

Vulnerability Assessment of HAZMAT Storage Tanks to Shooting Attacks

Matteo Iaiani*, Alessandro Tugnoli, Valerio Cozzani

LISES – Department of Civil, Chemical, Environmental, and Materials Engineering, Alma Mater Studiorum – University of Bologna, via Terracini n.28, 40131 Bologna (Italy)
matteo.iaiani@unibo.it

There is historical evidence of chemical and process facilities being the target of shooting attacks. A fundamental step in security risk assessment is the analysis of the vulnerability of the target installation against the physical effects of the attacks. While in the open literature, the vulnerability of industrial facilities to attacks with improvised explosive devices and to incendiary attacks have been assessed, the development of adequate damage models for the assessment of the vulnerability of process and HAZMAT storage equipment against shooting attacks is still lacking. The present study addresses this gap and provide a novel scientifically based modelling approach to calculate baseline values of standoff distances for atmospheric storage equipment that can be used to assess the potential damage of shooting attacks targeting them. The calculations were done for a standardized set of projectiles using perforation models suitable for industrial installations and selected in a previous work. The results show that the range of standoff distances varies depending on the type of firearm used. Standoff distances resulted in the range of less than 10 meters in case of handgun projectiles and up to 1130 meters in case of hard-core rifle projectiles. Important differences in standoff distances were found for atmospheric tanks.

1. Introduction

The analysis of past events proved that chemical and process plants processing and/or storing large quantities of hazardous substances (e.g., EU Seveso establishments) could be the target of intentional malicious attacks (security attacks) aimed at severely impact the safety of workers and population, as well as the environment and property (Iaiani et al., 2024a).

The security risk of industrial critical infrastructures is commonly addressed using Security Vulnerability Assessment (SVA) or Security Risk Assessment (SRA) methodologies to determine if existing security measures and process safeguards are effective or need improvement. Examples of such methods are the CCPS methodology, the VAM-CF methodology, the methodology proposed by API RP 780, and the RAMCAP methodology. These methodologies require information concerning the potential physical effects of the security attacks on chemical and process equipment in order to assess their vulnerability to such attacks and thus to implement proper security barriers within the Physical Protection System (PPS) in order to reduce the actual level of the security risk. Nevertheless, while the vulnerability of industrial facilities to attacks with improvised explosive devices (homemade explosives) and to incendiary attacks have been assessed in some relevant studies available within the literature (see respectively (Landucci et al., 2015) and (Dusso et al., 2016)), in case of attacks consisting of shooting physical plant equipment, the development of adequate damage models for projectile perforation of process and HAZMAT storage equipment is still lacking, evidencing a clear gap in the vulnerability assessment of shooting attacks. In facts, most of available perforation models focus on targets with design features and materials quite different from process or storage equipment (Anderson, 2017).

The present study aims at filling this gap by providing a novel scientifically based approach to evaluate baseline standoff distances for atmospheric storage equipment considering a set of standardized handgun and rifle projectiles (according to EN 1522 and EN 1063). The standoff distance is the minimum distance between the location of the adversary and the target asset that will not cause any significant damage to it. Such standoff

distances can be adopted to investigate the conditions for a successful shooting attack (and thus to assess equipment vulnerability) and to support the design of passive protection barriers within the PPS. The analytical perforation model adopted have been selected in a previous study of the authors who validated them against experimental data from perforation tests, allowing for the identification of the most suitable ones for typical materials of process and storage equipment (Iaini et al., 2022).

2. Method

The flowchart of the method proposed in the present study to calculate baseline values of standoff distances for atmospheric HAZMAT storage tanks (i.e., tanks storing flammable and/or toxic materials) is summarized in Figure 1-a. It is a 5-step method: selection of reference projectiles and target installations (steps 1 and 2), calculation of ballistic limit velocities (step 3), calculation of standoff distances (step 4), and selection of baseline values (step 5). Each step is described in the following.

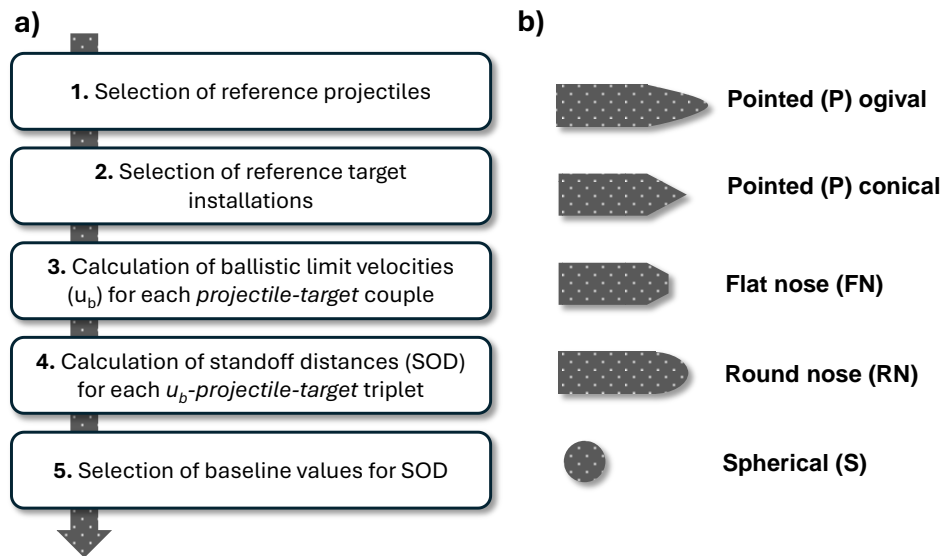


Figure 1: a) Flowchart of the method developed to calculate baseline standoff distances; b) Types of projectiles based on shape (Crouch, 2017).

2.1 Reference projectiles selected (step 1)

The reference projectiles were selected from standard EN 1063 which classifies bullets according to protection classes (FB codes), whose main information is summarized in Table 1 (for shape codes refer to Figure 1-b). It is important to note that projectiles FB2 and FB4 are suitable for handguns, while projectiles FB5, FB6, and FB7 are suitable for rifles.

Table 1: Selected reference projectiles from EN 1063. SC: Soft-core (lead), HC: Hard-core (steel, hardness more than 63 HRC). Adapted from Iaini et al. (2024b).

ID	Type of weapon	Reference projectile	Projectile type	d (mm)	m (g)	u_m (m/s)
FB2	Handgun	9 mm Luger	RN/SC	9	8	400
FB4	Handgun	44 Rem. Mag.	FN/SC	11	15.6	440
FB5	Rifle	5.56x45	PB/SC	5.56	4	950
FB6	Rifle	7.62x51	P/SC	7.62	9.5	830
FB7	Rifle	7.62x51	FP/HC	6.06*	3.7*	820

d : projectile diameter; m : projectile mass; u_m : muzzle velocity (projectile's velocity as it exits the muzzle of a firearm).

2.2 Reference target installations (step 2)

Atmospheric cylindrical installations were considered as target installations. Design data were retrieved from a study of Cozzani et al. (2006) and are summarized in Table 2.

Table 2: Design data of atmospheric cylindrical tanks selected as reference target installations in the present study. Retrieved from Cozzani et al. (2006).

ID	V (m ³)	D (mm)	t (mm)	t_d (mm)	t_{eff} (mm)
A#01	25	2700	5	0.3	4.7
A#02	100	4400	5	0.7	4.3
A#03	250	6700	5	1.2	3.8
A#04	750	10500	7	2.3	4.7
A#05	1000	15000	9	2.1	6.9
A#06	2500	16000	13	4.9	8.1
A#07	5200	25000	19	6.5	12.5
A#08	10000	30000	20.5	10.4	10.1
A#09	13390	34130	20	12.1	7.9
A#10	17480	39000	23	13.8	9.2

V : vessel volume; D : vessel diameter; t : target actual thickness; t_d : target thickness by design; t_{eff} : target effective thickness (maximum thickness that, if penetrated, determines perforation).

2.3 Calculation of ballistic limit velocity (step 3)

The ballistic limit velocity (u_b) is defined as the minimum projectile velocity required to perforate a target at normal incidence: therefore, it depends on both the projectile type and target material and thickness. In the present study, the perforation models applied to calculate u_b were validated in a previous study by the authors (Iaianni et al., 2022), to which the reader is referred to gather more details (e.g., model equations).

In particular, the *Modified De Marre* (Brown, 1986) model was applied for u_b calculation in case of soft-core (SC) projectiles (i.e., FB2, FB4, FB5, and FB6 classes reported in Table 1):

$$t_{max} = 5.42 \times 10^{-6} u_b^{4/3} m^{1/3} \quad (1)$$

where m is the projectile's mass (kg) and t_{max} is the maximum perforated thickness (m).

The *Recht* model (Stewart and Netherton, 2020) was instead applied for hard-core (HC) projectiles (i.e., FB7 class reported in Table 1):

$$t_{max} = \frac{4 \left(\frac{m}{\pi d^2} \right)}{0.62b} \left[u_{b,n} - \frac{a}{b} \ln \left(\frac{a + b u_b}{a} \right) \right];$$

$$a = 2\tau_s \ln(2Z_m) \cdot \left(1 + \frac{f}{\tan \alpha} \right);$$

$$b = 0.25 \sqrt{K\rho_t} \left(1 + \frac{f}{\tan \alpha} \right) \sin \alpha; \quad (2)$$

$$Z_m = \frac{E}{\sigma_T} \left(1 + 2 \frac{E}{\sigma_T} \right)^{-0.5}$$

where d is the diameter of the projectile core, α is the half-angle of conical nose (23.5 for standard ogives (Zukas, 1990)), σ_T is the target's static yield strength, E is the target's Young modulus, f is the dynamic friction coefficient (0.01 for friction between metals (Stewart and Netherton, 2020)), K is the target's bulk modulus, τ_s is the target's static shear strength.

It is important to underline that in the calculations, the effect of the steel plate curvature of tanks on projectile impact was considered negligible. This assumption stems from the fact that these installations are generally characterized by large diameters, resulting in a curvature radius much larger than the area affected by penetration. Furthermore, the models were developed assuming the velocity vector u_b to be perpendicular to the target surface, thereby normal incidence of the projectile impact on the tanks is assumed in the present study.

2.4 Calculation of standoff distances (step 4) and selection of baseline values (step 5)

The calculation of standoff distances (SODs) involves the calculation of the decay of the horizontal component of the projectile velocity as a function of the distance from the shooter to the target (downrange distance), by application of exterior ballistic models.

In a generic formulation:

$$SOD = f(u_b, u_m, C, G) \tag{3}$$

where u_m is the muzzle velocity, C is the ballistic coefficient, and G is the projectile’s drag function.

In the present study, the exterior ballistic model called *Siacci* (McCoy, 2012) was applied for this purpose. The SOD was calculated as the downrange distance for which the horizontal component of the projectile velocity equals the ballistic limit velocity.

Given the assumption of normal projectile incidence on the target, the calculated SODs represent the maximum possible values, providing conservative and safe-side results compared to alternative assumptions.

Finally, baseline standoff distances were evaluated considering the highest SOD values, for each projectile class, from those calculated for the set of atmospheric storage tanks considered as target installations in this study. These distances are suggested as reference baseline values for use in SVA/SRA studies aimed at evaluating the vulnerability of atmospheric tanks against the shooting threat.

3. Results and discussion

Figure 2-a presents the results of the calculation of the normal component of the ballistic limit velocity (u_b) for each projectile class considered in the present study (see Table 1) as a function of the target effective thickness. These curves were calculated by application of equations (1) and (2).

The results demonstrate that the required ballistic limit velocity increases with thickness, ending at the point where u_b matches the muzzle velocity (u_m). Beyond this point, perforation is no longer possible, defining a safe region for thicknesses exceeding the maximum perforable limit (the one in correspondence of u_m).

The analysis reveals substantial differences between handgun and rifle projectiles: while FB2 and FB4 (handgun projectiles) cannot perforate targets thicker than 4.5 mm, rifle projectiles such as FB7 can perforate up to 19.8 mm. These results underline the greater threat posed by rifles compared to handguns in terms of perforated thickness.

Table 3 reports the ballistic limit velocities calculated for each of the atmospheric steel storage tanks considered as the target installations in the present study with reference to each projectile class. These values are the input parameters of the exterior ballistic model for the calculation of the standoff distances.

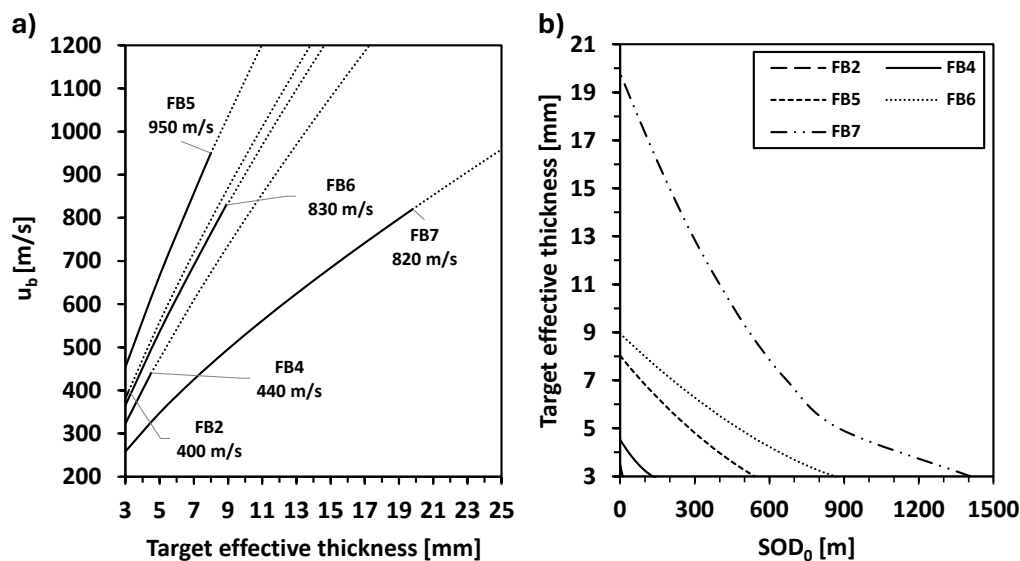


Figure 2: a) Normal component of u_b (m/s) vs target effective thickness (mm) calculated for all projectile classes; b) Maximum SOD (m) vs. target effective thickness (mm) calculated for projectile classes.

Table 3: Ballistic limit velocities (u_b) and maximum standoff distances (SOD_0) evaluated for the selected atmospheric storage tanks (**Errore. L'origine riferimento non è stata trovata.**). FB-codes defined in **Errore. L'origine riferimento non è stata trovata.**; IS: target is inherently safe.

ID	FB2 projectiles		FB4 projectiles		FB5 projectiles		FB6 projectiles		FB7 projectiles	
	u_b	SOD	u_b	SOD	u_b	SOD	u_b	SOD	u_b	SOD
A#01	534	IS	452	IS	635	307	512	522	335	930
A#02	500	IS	423	6	594	360	479	589	318	1000
A#03	456	IS	386	IS	542	420	436	683	296	1130
A#04	534	IS	452	IS	635	307	512	522	335	930
A#05	713	IS	603	IS	847	94	683	225	421	680
A#06	804	IS	680	IS	956	IS	770	90	465	580
A#07	1113	IS	942	IS	1323	IS	1066	IS	609	320
A#08	948	IS	803	IS	1128	IS	908	IS	532	450
A#09	789	IS	667	IS	938	15	756	112	457	600
A#10	884	IS	748	IS	1052	IS	847	IS	502	510

The results of application of the *Siacci* model in terms of calculated maximum standoff distances (assumption of normal incidence of the projectile on the target surface assumed as flat) as a function of the target effective thickness are reported in Figure 2-b.

As previously stated, the results reveal a significant disparity between the maximum standoff distances for handgun projectiles (FB2 and FB4 in Table 1) and rifle projectiles (FB5, FB6, and FB7 in Table 1). For instance, with an effective target thickness of 3 mm, the standoff distance increases markedly, being nearly four times greater when comparing FB2 (SOD = 10 m) and FB4 (SOD = 131 m) to FB5 (SOD = 540 m). This difference becomes even more pronounced for FB6 and FB7 projectiles, with SOD values reaching 870 m and 1409 m, respectively. Comparable trends are observed across the range of target thicknesses analyzed.

Based on these results, the calculated SOD values for the set of HAZMAT atmospheric storage tanks are reported in Table 3 for the different projectile classes considered. With reference to the table, tanks labeled A#01–10 are inherently resistant to shooting attacks involving FB2 handgun projectiles, as the ballistic limit velocity exceeds the muzzle velocity of the projectile (u_b always higher than $u_m = 400$ m/s) in all cases. Similarly, FB4 handgun projectiles were found ineffective, except for tank A#02, for which a standoff distance of 6 m was calculated. Consequently, for this specific vessel, a successful attack would require the shooter to gain access to the inner area of the site (e.g., by climbing fence or by counterfeit authorization at manned reception) and reach the place where the tank is located (attack path with higher detection probability than that consisting in shooting from the outside area).

Significantly greater standoff distances, often in the range of hundreds of meters, were determined for rifle projectiles (FB5, FB6, and FB7 classes). For example, FB7 hard-core projectiles fired at small-diameter tanks (vessels A#01–03) resulted in calculated SODs close or exceeding 1000 m. This suggests that an attacker equipped with such projectiles could potentially succeed without entering the industrial premises. However, while FB7 projectiles can penetrate all the considered tanks, some of the latter demonstrated intrinsic resistance to FB5 and FB6 projectiles. Specifically, vessels A#06, A#07, A#08, and A#10 resulted to be resistant to FB5 projectiles, whereas vessels A#07, A#08, and A#10 also to FB6 projectiles.

These findings provide critical insights for the design of passive protection barriers within the Physical Protection System (PPS) and for establishing internal and external response strategies for chemical and process facilities. For example, enhanced external security measures, such as creating clearance zones and implementing external Closed-Circuit Television (CCTV) systems, are necessary to improve the likelihood of attack detection and thus of timely intervention of security strategies (preventive such as police intervention, or mitigative such as shutdown activation) in case of shooting attacks that occur outside the site's fences.

Table 4: Baseline values for SOD proposed for HAZMAT atmospheric steel storage tanks with reference to FB2, FB4, FB5, FB6, and FB7 projectiles as defined in Table 1.

Projectile class	FB2 projectiles	FB4 projectiles	FB5 projectiles	FB6 projectiles	FB7 projectiles
SOD (m)	No perforation	6	420	685	1130

The results presented above were utilized to establish baseline standoff distances for generic HAZMAT atmospheric cylindrical storage tanks. These were proposed for each standardized projectile considering the highest SOD between those reported in Table 3 for the set of atmospheric vessels. These values are reported in Table 4 and can be taken as reference standoff distances to be used by authorities and practitioners in the context of SVA/SRA to assess the vulnerability of HAZMAT atmospheric storage tanks to shooting attacks. In the case of critical targets (e.g., tanks storing relevant quantities of highly hazardous substances such as liquid chlorine), the method described in Section 2 may be applied to the specific geometry, allowing for the calculation of case-specific standoff distances.

4. Conclusions

The present study focused on calculating, baseline standoff distances for shooting attacks targeting atmospheric steel cylindrical storage vessels storing hazardous material (HAZMAT), taking into account a representative range of light weapon projectiles specified by EN 1522 and EN 1063 standards.

The calculations were conducted using an innovative scientific methodology based on validated models for projectile penetration and flight trajectory analysis. The results showed standoff distances ranging from less than 10 meters for handgun projectiles to 685 meters for rifles firing soft-core projectiles (lead core with a steel penetrator) and up to 1130 meters for rifles using hard-core projectiles (steel core with a full copper alloy jacket). These outcomes provide valuable insights for Security Vulnerability and Risk Assessment (SVA/SRA) studies, supporting the development or improvement of the Physical Protection System (PPS) of a facility and improving the evaluation of target vulnerabilities to enhance the security of industrial sites against shooting attacks.

Acknowledgments

This work was supported by Ministero dello Sviluppo Economico (MISE), Direzione Generale per le Infrastrutture e la Sicurezza dei Sistemi Energetici e Geominerari (DGISSEG) and by INAIL (Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro).

References

- Anderson C.E., 2017, Analytical models for penetration mechanics: A Review. *International Journal of Impact Engineering*, 108, 3–26.
- Brown S.J., 1986, Energy release protection for pressurized systems. Part II. Review of studies into impact/terminal ballistics, *Applied Mechanics Reviews*, 39, 177–201.
- Cozzani V., Gubinelli G., Salzano E., 2006, Escalation thresholds in the assessment of domino accidental events, *Journal of Hazardous Materials*, 129, 1–21.
- Crouch I.G., 2017, Woodhead Publishing in Materials The Science of Armour Materials Edited by Elsevier.
- Dusso A., Grimaz S., Salzano E., 2016, Quick assessment of fire hazard in chemical and pharmaceutical warehouses, *Chemical Engineering Transactions*, 48, 325–330.
- Iaiani M., Musayev N., Tugnoli A., Macini P., Mesini E., Cozzani V., 2024^a, Identification of security scenarios in offshore Oil&Gas production facilities based on past incident analysis, *Process Safety and Environmental Protection*, 192, 926–945.
- Iaiani M., Sorichetti R., Tugnoli A., Cozzani V., 2024b, Modelling standoff distances to prevent escalation in shooting attacks to tanks storing hazardous materials, *Reliability Engineering and System Safety*, 241, 109689.
- Iaiani M., Sorichetti R., Tugnoli A., Cozzani V., 2022, Projectile perforation models for the vulnerability assessment of atmospheric storage tanks, *Process Safety and Environmental Protection*, 161, 231–246.
- Landucci G., Reniers G., Cozzani V., Salzano E., 2015, Vulnerability of industrial facilities to attacks with improvised explosive devices aimed at triggering domino scenarios, *Reliability Engineering and System Safety*, 143, 53–62.
- McCoy R.L., 2012, *Modern Exterior Ballistics, The Launch and Flight Dynamics of Symmetric Projectiles*, Schiffer Publishing Ltd.
- Stewart M.G., Netherton M.D., 2020, Statistical variability and fragility assessment of ballistic perforation of steel plates for 7.62 mm AP ammunition, *Defence Technology*, 16, 503–513.
- Zukas J.A., 1990, *High Velocity Impact Dynamics*, Wiley-Interscience.