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Vulnerability of industrial facilities to attacks with improvised explosive devices aimed at triggering domino scenarios

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ABSTRACT

Process- and chemical plants may constitute a critical target for a terrorist attack. In the present study, the analysis of industrial accidents induced by intentional acts of interference is carried out focusing on accident chains triggered by attacks with home-made (improvised) explosives. The effects of blast waves caused by improvised explosive devices are compared with those expected from a net equivalent charge of TNT by using a specific methodology for the assessment of stand-off distances. It is demonstrated that a home-made explosive device has a TNT efficiency comprised between 0.2 and 0.5. The model was applied to a case study, demonstrating the potentiality of improvised explosives in causing accident escalation sequences and severe effects on population and assets. The analysis of the case-study also allowed obtaining suggestions for an adequate security management.

1. Introduction

Industrial facilities where relevant quantities of hazardous chemicals are stored or processed may be possible targets for malicious acts of interference due to terrorist attacks. The credibility and potential severity of such scenarios was pointed out by several previous studies devoted to the evaluation of the potential impact of external attacks on process plants [1–9]. An important aspect associated to such integrated safety and security analysis is that accidents triggered by external attacks may damage multiple process units or eventually several neighboring industrial sites triggering domino effects [9–11].

According to the schematization reported in Fig. 1, the attack may take place inside the industrial domain, hence aiming at the direct damage of target equipment by bombs or firearms, and to trigger an escalation sequence leading to a domino scenario (also defined as a “cascading event”) [12–19]. Otherwise, an intentional act of interference still having the plant as the main target may as well be initiated outside the plant boundaries [14,20–22]. Moreover, intentional attacks to non-industrial targets (e.g. strategic buildings, urban areas, infrastructures) might produce a large-scale accident which may in turn trigger indirect external domino effects in an industrial facility. Domino scenarios triggered by such attacks are likely to have an extremely high severity [12–19], as remarked in Fig. 1. This highlights the importance of an appropriate security management of chemical and process facilities which should ideally be integrated with the analysis of the area surrounding the facility itself.

The fundamental basis of security management can be expressed in a similar manner to the Layers of Protection used in modern chemical process plants for addressing safety-related, accidental events. Examples of methods based on the analysis of layer of protection and accident causation are reported by CCPS [23] and were adopted in the development of methodologies for risk assessment such as ARAMIS [24] and SHIP [25]. These methodologies were aimed at supporting the risk evaluation and management in the framework of industries storing and handling relevant quantities of hazardous materials.

The concept of layers of protection is transferred in security studies by considering concentric “Rings-of-Protection” [26,27], also known as ‘layered defenses’. This is used as first guiding principle to define the spatial relationship between the location of the target, the location of the physical countermeasures and the location of adversary. Besides, an effective countermeasure deploys multiple defense mechanisms between the adversary and the target asset. Each of these mechanisms should present an independent obstacle to the adversary, as schematized in Fig. 1. These concepts are directly

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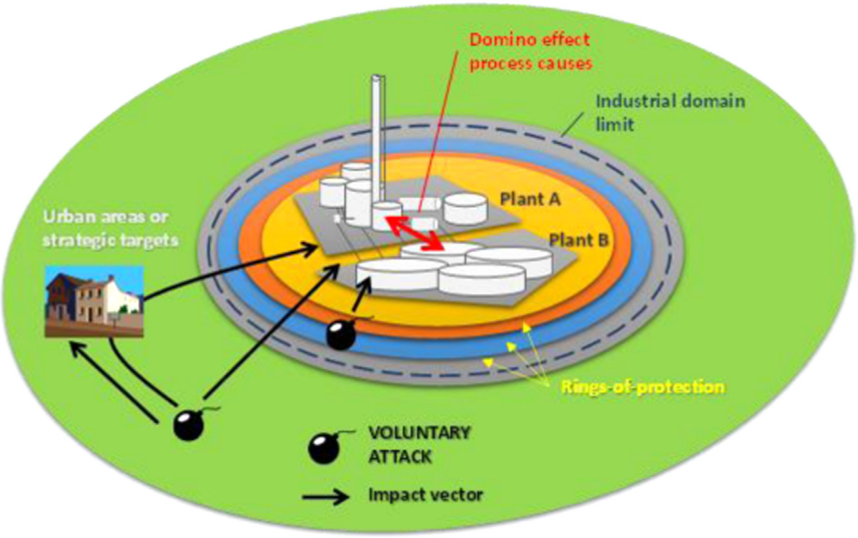

Fig. 1. Possible interactions of industrial facilities with the surrounding area leading to domino scenarios or cascading events.

applicable to contrast the effects produced by home-made (improvised) explosives in a non-military context. However, in this paper deliberate attacks on industrial plant are considered [28]. In this case, (i) the resistance of the barriers, (ii) the time it takes an adversary to get to the target, and (iii) the distance an adversary might take to place a home-made explosive are the most important factors to take into account to assess the probability of success and to minimize the damage. However, the design of the three cited countermeasures (resistance, time, distance) is not straightforward and depends on several deterministic variables.

The present study investigates the possibility that a shock wave generated by home-made (or improvised) explosives may damage process equipment and/or trigger an escalation sequence resulting in a domino scenario. No effects of fragments or projectiles produced by the improvised explosives have been considered. The analysis was mainly based on the assessment of stand-off distances between the explosion source and the target (the industrial plant) as principal countermeasure, but the barrier resistance was also addressed. Specific curves were defined in order to determine the peak overpressure on the basis of the explosive type and amount. A case study is also analyzed in order to evaluate the vulnerability of process plants to attacks based on improvised explosives. The case study also compares the impact of the worst-case accidents triggered by external attack with domino chains induced by internal process failures.

2. Home-made explosives

According to the US Government Hazardous Substances Database, several substances and mixtures can be used for the realization of this kind of explosives, starting from chemicals sold in markets and pharmacies. Among others, two were often adopted for terrorist attacks, suicide bombing, and other malicious uses: Ammonium Nitrate (AN) – Fuel Oil (i.e. ANFO) mixtures and Acetone Peroxide or Triacetone Triperoxide Peroxyacetone (TATP) mixtures [29–31]. These two materials were considered as reference explosives for the analysis presented in the present study.

ANFO is a tertiary explosive (note that TNT is a secondary explosive) and is generally composed by 94% of AN prills and 6% of adsorbed fuel oil [32]. It is extensively used for several authorized purposes as in mine blasting. The TNT equivalence is typically around 80% and the ideal explosion (detonation) energy is 3890 kJ/kg (pure ammonium nitrate has an explosion energy of 1592 kJ/kg). AN prills used for mining applications are however physically different from fertilizer prills used in home-made explosives. The commercial ammonium nitrate prills used for mine blasting have a 20% void fractions and are coated with #2 fuel oil (mainly C10 – C20 linear hydrocarbons) or kerosene. Hence, ANFO has a bulk density of approximately 840 kg/m^3 when starting from AN prills for mining applications, having a density of about 1300 kg/m^3 (the density of pure crystalline ammonium nitrate is 1700 kg/m^3). On the other hand, homemade explosives prepared from AN fertilizers do not have a so high void fraction and are less efficient: e.g. the new European regulations for fertilizers [33] state that they must contain less than 45% of AN (16% N) for being traded to the general public. Such fertilizers still may be used to obtain explosives, but require processing to achieve a detonation. If commercial AN (containing about 50% of inert, as dolomite) and diesel fuel is used, a detonation energy of about 1071 kJ/kg is obtained, much less than pure ANFO [30]. Furthermore, it has been observed that when amounts of dolomite higher than 30%, are present, no detonation is observed [30].

TATP is a primary explosive which is notable since it does not contain nitrogen. Thus, it is used to avoid conventional chemical bomb detection systems, and it is almost undetectable by either analytical system or by sniffer dogs [34]. It can be obtained from common household items such as sulphuric acid, hydrogen peroxide, and acetone [35].

TATP is very unstable: it can be ignited by touch and can explode spontaneously. It is often used for improvised detonators itself. It is actually composed by isomers and conformers, the dimer being more stable but having lower decomposition energy (see Fig. 2).

The density of the pure molecule is typically considered to be 1220 kg/m^3. However, home-made TAPT formulations are typically in the range of 450–500 kg/m^3 [36]. Finally, TATP is often stabilized with carbonaceous liquids and waxes so that the net charge is even lower [37]. Nevertheless, Lefebvre et al. [38] have demonstrated that home-made TATP is a primary explosive and very sensitive to impact or friction, although the strength of explosion may strongly vary since the quality of the final product is very sensitive to the temperature during its synthesis.

TATP is highly volatile and decomposes to form large number of gas phase molecules (entropic explosion) [39,40]. Acetone and ozone are predicted to be the main decomposition products, along with oxygen, methyl acetate, ethane, and carbon dioxide [41].