protection of munition storage structures, and can help to communicate these risks to non-experts.

4.5.1 Risk of loss of human life

The total risk of loss of human life is the sum of all relevant risk components as given in eqn. (2). Now that L_O = 0, and using eqns. (4-5) this reduces to:

$$R1 = \left(N_D \cdot P_B{}^* \cdot L_{B,1}\right) + \left(\left(N_L + N_{DJ}\right) \cdot P_V \cdot L_{V,1}\right) \tag{6}$$

Here N_D is the annual number of flashes to structure, P_V is the total probability that a flash to line will cause physical damage, and N_{DJ} is the number of flashes on a connected structure. Normally, N_{DJ} may be assumed to be equal to N_D, as the main power lines (and other lines) will run from magazine to magazine. The 62305 recommends a threshold value for R1, such that:

$$\mathrm{R1} \leq 1 \cdot 10^{-5} \text{ per year} \quad (7)$$

If warranted, for example by national laws and regulations, this threshold value can be adjusted.

4.5.2 Risk of loss of assets

For the loss of assets, for each combination of strike route (S1 – S4) and damage type (D2 and D3), a risk matrix is used to determine the resulting qualitative level of risk, see Table 4. The risk matrix uses ALARP principles, with four risk levels, from low to high, to assess the risks and serve as a basis for risk acceptance.

For both strike route S1 and S3, f_x (the expected annual frequency of dangerous events) is determined, using eqn. (4) for S1:

$$f_x(S1) = N_D \cdot P_B{}^{*} \quad (8)$$

And for S3:

$$f_x(S3) = (N_L + N_{DJ}) \cdot P_V \quad (9)$$

Again, normally N_{DJ} may be assumed to be equal to N_D.

When very high, high or medium risks for R4 are found, risk mitigation is recommended to prevent potentially unnecessary loss of assets, according to ALARP principles. By re-calculating the level of risk when including particular mitigation measure(s), one can determine which measures are the most effective ones. Hence, the SRA also provides a tool to judge the effectiveness of measures, and aid in the decision making process.

Table 4 Semi-qualitative risk assessment matrix for R4.

Loss factor depending on the expected loss of assets, $L_{F,4}$ [-]	Expected annual frequency of dangerous events, f_x [-/yr]: $f_x < 10^{-7}$	$10^{-7} \leq f_x < 10^{-5}$	$10^{-5} \leq f_x < 10^{-4}$	$10^{-4} \leq f_x < 10^{-3}$	$10^{-3} \leq f_x < 10^{-2}$	$f_x > 10^{-2}$
$L_{F,4} = 0$					Low risk	
$L_{F,4} = 0.1$		Low risk		Medium risk (ALARP)	High risk (ALARP)	
$L_{F,4} = 0.5$			Medium risk (ALARP)	High risk (ALARP)		
$L_{F,4} = 1$		Medium risk (ALARP)	High risk (ALARP)			Very high risk

5 Conclusion

A safety risk analysis (SRA) method has been developed that allows to assess the risks of lightning strikes on and/or nearby munition storage structures. In essence, the developed SRA-method based on the international standard NEN-EN-IEC 62305 and is tailor-made for munition storage structures. Such an analysis tool was previously not available. The SRA assesses the risks for loss of human life (individual risk) and loss of assets, i.e. munitions and structures. The probability of an accidental ignition of a munition due to the effects of a lightning strike can be addressed in both a quantitative and qualitative way.

The SRA-method is focused on regular munition storage structures. No considerations have been made yet for e.g. explosives workshops, field storage or (explosive) parking areas.

The risk assessment allows to identify risk mitigation measures for the entire lightning protection system of a structure, which aids to make informed risk decisions. Also the results of the SRA, namely the risk matrix for loss of assets and individual risk level, allow to communicate these risks to stakeholders, users and non-experts.

CRediT authorship contribution statement

H. Dijkers: Conceptualization, Investigation, Methodology, Software, Visualization, Writing – Original Draft. **J. van Middelaar:** Conceptualization, Investigation, Methodology, Resources, Software. **D. van der Pol:** Software, Validation, Writing – Review & Editing. **R. Bouma:** Validation, Writing - Review & Editing. **F.P.**

Weterings: Supervision, Project administration, Funding acquisition.

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