Developments towards the munition storage depot of the future

Y.J.M.A. Verberne, S. Schouwenaars, D.G.M. van der Pol, H.P.A. Dijkers, M.M. van der Voort
TNO Defense, Safety and Security

Abstract

TNO is supporting the Dutch Ministry of Defense (MoD) in the development of future munition storage depots. Munition storage is highly relevant today given the growing need for storage capacity and associated spatial planning issues. This paper explores new storage concepts and their integration within current and future munition depots. Preliminary results and a vision for future work are shared with the aim of gathering feedback from the international community. By exploring novel magazines in terms of both geometry and material, the safety performance of munition magazines can be improved compared to state-of-the-art earth-covered magazines (ECMs), with the goal of reduced safety distances and/or increased storage capacity. The challenge is addressed from two perspectives: i) mitigating outgoing explosion effects and ii) increasing resistance against incoming explosion effects. This effort has led to four promising new magazine designs, e.g. a sunken street with neighboring storage cells and an underground magazine that is (un)loaded with a crane from the top. An important part of the current work is to better quantify the envisioned reduction in blast effects from these design concepts. In addition, we discuss the integration of the new magazines on different storage depots by defining (future) requirements together with military stakeholders, including amongst others operational commanders, real estate managers, and munition safety personnel. Key Performance Indicators (KPIs) are identified, such as the storage density, costs, logistical aspects and energy security, which can help determine the optimal layout of the depot.

Introduction

Munition safety, explosives safety, and safe handling of munitions are being scrutinized. At the same time, recent developments have put a renewed focus on the first core task of the armed forces, namely the protection and defense of our and ally territory in the event of armed conflict. This leads to the need for larger munition stockpiles, making munition storage capacity an increasingly relevant topic. This is especially of interest in the Netherlands, given the associated spatial planning issues to find the required space [1]. The spatial footprint of a munition storage site is largely defined by the physical area occupied by the site itself and the required external safety zones surrounding the site. The internal layout of the site is shaped by the size and orientation of the magazines and the required spacing between them, known as the Inter-Magazine Distance (IMD). NATO AASTP-1 [2] defines IMD as the minimum permissible separation distances between PES and storage sites containing munitions or explosives, intended to provide specified degrees of protection to the munitions and explosives at the ES.

In general, IMDs ensure that the prompt propagation of explosions between Potential Explosion Sites (PES) and Exposed Sites (ES) have a sufficiently small probability of occurrence. As a result, the observed explosion effects cannot be larger than the effects of any single magazine. In addition to IMD, various types of external safety zones, such as the Inhabited Building Distance (IBD) and the Vulnerable Building Distance (VBD), are specified by NATO AASTP-1 and adapted in national regulations. For conventional magazine types, these prescribed distances are calculated on the basis of magazine type and the Net Explosive Quantity (NEQ). These distances are effect-based, meaning that they correspond to expected levels of explosion effects in those ranges. Figure 1 schematically depicts the IMD, IBD and VBD of a munition storage depot.

By innovating magazine designs compared to state-of-the-art Earth-covered magazines (ECM) (for example, those included in the Whole Building Design Guide (WBDG) [3] [4]), the magnitude of outgoing explosion effects (e.g., blast, debris) and resistance of the structure to incoming explosion effects can potentially be improved. This would directly impact the required internal and external safety distances, and eventually the spatial footprint of the storage site. Four concepts are put forward in the first section, which aim to achieve this. However, before realizing new magazine types and including them in explosives safety guidelines, more research is required to quantify the expected effects and performance. This will be the focus of the second section where modeling approaches are discussed to quantify the performance of new magazine designs, with a focus on external blast effects. In the remainder of this paper (third section), we shift to the integration of the novel magazine designs on munition storage depot as a whole. Different types of depots (e.g. stockpiles, rapidly deployable capacity) are explored to assess which storage configurations are best suited to site-specific requirements. Key considerations include e.g. logistical flow and total stored quantity, all of which play a critical role in determining the optimal layout of a storage site. To support this evaluation, a set of Key Performance Indicators (KPIs) is introduced that can be used to assess the various aspects of depot performance. Finally, we present a preliminary optimization strategy for siting storage depots based on some of these KPIs.

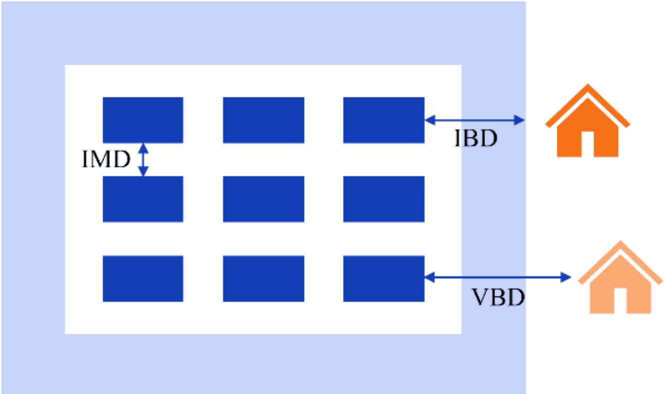

Figure 1: Schematic of the safety distances related to a munition storage depot.

Novel magazine designs

Four novel magazine designs are proposed with safety requirements as a primary concern [5]. In particular, designs seek to decrease both the interior and exterior quantity distances, since the spatial footprint is a particularly serious problem in the Netherlands. To achieve this, we formulate a two-fold safety requirement as follows: magazine design should i) mitigate outgoing explosion effects in case of an internal explosion (i.e. PES performance), and ii) enhance resistance to explosion effects generated by an explosion in a nearby magazine (i.e. ES performance).

Munition magazines can be innovated in terms of *geometry* and *material usage*, and by following clear design strategies. Design strategies provide practical ways to meet the two-fold safety requirement. For instance, certain geometries can be applied to redirect outgoing blast effects in case of an inside explosion. By applying directionality to the outgoing blast, its effect can be mitigated at short distances. Alternatively, emphasis can be placed on building materials that directly control the debris properties when the magazine acts as a PES. In what follows, we present four concepts for the munition magazine of the future, each of which combine geometry and materials in a way that is novel compared to regular ECMs.

Design 1: Stabilized earth magazine

The first design concept, illustrated in Figure 2, distinguishes itself from a conventional ECM by using packs of reinforced soil as a building component. By using mechanically stabilized earth as a structural element, the amount of concrete required for the inner structure can be significantly reduced. Note that the inner structure is always necessary to enable facilitation of environmental regulation, e.g. temperature and moisture management. Stabilized earth enables structural applications and is already used in contexts such as bridge reinforcement [6], wind turbine foundations, and military-grade HESCO bastions [7]. This approach also allows the earth cover to extend partially over the front wall of the magazine. To support the additional earth load, the design incorporates an arch-shaped roof, which enhances the roof's load-bearing capacity and enables more earth to be added on top. The idea to use extra earth cover is also explored by Singapore by the heavy earth-covered magazine (HECM) [8]. It should be noted however that this design employs rectangular boxes, rather than arched roofs.

Expected resistance (ES performance)

The added mass and earth cover make the magazine better equipped to resist external blast loads, and impact of fragments and debris. This is also the motivation behind current ECM designs, but more mass further enhances this resistance. Besides, the extended earth cover at the front protects the most vulnerable area of the magazine better. The arch-shaped roof helps to support outside loads as this geometry creates a more equal load and stress distribution throughout the structure. This makes supporting columns inside redundant, which increases storage capacity. Moreover, the lighter (concrete) inner structure can prevent the issue of heavy spall hitting the munition, which can be a sympathetic detonation mechanism according to NATO AASTP-1.

Expected effects (PES performance)

In general, a lightweight inner structure reduces the throw of hazardous debris in the event of an internal magazine explosion [9]. As an alternative to concrete, lightweight materials such as Fiber Reinforced Polymers (FRP) can also be explored. In this case, most of the debris mass ejected in case of an internal explosion consists of earth that tears out of the textile fabrics. As a result, the magazine made of earth generates a lot of nonhazardous debris that is less likely to result in injury or severe damage to neighboring constructions compared to concrete debris. Lighter and smaller debris tend to have a shorter throw distance and a lower impact force upon contact. The increased amount of earth cover, and inherently increased mass of the overall structure, is enabled by the arch-shaped roof of the inner structure. With the addition of extra mass, more of the explosion's energy is absorbed by the earth and used to move it, leaving less energy to be released as air blast. As a result, the overall blast effects are reduced. In the near-field, directional effects due to the magazine structure are also foreseen, for example higher peak overpressure from the front compared to the side or rear. In the far field, blast waves tend to restore and lose this directionality. The overall energy is however still expected to be decreased due to the energy absorption.

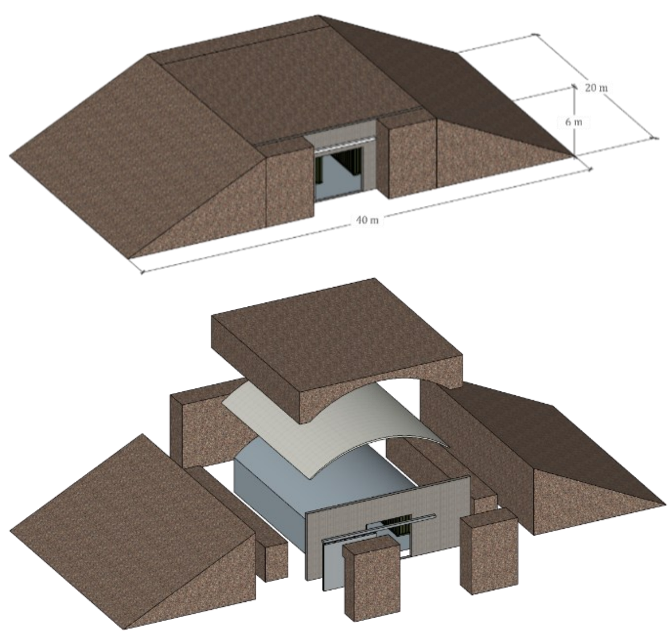

Figure 2: Impression of the stabilized earth magazine (top) and exploded view drawing (bottom). Dimensions are indicative.

Design 2: Multi-layered magazine

The design illustrated in Figure 3 primarily focuses on innovative material usage. The magazine walls are composed of sandwich-layered materials, which combine inherent advantages of individual materials to arrive at enhanced overall characteristics. The proposed concept walls consist of concrete, polyurethane (PU), a graded density core, and a fiber-reinforced plastic (FRP) face sheets. The layers are implemented in an arch-shaped configuration. A barred protective fence is an optional addition to this magazine design.

Expected resistance (ES performance)

The structural concrete is covered by multiple layers. On the outside, the FRP face sheet increases strength and distributes incoming loads across the underlying layers [10]. Graded density cores can provide light-weight blast absorption [11], while the PU layer adds ductility to the overall system and may prevent spalling [12]. An earth cover offers additional shielding from external loads. The arch-shaped geometry contributes to efficient load distribution across the structure. Furthermore, the optional barred protective fence is positioned at the door, a known weak spot in many magazine designs, to diffract blast waves and reduce their energy. This effect has been proven for smaller blasts [13], but additional investigation for this application is required.

Expected effects (PES performance)

By combining material effectively, the overall weight of the magazine structure can be reduced. Significantly less concrete is implemented compared to a solely concrete magazine due to the surrounding layers, which in turn reduces the potential amount of hazardous debris. The PU layer and earth cover also help capture and contain debris, contributing to improved safety in case of an internal magazine blast.

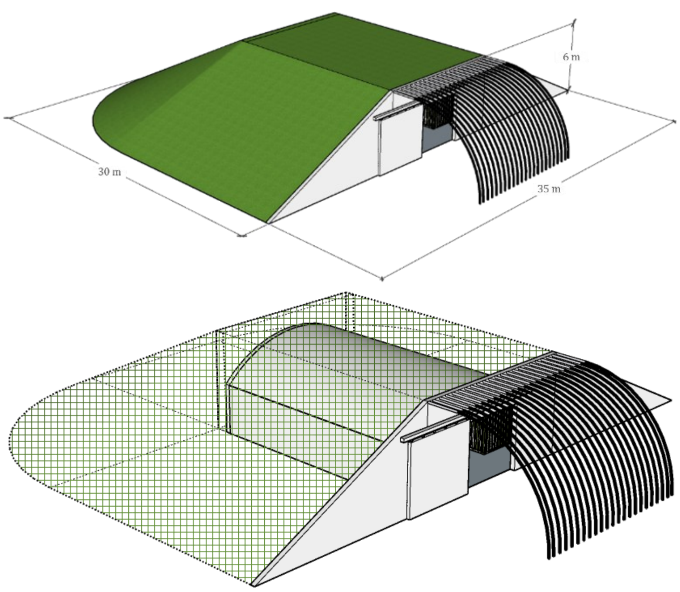

Figure 3: Impression of the multi-layered magazine including roof material specifications (bottom). Dimensions are indicative.

Design 3: Underground storage

The third design introduces an underground storage, see Figure 4. The magazine has a top entrance, impacting logistics and making this concept highly suitable for automation. The roof slides open, after which containers be loaded and stacked using automated crane equipment. Surface area for (human) interventions inside the magazine is no longer required, enabling efficient storage. Potential risks introduced throughout automatic (un)loading, such as munition falling from a height, need to be considered. Furthermore, the storage of munition within containers allows for multiple storage strategies, such as storage per munition article type or a combined storage tailored for specific deployments. The latter is often referred to as rapidly deployable capacity containers. As the magazine is underground, water management strategies are essential elements to explore further.

Expected resistance (ES performance)

The walls of the magazine are completely surrounded by earth, making use of its protective properties. By simplification, the walls are of "infinite thickness", effectively protecting the sides against blast energy and debris. However, it is important that the walls can withstand external forces such as the weight of the surrounding earth and potential ground shock. Mechanically stabilized earth can be implemented as a structural solution to resist these loads effectively. The properties of the sliding roof can vary within this design and are not defined in this concept. This structure should be resistant to the effects of an incoming explosion. For example, a steel roof can be employed.

Expected effects (PES performance)

In case of an internal explosion, the surrounding earth absorbs blast energy and (partially) captures outgoing debris. As the door is the weakest element within the design, the blast load will mainly be released through the top of the magazine. Compared to an ECM, both the blast load and debris is redirected in a favorable manner. The subsequent blast wave propagation and the impact of ground shock should be explored further.

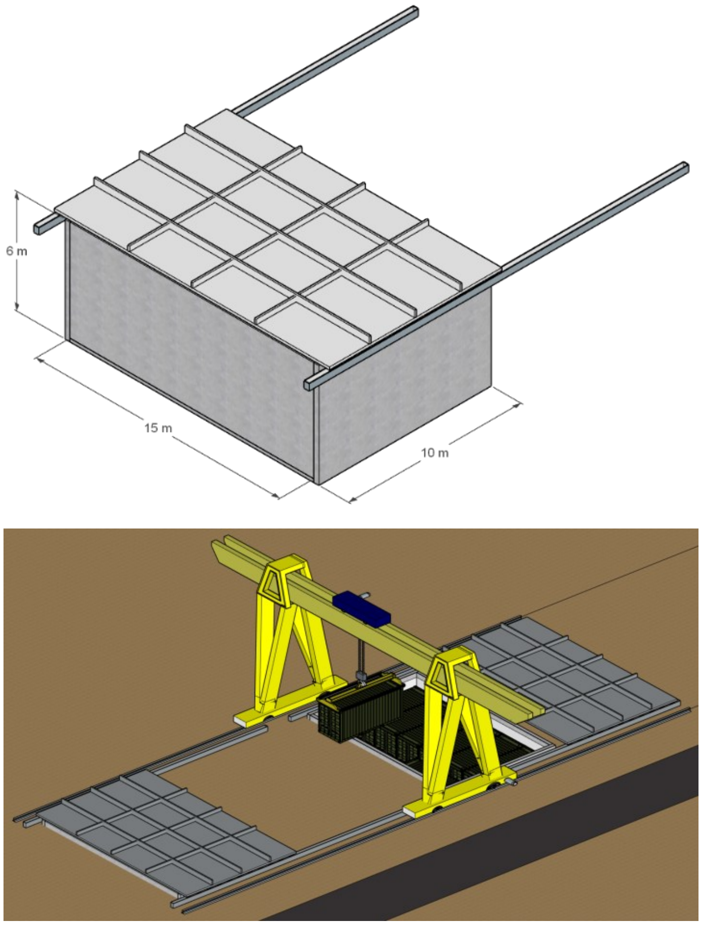

Figure 4: Impression of the underground storage with crane-entrance. Dimensions are indicative.

Design 4: Sunken street storage

The fourth design concept, illustrated in Figure 5, is another form of an underground storage. Here, accessibility of the magazines is enabled through a sunken street, where neighboring magazines can have their entrance on the same street. The materials used in the design can vary. Within this concept, a light reinforced concrete inner structure is suggested, along with a steel sliding door comparable to ECMs. In this example, another key feature is the integration of solar panels on the magazine roof, serving as a source of renewable energy (also see section 3 about KPIs). Safety with regards to the integration of solar (and wind) energy on munition storage depots is discussed in a separate report by TNO [14].

Expected resistance (ES performance)

The walls of the magazines are fully embedded in earth, utilizing its inherent protective properties to resist external forces (e.g. blast, fragment impact) from explosions in adjacent magazines. Note that ground shock is a point of attention for these designs. This is also reflected by AASTP-1, by prescribing larger IMD if magazines share an earth cover, just because of ground shock. To further enhance this resistance, stabilizing the earth walls with geotextiles may be beneficial. In general, ground shock effects should be examined in more detail when determining the appropriate spacing between the magazines.

Due to potential blast reflections and pressure buildup within the sunken street, the magazine door becomes the critical element for evaluating ES performance. A heavier door than typically used in ECM designs may therefore be considered. Favorably, the earth barricade in front of the door gives additional protection.

Expected effects (PES performance)

The specific geometry of a sunken-street design can positively influence the outgoing explosion effects. In such a scenario, the structure leverages controlled failure mechanisms: with earth walls approximating "infinite thickness", failure is most likely to occur at the roof or the door. This directionality in blast exiting could be beneficial in protecting neighboring magazines. Moreover, the sunken street itself acts as a natural barricade, capable of intercepting debris or a dislodged door ejected from the front of the magazine. Additionally, the excavated soil from the street can be repurposed to increase the height of this barricade, further enhancing its protective function. However, the sunken street can also lead to significant blast reflection and impulses can get high. Careful consideration of the street width and distance between magazines is therefore crucial.

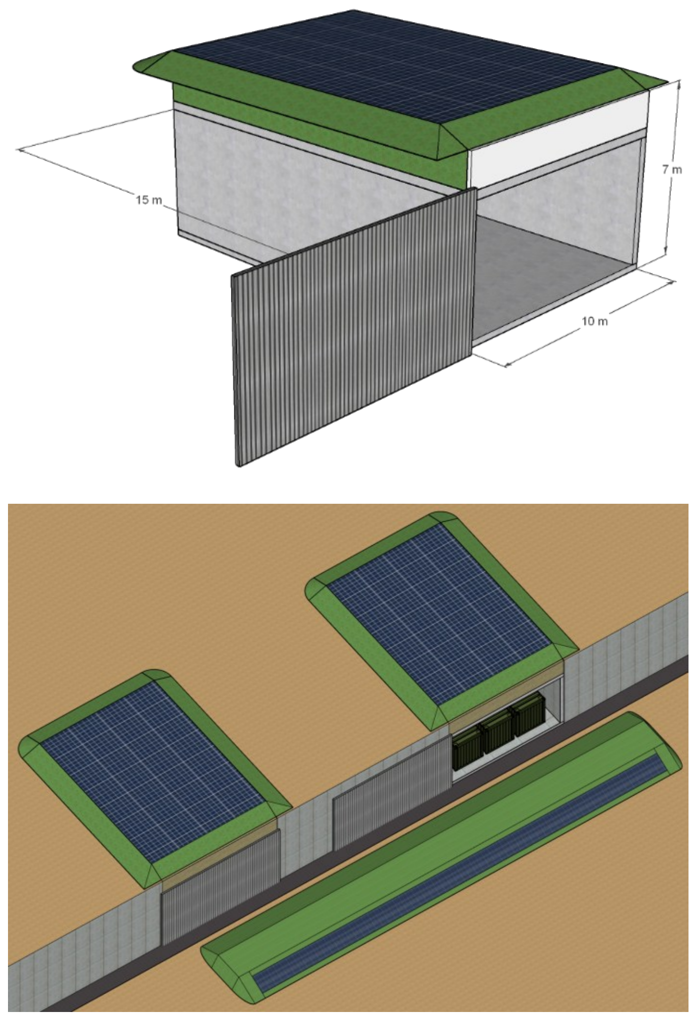

Figure 5: Impression of the underground storage with sunken-street access. Dimensions are indicative.

Modelling approach

The presented magazine designs aim to minimize interior and exterior safety distances. However, their effectiveness in achieving this objective has yet to be assessed in more detail. Performance evaluation encompasses several criteria, such as the intensity of outgoing air blast and projected debris from the PES, and structural resilience against incoming explosion effects at the ES. The current phase of research, however, focuses on predicting the outgoing blast effects of new PES structures using computational fluid dynamics (CFD) tools such as Viper::Blast [15]. Additional analyses, including (scaled) tests and other simulation efforts, are part of ongoing efforts to fully quantify the expected performance of the proposed magazine designs.

Methodology

To assess the outgoing blast effects, CFD simulations will be conducted. A stepwise methodology is introduced to enable intermediate verification of the results and gain confidence in the approach. This methodology is initially performed on conventional ECMs as experimental data is available for validation. An example is the magazine type which was recently subject of the CUIRA test series [16]. The simulation workflow is illustrated in Figure 6.

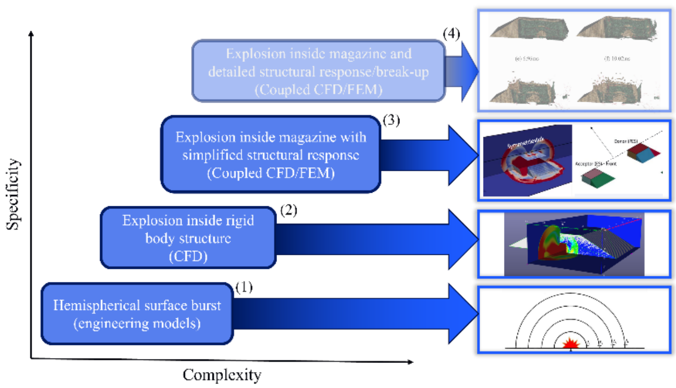

Figure 6: Schematic of the modelling methodology.

Initially, free-field simulations are performed (step 1) to benchmark the CFD-model with existing empirical relations, such as included in the Blast Effects Computer (BEC) [17]. Once confidence is established in the accuracy and reliability of the simulation output, the magazine geometry is introduced. It is chosen to initially model the magazine as a rigid body (step 2), excluding material response effects. The simulations results are compared with experimental data in which structural breakup does not play a significant role in the absorption of explosion energy. For relatively low loading densities (NEQ/m^3), this assumption is deemed valid. Once this step is completed with sufficient accuracy, the structural response of the magazine is addressed, and larger stored quantities can be evaluated (step 3). Several approaches are explored in simulation, including: assigning void times to individual components such as a magazine door or roof (i.e. the time after which structural components are instantly removed from the simulation to emulate failure), estimating quasi-static pressure (QSP) build-up, specifying component masses to account for inertial effects, or integrating complete material strength curves to simulate realistic mechanical response, i.e., using FEM models. The aim is to progressively build up to simulations that have the right balance between complexity and accuracy, e.g. which are able to reproduce blast measurements up to a sufficient level. Note that the end goal is to quantify blast effects up to a point where these can inform safety distances. Since these safety distances are preferably applicable to a broader category of magazines, attention must be given to the risk of over-specifying these cases.

At this stage of research, the modeling strategy is applied to the ECM design from the CUIRA tests [16]. This magazine type is chosen because of its availability of experimental data for comparative analysis. This enables us to identify ways to account for the structural response in simulation, such that the empirical data can be reproduced. A similar approach is planned for the newly proposed magazine designs in subsequent phases. In these simulations, the concepts are modelled in generalized form, without getting lost into details. This is also illustrated in Figure 7.

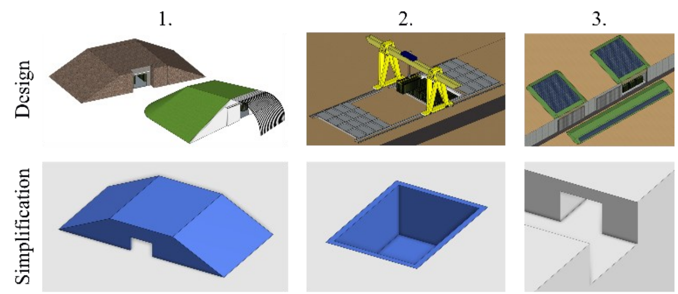

Figure 7: Magazine design simplification for CFD analysis.

Expected effects

The CFD simulations typically output the blast effects of an explosion, e.g. peak overpressure and impulse, around the PES at predefined gauge locations. It is desired to compare data of this kind between the different magazine concepts to evaluate their performance. For currently known magazine types, the expected effects can be conveniently represented in graphs, where side-on peak overpressure and scaled side-on impulse are plotted as a function of scaled distance (m/kg$^{1/3}$). For instance, AASTP-4 [18] includes such graphs that illustrate the effects of detonations inside various kinds of magazines, such as ECMs, hardened aircraft shelters (HAS), above-ground structures or ISO containers. The black, red and blue curves in Figure 8 depict the side-on peak overpressure from ECMs taken from AASTP-4. The curves show that at short scaled distances, ECM blast loads are greater in front of the magazine; however, as the distance grows, these loads become comparable to those expected at the sides. These data can be used to establish the IMD and IBD for each magazine side. In addition, these graphs can help determine the maximum NEQ or minimum separation based on permissible blast loads. The curves are typically derived from extensive sets of experimental data collected over the years.

Through the numerical simulation methodology, we intend to construct similar curves as the ones currently taken up in AASTP-4 for known magazine types. The yellow, orange and green curves in Figure 8 give example-effect curves for the new magazine designs proposed in this paper. Note that these curves are currently purely indicative as numerical work is still being carried out. As for ECM and HAS magazines, these curves would depend on direction, but also on design parameters such as internal dimensions, loading density and earth cover thickness. This would enable optimization of the magazine layout. Moreover, validation through (scaled) experiments will be important to validate the numerical simulations on which these curves will be based. This methodology is useful to gain first insight into the expected effects of novel magazine designs.

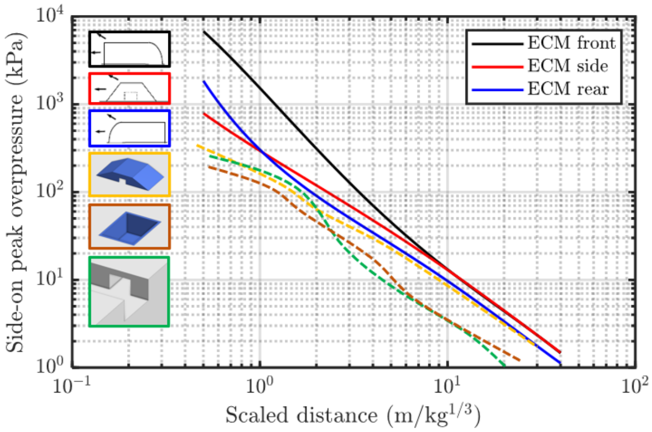

Figure 8: Example data analysis of CFD output for various magazine designs, including ECM [18].

Integration into future munition storage depots

Although the munition magazine is a critical component, it represents only part of a larger munition storage depot. These storage sites often serve multiple purposes beyond housing munitions, and various types of depots can be distinguished. For instance, there are large-scale depots intended for long-term national stockpiling, facilities designed for rapidly deployable capacity, storage integrated within naval or air bases, or those co-located with training grounds [19]. Each type of depot comes with its own set of requirements, ranging from terrain layout and total storage capacity to logistical processes. Additionally, munition magazines are often specifically tailored to suit the characteristics and operational needs of their respective locations. This section expands on KPIs and presents preliminary optimization strategies for future depots.

Key performance indicators

Key performance indicators (KPIs) aid in quantifying and differentiating the characteristics and operational needs of munition storage depots. Table 1 shows a list of possible KPIs and some corresponding quantities. Note this is a non-exhaustive list that is subject to change.

Table 1: Proposed munition storage depot KPIs.

KPI	**Description**	**Quantity (units)**
Safety distances	Interior and exterior safety distances determine the spatial footprint and magazine layout	IMD, IBD (m)
Storage capacity	The storage capacity per surface area is an indicator for storage efficiency	NEQ/surface area (kg/m^2)
Logistical performance	Storage depots can aim for various logistical performances, which can be magazine inherent	NEQ/day (kg/day) $t_{\text{magazine (un)loading}}$ (s)
Costs	Relevant costs for munition storage realization	EUR/USD
Energy security	Storage depots require large amounts of energy which can be supplied by its own generation (e.g. solar and wind power).	% of self sufficiency

The principal KPIs depend primarily on the type of munition storage depot and corresponding priorities, in combination with the available flexibility in parameters. The following list briefly links two types of munition storage depots to the KPI principles and proposed concept designs.

- *Stock piling:* the main purpose of these depots is to store large amounts of munition. The storage capacity ought to be as efficient as possible, aiming for a maximized NEQ per surface area. Different types of munition are often stored per article type, to avoid unfavorable safety distances due to aggregation rules for hazard- and storage sub-divisions as defined in AASTP-1 [2]. Therefore, the depots should remain easily accessible to collect the various types of munition for deployment. Both the arch-shaped earth- and multi-layered magazine (design 1 and 2) are suitable for this application. These magazines are spacious on the inside and enable frequent logistical flows through manual (un)loading.
- *Rapidly deployable capacity:* this type of depot aims to be prepared for quick deployment of munition. Storage and logistical processes ought to be optimized such that munition is readily available for specific needs, such as missions or trainings. Ideally, munition types are pre-assembled and combined in storage, potentially impacting the accompanied safety distances. The underground magazine (design 3) effectively mitigates these effects and enables storage of combined munition within containers, tailored for specific operational needs. This principle allows for rapidly deployable capacity containers, compiled per purpose. The containers are only accessible by automated equipment, but handles larger volumes per operation compared to a manual approach.

Munition storage depot optimization

The next step is to optimize for the best possible balance between the KPIs as introduced earlier. This is essential, as certain KPIs may conflict, for example, increasing storage capacity also increases the required safety distances. The optimization process will be subject to constraints such as operational requirements and local conditions. We discuss a first optimization method that considers spatial footprint (i.e. safety distances and magazine dimensions), storage capacity, and costs. In future work, this method can be expanded to include all KPIs.

As a starting point, let us assume we want to store a total quantity on a storage depot, say $Q_{\text{total}} = 10^6$ kg HD1.1 TNT equivalent. This quantity is stored in a group of N identical magazines of length l and width w. For now, we assume fixed magazine dimensions, though in reality, dimensions would vary with storage quantity. This issue will be addressed in future work. The quantity stored per magazine Q_{mag} is thus given by:

$$Q_{mag}(N) = \frac{Q_{\text{total}}}{N} \tag{1}$$

Subsequently, we attribute the IMD and IBD to each side (front, rear, side) of each magazine based on this quantity. NATO AASTP-1 can be used in case of regular 3-bar or 7-bar ECMs, but for the novel designs presented above, the expected effects and resistance should first be derived with simulation and testing (second section). In the current example we assume simplified QD equations based on cube-root scaling (i.e. Hopkinson-Cranz scaling [20] [21]) and a, minimum of 10 m is applied to enable access and roads. The safety distances for the front are given by:

$$IBD_{\text{front}}(Q_{mag}) = \max\left(10, \alpha Q_{mag}^{1/3}\right) \tag{2}$$

$$IMD_{\text{front}}(Q_{mag}) = \max\left(10, \beta Q_{mag}^{1/3}\right) \tag{3}$$

These are defined similar for the side and rear of the magazine. Note that directional effects to/from an ECM are specified in AASTP-1 Annex I-A Section I [2], for example that HD 1.1/1.3 from ECMs are considered to occur through the front in the area bounded by lines drawn at 150° to the front face of the PES from its front corners. Selecting the appropriate safety distance (in essence, filling out α, β) depends on the type of magazine and the available knowledge. In the current example arbitrary values of α *and* β have been chosen.

When more knowledge becomes available these equations may also be replaced by more complex ones. The question at hand now is: 'What is the optimum number of magazines for the given quantity of munition?".

First, we consider the KPI of spatial footprint of a storage depot. This may vary depending on whether large quantities per magazine are stored in few magazines (large safety distances), or small quantities per magazine are stored in many magazines. The latter increases the depot area, but individual magazines have shorter safety distances. The area required for the storage depot can be expressed as the sum of area taken up by the site itself, and the area covered by the external safety distances, i.e.:

$$A_{\text{total}}(N) = A_{\text{depot}} + A_{\text{zones}} \tag{4}$$

The magazines, with dimension length l and width w, are assumed to be positioned on a rectangular floor plan such that $N = N_l N_w$, where N_l and N_w are respectively the number of magazines in each column and row of the site. For now, we assume that the floorplan is as square as possible, i.e. $N_l \approx N_w$. The area covered by the depot itself is calculated by the magazine dimensions and required spacing between the magazines:

$$A_{\text{depot}}(N) = (N_l l + IMD_{\text{front-rear}}(N_l - 1)) \times (N_w w + IMD_{\text{side}}(N_w - 1)) \tag{5}$$

The area covered by the external safety distances A_{zones} is determined by dividing up the surrounding area in geometrical segments (rectangles, circle sections, etc.) and add those together, see Figure 9. For now, we assume the same directional boundaries as for an ECM from AASTP Annex I-A Section I and the same QD for the side and rear. This may be subject to change in future iterations. Together, this yields an expression for the total spatial footprint of the storage depot which depends on N.

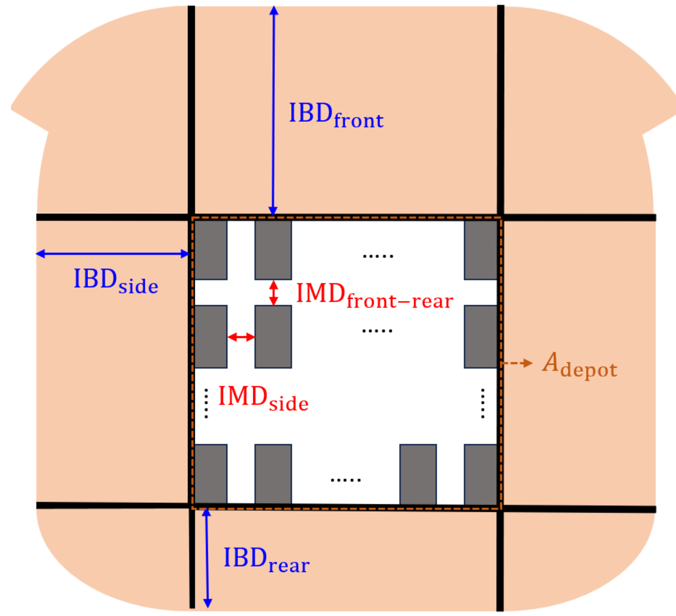

Figure 9: Visualizing the safety zones that determine the spatial footprint of the magazine.

Second, we bring in the KPI of costs to construct this depot. Let us assume that the total costs are determined by the (i) costs of construction per magazine C_{mag} and (ii) costs per square meter of land C_{m^2} . The total costs C_{total} is then written as:

$$C_{\text{total}}(N) = C_{mag} N + C_{m^2} A_{\text{total}}(N) \tag{6}$$

In the current example arbitrary values have been chosen for these constants. Important to note is that both KPIs can thus be expressed as functions of N that each have a (different) minimum, as is seen in Figure 10. The minimum land usage would be reached if the 10^6 kg HD1.1 is divided over 289 magazines (for example in a grid of 17 by 17 magazines), so that each magazine holds 3,460 kg HD1.1. The minimum cost would however be used if the 10^6 kg HD1.1 is divided over 36 magazines (for example in a grid of 6 by 6 magazines), so that each magazine holds 27,777 kg HD1.1.

As an alternative, an *optimum* number of magazines ($N_{\text{optimized}}$) can be determined by a balanced compromise. In this example, we define the optimized number of magazines as the number which minimizes the sum of both (min-max normalized) metrics:

$$\text{Metric}(N) = \frac{C_{\text{total}}(N) - \min(\text{C}_{\text{total}})}{\max(C_{\text{total}}) - \min(\text{C}_{\text{total}})} + \frac{A_{\text{total}}(N) - \min(\text{A}_{\text{total}})}{\max(A_{\text{total}}) - \min(\text{C}_{\text{total}})} \tag{7}$$

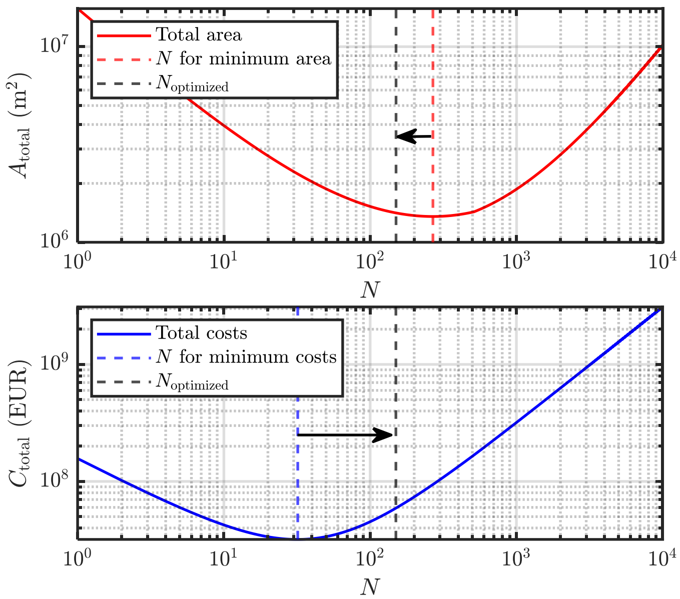

Figure 10: Total required area (top) and costs (bottom) for the storage depot as function of the number of magazines. Both graphs indicate the optimized number of magazines.

Above example demonstrates how to arrive at an optimal munition storage site based on limited user input, consisting of:

- Required storage capacity of the depot (HD1.1);
- Magazine type: construction cost, dimensions, associated safety distances;
- Cost per land area.

This returns an optimum number of magazines and associated floorplan. This tool is flexible in balancing between different KPIs and makes it easy, for instance, to see the impact of novel magazine designs. For example, an optimal storage site with 3-bar ECM's can be directly compared to the optimal site with underground storage. Eventually, the other KPIs should be included in the optimization as well to give a complete picture. For example, increasing the number of magazines may complicate logistics which is an aspect that is ideally taken into account as well. Finally, the starting point for optimization may be different. In some cases, it may be more insightful to start with a fixed spatial footprint and optimize for the maximum stored quantity.

Recommendations and future work

The presented results are part of an ongoing research. The performance of the proposed magazine designs has to be assessed in more detail. The modelling approach for outgoing blast effects will be applied to define safety distances. Additionally, it is recommended to quantify the debris throw effects and the resistance against incoming impacts. All contribute to the ability to compare the capabilities of the designs thoroughly and make well-considered choices for munition depot integration. Furthermore, the KPIs ought to be expanded in collaboration with the MoD. Their perspective is crucial in the development of a meaningful methodology and assessing the feasibility of various approaches. The munition storage depot optimization can be expanded accordingly. For example, including logistical performance and energy demands but also enhancing the level of detail.

Conclusions

This paper has presented an overview of research activities related to the development of future munition storage depots. Four innovative magazine concepts are proposed that challenge conventional ECM configurations. By controlling both the outgoing and resistance to incoming explosion effects through smart design, the safety performance can potentially be enhanced. These designs, such as sunken streets with adjacent cells and top-loaded underground magazines, offer promising strategies for reducing safety distances and thereby increasing storage density. To support the integration of these concepts into operational environments, a modeling approach has been outlined that can quantify the (mitigated) blast effects. This is where research efforts are currently concentrated. This paper also introduces a framework for depot-level evaluation using KPIs, enabling a structured comparison of different storage configurations, for example stockpiling and rapidly deployable capacity. These KPIs, covering aspects such as the spatial footprint cost, logistics and energy security, provide a foundation for evaluating and optimizing depot layouts. The optimization method can be explored in close collaboration with military stakeholders.

Ultimately, this work aims to stimulate international dialogue and feedback to guide future research and validation efforts. The insights shared here contribute to a broader understanding of how munition storage can evolve to meet emerging defense needs while adhering to stringent safety and planning requirements.

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Contact Information

Y.J.M.A (Yinte) Verberne - yinte.verberne@tno.nl

+31625378447

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