Vulnerability to Perforation from Shooting Attacks of Tanks Storing Hazardous Materials

Matteo Iaiani[a], Riccardo Sorichetti[a], Alessandro Tugnoli[a,*], Valerio Cozzani[a]

LISES – Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Alma Mater Studiorum – Università di Bologna, Italy
a.tugnoli@unibo.it

Due to the large quantities of hazardous materials stored and processed, chemical and process plants may be attractive targets for security attacks (e.g. terrorist attacks) that can severely impact workers, the population, the surrounding environment, and property. According to well established Security Vulnerability Assessment (SVA) and Security Risk Assessment (SRA) methodologies, the shooting threat to a chemical and process facility shall be investigated; however, the development of adequate damage models in case of shooting attacks using small/light weapons to industrial equipment units is still lacking. In the present study, an extended set of perforation models was retrieved from the literature and was validated against experimental data from perforation tests. The most reliable perforation models for soft core projectiles were selected and used to assess the vulnerability to perforation of atmospheric tanks storing hazardous materials for two reference projectiles enabling the identification of inherent safety threshold values for perforation thickness.

1. Introduction

Large amounts of hazardous materials are handled in chemical and process plants potentially leading to severe consequences on workers and external population, as well as on the environmental and property when their inherent hazard is exploited by malevolent agents (security causes, e.g. acts of terrorism, vandalism, sabotage, etc.) (Landucci and Reniers, 2019). The management of security risks received increasing interest in the last decade (Boustras and Waring, 2020) also due to the increasing number of events recorded worldwide, both in the physical (Iaiani et al., 2021a) and cyber (Iaiani et al., 2021b) domains.

Security risks are typically addressed by Security Vulnerability Assessment (SVA) and Security Risk Assessment (SRA) methodologies (e.g. CCPS, API RP 780, VAM-CF, and RAMCAP methodologies) which allow to determine if security barriers and procedures are effective or need improvement (Matteini et al., 2019). While vulnerability of industrial equipment to attacks with homemade explosives (Landucci et al., 2015) and to incendiary attacks (Dusso et al., 2016) has been investigated in available studies, damage models for shooting attacks using small/light weapons (e.g. handguns and rifles) to storage and process equipment are still lacking (Argenti et al., 2018). In facts, most of available perforation models have been developed for target materials with different properties from the ones used for industrial equipment (e.g. armours, bulletproof glasses, buildings) and studies to support the choice of the most reliable perforation models are limited in the literature. Moreover, most of the studies specifically dedicated to the perforation of process and storage equipment from shooting attacks focus on high velocity projectiles (velocity higher than 960 m/s) which are never reached by projectiles fired by small/light weapons (Lecysyn et al., 2010).

In the present study an extensive set of empirical and analytical perforation models was retrieved from the literature and was validated against available data of perforation tests of steel plates with characteristics similar to those of the construction materials used for industrial storage tanks (e.g. the ones reported in standard API 650). Using specific statistical performance indicators, the most reliable perforation models for soft core projectiles were selected and used to assess the vulnerability to perforation of steel atmospheric storage tanks when impacted by two reference projectiles. This allowed to obtain baseline information for vulnerability to shooting attacks of steel atmospheric storage tanks to be used in the context of SVA/SRA studies. The results

are also the starting point for future development of quantitative methods (e.g. based on calculation of standoff distances) for the assessment of the shooting threat.

2. Method

The method applied in the current study consists in the application of four steps (see flowchart in Figure 1a). In Step-1 perforation models (PMs) were retrieved from the literature and reviewed. Generally, a PM is a multi-parameters function, both projectile parameters (e.g. mass and diameter) and target parameters (e.g. thickness and Brinell's hardness number), which allows for the prediction of the perforation of a specific target element. PMs are classified according to model type (empirical (E), analytical (A), numerical (N)), projectile shape (pointed conical or ogival (P), with a round nose (RN), flat nose (FN), and spherical (S)), and projectile type (soft-core (SC, generally lead or soft steel) and hard-core (HC, generally hardened steel or tungsten carbide). The scope of the present study was restricted to SC projectiles only due to their wider usage in shooting applications than HC projectiles (Crouch, 2017). A total of 11 PMs suitable for SC projectiles were retrieved.

Step-2 consisted in the collection of data of experimental perforation tests to be used in the validation of the PMs retrieved in Step-1. A perforation test consists in the shooting with a standardized projectile (European Committee for Standardization (CEN), 2019) at a specific distance (test range) of a target element (test piece) characterized in terms of shape, size, and material. Even if data concerning the perforation of actual storage tanks are not available, still the analysis presented is based on a set of representative experimental data, most of which refer to projectiles that can commonly be fired in the context of a shooting attack to atmospheric storage tanks and to materials with similar characteristics to those used in the tank construction. It is important to remark that effect of the filled media (empty tank or filled tank) on the ballistic limit velocity was not taken into account due to lack of data on simple experiments (Lu et al., 2007). A total of 6 experimental data of perforation tests of SC projectiles were collected.

In Step-3, the retrieved PMs were validated using the experimental data of perforation tests. The parameter used for the validation and consequent comparison is the ballistic limit velocity (u_b), which is defined as the minimum required projectile velocity needed to perforate a particular target element of thickness "t" at normal incidence (Carlucci and Jacobson, 2008). The results are shown using parity plots. In order to find the most reliable PMs a quantitative comparison was done using statistical performance indicators: the Mean Absolute Percentage Error (MAPE), the Mean Percentage Error (MPE) and the Root Mean Square Deviation (RMSD). MAPE and MPE are used to assess the average of percentage errors between model predictions and experimental data. However, MPE makes use of actual percentage errors rather than the absolute percentage errors considered in MAPE, allowing to measure the prediction accuracy of a model in relative terms. The RMSD

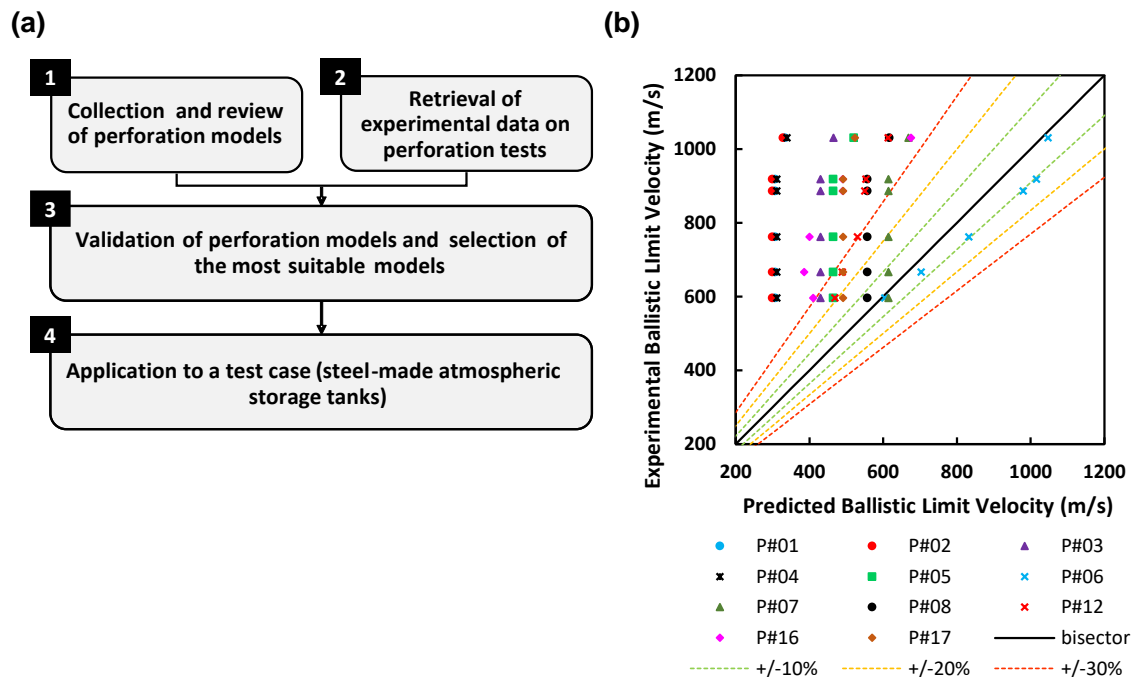**(a)**   **(b)**

Figure 1: (a) Flowchart of the method applied in the current study; (b) Parity plot comparing ballistic limit velocity (m/s) calculated with projectile perforation models (x-axis) with the one obtained in the experimental perforation tests (y-axis) for SC projectiles. P#-codes are used to specify the perforation models.

computes the square root of the average of squared errors and, as it is not scaled to experimental data (as MAPE and MPE), it is a measure of the model accuracy in absolute terms. The closer these three parameters are to zero, the better the PM predict perforation experimental data. The most reliable PMs for SC projectiles were then identified.

Finally, in Step-4 application cases were defined in order to show the potential use of the selected PMs in assessing the vulnerability of real targets against shooting attacks in the context of SVA/SRA. In particular, the projectiles listed in standard EN 1063 (European Committee for Standardization (CEN), 2019) were used as reference projectiles in the application cases, while steel atmospheric storage tanks were chosen as target elements retrieving design data and mechanical properties from standard API 650 (American Petroleum Institute (API), 2021).

The results in terms of ballistic limit velocity vs target thickness for the considered standardized projectiles allowed to provide inherent safety thickness threshold values for shooting attacks to steel atmospheric storage tanks. For the sake of brevity, in the following sections, the entire dataset of the 11 PMs retrieved and the one of the 6 experimental perforation tests are not reported.

3. Selected perforation models (PMs)

The parity plot obtained is reported in Figure 1b, showing the experimental ballistic limit velocity in the y-axis and the one predicted by PMs in the x-axis. The two most reliable perforation models selected for SC projectiles are summarized in Table 1, which also reports the specific correlations of each PM, the applicability range, and the values of the statistical performance indicators used for the validation. The MODIFIED DE MARRE model (P#07, dark green triangles in Figure 1b; MAPE=21.5, MPE=21.5, RMSD=231.1 m/s) and the THOR model (P#08, black dots in Figure 1b; MAPE=27.7, MPE=27.7, RMSD=278.0 m/s) in Table 1 are empirical models specific for steel target elements. The two models better predict the ballistic limit velocity at velocities lower than 800 m/s as all results except one fall below the 20%-error dotted line. The behavior of these two PMs is also conservative (positive MAPE values), since the results are all above the bisector with the exception of a single results for P#07 which is however very close to it, and thus, they are on the safe side for prediction of the target protection. Nevertheless, since the two models lack in the possibility to account for the mechanical properties of the target element, their use shall be limited to the range of target hardness for which validation is explored in the current study and that provided errors below 30% (i.e. 200 < BHN < 400).

It is important to underline that the error shown by perforation model P#06 (light blue crosses in Figure 1b; MAPE=6.5, MPE=-6.5, RMSD=64.7 m/s) is the more limited, being always under the 10%-error dotted line. However, all the points are under the bisector, meaning that this PM provides for non-conservative estimations of the ballistic limit velocity from the point of view of target protection from perforation. For this reason, in the context of the current study, model P#06 was excluded from the list of most suitable PMs for SC projectiles.

All the other PMs (P#01, P#02, P#03, P#04, P#05, P#12, P#16, P#17) were not selected as they are overconservative in predicting perforation with most of the ballistic limit velocities that are more than 30% smaller than those in experimental tests.

Table 1: Selected PMs for SC projectiles reporting the specific correlations, applicability range and statistical performance indicators used for validation. m=projectile mass; t=perforation thickness; u_b=ballistic limit velocity; ϑ=obliquity angle.

Perforation model	MODIFIED DE MARRE model (P#07)	THOR model (P#08)
Reference	(Brown, 1986; Hazell, 2015)	(Ballistic Research Laboratories, 1961)
Parameters	u_b (m/s), t (m), m (kg)	u_b (ft/s), t (in), m (grains), ϑ (rad)
Correlation	$t = 5.42 \cdot 10^{-6} \cdot u_b^{4/3} \cdot m^{1/3}$	$u_b = 10^{4.608} \cdot t^{0.906} \cdot m^{-0.359} \cdot (sec\theta)^{1.286}$
MAPE	21.5	27.7
MPE	21.5	27.7
RMSD (m/s)	231.1	278

4. Application cases: perforation of steel atmospheric storage tanks

The MODIFIED DE MARRE model (P#07) and the THOR model (P#08) were then applied to assess the vulnerability to perforation of industrial steel-made atmospheric tanks for the storage of chemicals (selected as target elements in the application cases in the current study) against SC projectiles.

4.1 Reference projectiles and target material

Due to the high variability in geometries and sizes of both target atmospheric storage tanks and projectiles, a set of reference application cases was considered in the current study.

Reference projectiles were selected according to standard EN 1063 which defines the requirements and classification that windows, doors, shutters, and blinds must satisfy when tested against projectiles shot by small/light weapons. Particularly, target resistance to perforation is classified by the standard according to protection classes (FB codes). To each protection class a reference projectile is defined in terms of type, shape, calibre, mass, and muzzle velocity (u_m, i.e. the velocity of a projectile as it exits the muzzle of a firearm).

Two reference SC projectiles (alias protection classes according to EN 1063) were considered for the application cases (Table 2). The code name used in the table (FB code) refers to the original specification in EN 1063.

Table 2: Selected reference SC projectiles from EN 1063. FMJ=Full metal jacket bullet, RN=Round nose, SC=Soft-core (lead), P=Pointed, SCP1=Soft-core (lead) with steel penetrator.

ID	Type of weapon	Reference projectile	Projectile type	d (mm)	m (g)	u_m(m/s)
FB2	Handgun	9 mm Luger	FMJ/RN/SC	9	8	400
FB5	Rifle	5.56x45	FMJ/P/SCP1	5.56	4	950

The standard API 650 was used as a reference document for retrieving data for the steel atmospheric storage tanks selected as target elements in the application cases as it establishes the minimum requirements for material, design, fabrication, erection, and testing of vertical, cylindrical, aboveground, closed- and open-top, welded oil storage tanks in various sizes and capacities for internal pressures approximating atmospheric pressure. To be on the conservative side, the lowest strength steel (coded as A 285M-C) among the ones specified in API 650 as allowed vessel shell construction materials, was selected as the target material for the atmospheric storage tanks (BHN=110).

Due to the fact that these installations are generally characterized by large diameters (e.g. typical applications considered in API 650 range from 3 m to 60 m), the effect of the steel plate curvature on projectile impact was considered negligible as the curvature radius is much bigger than the area affected by the penetration phenomenon (in the retrieved experimental data the effect of the penetration on the target extended no more than three projectile diameters from the impact point while no reinforcement or support on the plate was present within 30 times the projectile diameter).

Shell thickness of atmospheric storage tanks shows large variability in practical application as it depends on design (e.g. variable thickness with height) and operative requirements (e.g. corrosion allowance). As reported in (Cozzani et al., 2006), typical shell thicknesses of these installations range from 5 mm to 23 mm with larger tanks characterized by variable thickness with height. However, minimum thicknesses specified in standard API 650 vary from 5 mm (tank diameter less than 15 m) to 10 mm (tank diameter greater than 60 m), and thus this range can be considered as worst-case scenario for atmospheric storage tanks. In the current study, thickness range between 3 mm and 25 mm was conservatively explored.

4.2 Ballistic limit velocities vs target thickness

The curves (one obtained with P#07 and the other with P#08) of calculated ballistic limit velocities (m/s) vs. target thickness (mm) are graphically shown in Figure 2 (two panels, one corresponding to SC projectile class FB2 and one to class FB5).

The horizontal dashed red line in the two panels of Figure 2 corresponds to the muzzle velocity (u_m) of each projectile class (reported in Table 2): as this velocity stands for the maximum velocity at which a projectile can impact a certain target element (i.e. when the muzzle of the firearm is next to the tank shell), perforation is possible only if the calculated ballistic limit velocity is lower than the muzzle velocity (i.e. the ballistic limit velocity curves of Figure 2 are below the red lines). This condition denies the possibility of tank perforation even in the worst-case scenario (normal incidence and projectile at muzzle velocity) providing an inherent safety criterion (Cozzani et al., 2007). The inherent safety threshold for perforation thickness can be defined as the tank shell minimum thickness preventing perforation for each projectile class.

Perforation model P#08 predicts a higher perforation thickness than P#07 for FB2 projectiles (see Figure 2a), while for FB5 projectiles it is true for thickness values up to 6 mm (see Figure 2b): overall, this agrees with the more conservative behavior of P#08 evidenced in Section 4.1.

According to perforation model P#07, if a FB2 projectile hits an atmospheric steel storage tank at muzzle velocity, perforation is possible till 3.2 mm, while for perforation model P#08 perforation is possible till 3.9 mm

(see Figure 2a). Therefore, an inherent safety thickness threshold of 4 mm may be assumed for FB2 projectiles: if compared to the minimum thickness range required for atmospheric storage tanks by standard API 650 (5–10 mm), inherent safety with respect to FB2 projectiles is granted for tanks of any size.

In case of FB5 rifle projectiles, perforation model P#07 predicts perforation till 8.1 mm, while P#08 predicts perforation till 7.7 mm, and thus an inherent safety thickness threshold equal to 9 mm was set for these projectiles. Therefore, perforation is possible almost over the entire range of minimum thicknesses expected for atmospheric storage tanks (5-10 mm, see the green-shaded area in Figures 2b), making also medium and large size tanks potentially vulnerable to shooting attacks using FB5 projectiles.

In conclusion, if an attacker shoots with a handgun (e.g. FB2 projectiles) he/she will not be able to perforate atmospheric storage tanks of any size. On the other hand, if the shooter uses a rifle (e.g. FB5 projectiles) perforation of tanks with thickness lower than 9 mm is potentially possible. Therefore, a higher level of threat should be associated to rifles with respect to handguns and this is related to the higher destructive power of rifles rather than that of handguns due to the larger propellant charge and to the longer period of acceleration available within the longer gun barrel of rifles which allow adequate time for the propellant to fully ignite before the projectile exits.
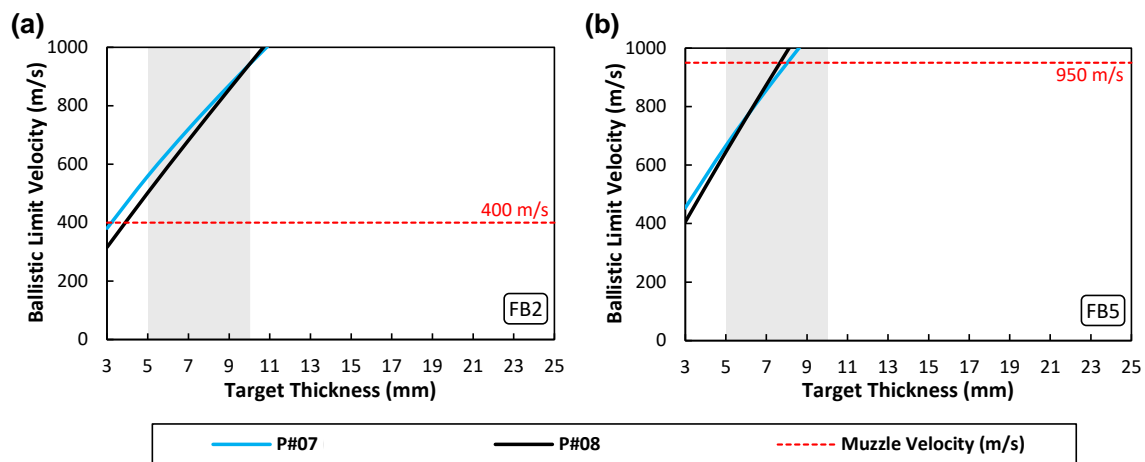

Figure 2: Ballistic limit velocity (m/s) vs. target thickness (mm) calculated for: (a) FB2 projectiles; (b) FB5 projectiles. The grey region is the range of the minimum thickness values for large diameter atmospheric storage tanks (5-10 mm). FB-codes are defined in Table 2; P#-codes are defined in Table 1. AST: Atmospheric Storage Tank.

5. Conclusions

In the current study, perforation models suitable for soft-core (SC) projectiles and available in the literature were collected, reviewed and validated against experimental data from perforation tests. The most reliable perforation models were identified using statistical performance indicators (MAPE, MPE and RMSD). The selected PMs were then applied to assess the vulnerability to perforation of steel atmospheric storage tanks against standardized projectiles (EN 1063).

The application of the PMs allowed the evaluation of the ballistic limit velocity (i.e. the minimum velocity required for perforation) as a function of the target element thickness. These results were used to identify the minimum thickness required to protect the target from perforation (i.e. inherent safety thickness threshold) for the reference projectiles considered highlighting significant differences between handguns and rifles, with protection thresholds for rifles more than 2 times the ones needed in the case of handguns. Important differences between handguns and rifles were found in the shell thickness that can be successfully perforated: e.g. FB2 projectiles (handgun) are not able to perforate atmospheric storage tanks of any size (according to design specification of tanks in standard API 650), while FB5 projectiles (rifle) are potentially able to perforate medium and large size tanks.

These results can support SVA/SRA studies in the assessment of vulnerability to perforation of atmospheric storage tanks as well as may be used as the starting point for future development of quantitative methods (e.g. based on calculation of standoff distances; i.e. the minimum distance from the attacker to the target element that prevents a successful attack) for the assessment of the shooting threat.

Nomenclature

u_b – ballistic limit velocity, m/s
u_m – muzzle velocity, m/s
BHN – Target Brinnel's hardness number, -
m – projectile mass, kg
d – projectile diameter, m
t – target thickness, m

Acknowledgments

References

American Petroleum Institute (API), 2021, API standard 650: Welded Tanks for Oil Storage, 13th ed.

Argenti F., Landucci G., Reniers G., Cozzani V., 2018, Vulnerability assessment of chemical facilities to intentional attacks based on Bayesian Network, Reliability Engineering & System Safety, 169, 515–530.

Ballistic Research Laboratories, 1961, Project THOR Technincal Report No.46: The resistance of various metallic materials to perforation by steel fragments; empirical relationships for fragment residual velocity and residual weight.

Boustras G., Waring A., 2020, Towards a reconceptualization of safety and security, their interactions, and policy requirements in a 21st century context, Safety Science, 132, 104942.

Brown S.J., 1986, Energy release protection for pressurized systems. Part II. Rewiew of studies into impact/terminal ballistics, Applied Mechanics Reviews, 39, 177–201.

Carlucci D.E., Jacobson S.S., 2008, Ballistics: theory and design of guns and ammunition, CRC Press/Taylor & Francis Group.

Cozzani V., Gubinelli G., Salzano E., 2006, Escalation thresholds in the assessment of domino accidental events, Journal of Hazardous Materials, 129, 1–21.

Cozzani V., Tugnoli A., Salzano E., 2007, Prevention of domino effect: From active and passive strategies to inherently safer design, Journal of Hazardous Materials, 139, 209–219.

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.

European Committee for Standardization (CEN), 2019, EN 1063: Glass in building - Security glazing - Testing and classification od resistance against bullet attack.

Hazell P.J., 2015, Armour: Materials, Theory, and Design, CRC Press.

Iaiani M., Tugnoli A., Bonvicini S., Cozzani V., 2021a, Major accidents triggered by malicious manipulations of the control system in process facilities, Safety Science, 134, 105043.

Iaiani M., Tugnoli A., Bonvicini S., Cozzani V., 2021b, Analysis of Cybersecurity-related Incidents in the Process Industry, Reliability Engineering & System Safety, 209, 107485.

Landucci G., Reniers G., 2019, Preface to special issue on quantitative security analysis of industrial facilities, Reliability Engineering & System Safety.

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 & System Safety, 143, 53–62.

Lecysyn N., Bony-Dandrieux A., Aprin L., Heymes F., Slangen P., Dusserre G., Munier L., Le Gallic C., 2010, Experimental study of hydraulic ram effects on a liquid storage tank: Analysis of overpressure and cavitation induced by a high-speed projectile, Journal of Hazardous Materials, 178, 635–643.

Lu G.Y., Zhang S.Y., Lei J.P., Yang J.L., 2007, Dynamic responses and damages of water-filled pre-pressurized metal tube impacted by mass, International Journal of Impact Engineering, 34, 1594–1601.

Matteini A., Argenti F., Salzano E., Cozzani V., 2019, A comparative analysis of security risk assessment methodologies for the chemical industry, Reliability Engineering & System Safety, 191.