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ACCIDENTS IN FACILITIES FOR STORING HAZARDOUS MATERIALS

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Abstract. *The vital elements of numerous industrial plants include the process equipment which, depending on the nature of the technological process, can be exposed to internal pressure in the general case of a variable size. The typical examples of process equipment are available at LPG stations (distribution centers), fuel tanks, gas boilers, combustion plants, etc. Practical experience and the analysis of the cause of accidents have shown that damage to process equipment is most often followed by the explosions of the tanks in which the flammable substances, such as LPG, petrol, diesel and jet fuel, oils, etc. are stored. The explosion of a tank cannot occur spontaneously, but only results from external factors. This means that the explosion of process equipment is preceded by the primary events whose harmful effects are manifested through the following phenomena: the weakening of the strength of a tank, an increase in pressure above the nominal value, or a combination of the two preceding cases.*

Key words: *risk assessment, accidents, hazardous materials, process equipment, domino effect, BLEVE.*

1. Introduction

The rapid industrial development of the world's leading economies requires the increasing use of hazardous substances and chemicals in many segments of social activities. Modern production conditions and strict market demands in achieving certain product properties require the presence of hazardous substances in many processes that emerge from the framework of the petrochemical industry with a relatively small product range, which has been the case in the past decades with developing countries. Today, hazardous substances are present in all social spheres,

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ranging from industrial plants, agriculture, and medicine to national security and everyday use in the household.

The inevitable followers of hazardous substances are their hazardous characteristics that can adversely affect human or animal health and the environment in a direct or indirect manner.

The distribution of accidents within the logistics system is based on the elementary structure of logistics subsystems and has five discrete states: production, storage, reloading, transport, and use (Tanackov et al. 2018). On the one hand, no direct risk modeling in the production, storage, handling and transport of hazardous substances can be performed. The concept of dangerous goods operations is heterogeneous, starting with a range of hazardous materials, transport supplies, installed equipment, traffic intensity, the distribution concept, employee training, etc., whereas on the other, it is indirectly possible within statistical probabilities, i.e. within data from accidental databases. These data are the expensively paid mistakes that are measured by human lives, great material damage and long-term environmental consequences. The databases such as MHIDAS, MARS, FACTS, MAHB, CARAT, ARIP, NEDIES, ECCAIRS, and IRDAT represent *a posteriori* significant data in risk modeling.

Accidents in the system of hazardous substances, such as a chemical release, a fire, an explosion or the BLEVE effect, may cause great catastrophic consequences not only for employees in their workplaces, but also for the residents and the environment. In addition, the financial losses caused by damage on objects (parts of production plants, tanks) are enormous, and rehabilitation and their re-entry into operation require a lot of time. These effects also result in other serious influences, such as, for example, the inability to provide sufficient quantities of raw materials to connected and/or related industries.

The development of the oil and chemical industry has caused the use of large and complex facilities in their plants, resulting in a large increase in the storage space (tanks of different shapes and dimensions). In the meantime, due to the use of land (a lack of space) and for economic reasons, the distances between installations and warehouses have become increasingly smaller. This branch of industry continues to develop in the direction of intensive and deep processing, chemical processes end up mainly through a series of physical and chemical reactions, and their main raw materials and products are in the liquid and gaseous states that are toxic, flammable and corrosive (Liu, Zhang, & Xu, 2013). Therefore, risk for oil and chemical plants has dramatically increased, in particular so when the risk of explosions and fires is concerned.

In the case of an accident (a fire or an explosion), and bearing in mind all of the foregoing, there may be a chain disaster, and therefore it may endanger human lives, environmental safety, and material assets, and may also cause high environmental pollution, as well as other secondary consequences (Yu & Guan, 2016), (Pasley & Clark, 2000), (Kim et al. 2009).

Accidents in the process industry are most frequently a result of the release of hazardous materials, fires and explosions of process installations (Hemmatian et al. 2014.). The effect of the technical-technological connection of process installations is such that the occurrence of an accident in one part of the plant may lead to the escalation and occurrence of a series of cascade accidents – a domino effect (Abdolhamidzadeh et al. 2011), (Dabra et al. 2011). The storage of eco-friendly substances, such as TNGs, is particularly characteristic from the aspect of the appearance of a domino effect and the escalation of the initial incidents. A domino effect is a very important phenomenon in the process industry and was specifically referred to in the first version of the Seveco Directive (European Council Directive 82/501/ECC). The modifications of this Directive prescribe that the dangers of a domino effect must be assessed differently, depending on whether they work on indoor or outdoor industrial plants and whether they are reflected in the application of Directive 96/82/EC and 96/82/EC, or not. The occurrence of fire within technological installations is predominantly preceded by a discharge of inflammable liquids, gases or vapors (Bariha et al. 2016). The explosions of process equipment are most often due to the BLEVE effect or a mechanical damage caused by the fragmentation of fragments (Eckhoff, 2014), (Sun et al. 2015). The phenomenon of the fragmentation of a tank is characterized by the cause-effect relationship between the cascading events in the accidental chain (Khan & Abbasi, 1999). The occurrence of critical pressure in process equipment can be due to a mechanical (physical) explosion, a cold or warm BLEVE effect, a closed explosion or uncontrolled chemical reactions.

Failures on the installations and a potential escalation of accidents due to the fragmentation of process equipment are characterized by a high degree of uncertainty (Khakzad et al. 2018). Therefore, the analysis of a domino effect implies a previously conducted assessment of the fragmentation risk since the subsequent fragmentation of damaged process equipment establishes a potential accidental chain. The intensive development of the modern processing industry is characterized by a considerable risk of large-scale domino effects. The prevention of potential accidents is conditioned by the use of fragmentation barriers (Landucci et al. 2016), (Kang et al. 2016), the identification of the fragmentation mechanism (Baker et al. 1983), and the basic characteristics of the primary fragments that are defined by the number, shape, velocity, and trajectory (CCPS, 1994). The procedure for predicting the number and the mass of the fragments of cylindrical storage tanks for LPG was proposed by Baker et al. (Baker et al. 1997). The results of their study were the basis for several recent research studies in the field of the fragmentation of tanks (Hauptmanns, 2001), (Hauptmanns, 2001a). The purpose of fragmentation analysis is to prevent the installations and equipment of process plants from potential fragment impacts (Sun et al. 2017). The escalation of a potential damage to process installations is prevented by using the fragmentation barriers first implemented in nuclear installations (Moore, 1967).

Risk assessment due to the fragmentation of pressure vessels requires adequate hazard modelling, and the creators of the first fragmentation models were Moore and Baker (Moore, 1967), (Baker et al. 1983). In 77% of accidents, fragmentation was a result of the explosions of the pressurized vessels generating from 1 to 9 fragments (Holden & Reeves, 1985). Holden found that 60% of the generated fragments covered a sectoral angle of ±30° on both sides of the tank (Holden, 1988). Some recent studies have been based on the results of these studies (Mébarki et al. 2009), (Mébarki et al.2009a). Mébarki et al. suggested an entropy model for estimating the number of generated fragments (Mébarki et al. 2009). The typical explosions of tanks following industrial accidents were related to the BLEVE phenomenon (Eckhoff, 2014), (Zhang et al. 2016). Risk assessment due to the fragmentation of a tank involves modelling the fragment flight, and in the literature a simplified model for fragmentation analysis has exclusively been applied (Mannan, 2012).

2. BLEVE Effect

Among different possible major accidents, Boiling Liquid Expanding Vapor Explosions (BLEVEs) keep occurring from time to time. A number of pieces of equipment and activities such as: steam boilers, liquefied gas storage tanks, road and rail tankers, etc. can originate them (Hemmatian et al. 2019). Boiling Liquid Expanding Vapor Explosions (BLEVEs) are a major accident which can have severe consequences; they occur from time to time, both in fixed plants and in the transportation of hazardous materials. Overpressure and the ejection of vessel fragments are the common effects of such an explosion; these can be followed by a fireball if the substance is flammable. If a tank containing liquid or a liquefied gas is subjected to thermal loading from a fire, an explosion of the tank is possible. Such an event is called a BLEVE (Boiling Liquid Expanding Vapour Explosion) (Marshall, 1987), (Baker et al. 1983). If a liquid or a liquefied gas is combustible, a fireball (a large-scale diffusion flame with strong thermal radiation) is formed. During the destruction of the tank, the shock waves of a high amplitude are produced. Accidents involving BLEVE are characterized by the severe destruction of the plant, with people being killed. Such accidents took place in Fazen, France (1966), Mexico (1984), and Alma-Ata, Kazakhstan (1989). The serious consequences of BLEVE and a damage to the vessels containing LPG subjected to fire have drawn the attention of many investigators. Impact failure (44.8%) and the human factor (30.3%) were the most common causes of BLEVEs (Hemmatian et al. 2019).

The fragmentation of a tank due to the BLEVE effect is usually followed by the generation of two or three fragments, and very rarely four or five fragments (Nguyen et al. 2009). The fragmentation of a tank due to the BLEVE effect is characterized by the obligatory fire occurrence in the case of the generation of a smaller number of fragments (Mishra, 2016). In the literature, the assessment of the number of generated fragments is carried out by means of the entropy model using accident data (Mébarki, 2009). The number of generated fragments in the explosion of a tank is usually up to five, and very rarely exceeds nine (Holden, 1985), (Holden,1988). Nguyen et al. state that, according to the scientific reports of the INERIS, typical explosions (BLEVE) of cylindrical tanks are most often followed by the generation of two or three primary fragments (Nguyen, 2006). The application of the entropy model requires the mandatory inclusion of accident data (Sun et al. 2012). The accidents accompanied by the explosion of a tank are distinguished by the three effects: a blast wave, thermal radiation and fragmentation. The fragmentation of a tank is followed by the generation of primary fragments, while the blast wave initiates the formation of secondary fragments. Thermal radiation is a result of the formation of a fireball, whose influence in the explosion of the LPG tank having a volume of about 50 m^3 is manifested at the distances of up to 170 m, whereas the effect of secondary fragments is intensely expressed at the distances of up to 125 m (Plans et al. 2015.). The most pronounced effect of the explosion of a tank relates to fragmentation, since the range of fragments can reach as far as 1.2 km (Tugnoli et al. 2014).

BLEVE affects the previous occurrence of an incident in the form of a fire in the immediate vicinity of the tank, most often due to a discharge of inflammable substances or as a result of some other cause. A thermal impact on the walls of the tank is manifested by a reduction in the resistance of the material (a tensile strength), so that the destruction of process equipment will follow a lower critical pressure than the normal value (a value corresponding to a no-fire effect). The temperature effect is exclusively reserved for the BLEVE effect as there is not enough time for the other types of explosion to transfer heat to the walls of the tank (for example, in an uncontrolled chemical reaction, etc.).

Each type of indoor explosion (a tank) must be accompanied by shock waves, and in the case of fire-extinguishing substances by the emergence of a fireball (thermal radiation), too. The amount of these energies depends on the type of the explosion and the type of the dangerous substance. The explosion of toxic substances with non-flammable substances is not accompanied by thermal radiation, but due to the dispersion of toxic substances, additional hazardous substances arise in the form of the contamination of the surrounding area. A hazard due to thermal radiation does not exceed 200 m for an explosion of about 50 m^3 of TNG, whereas a toxic hazard from the same volume with unfavorable meteorological conditions may be up to several kilometers (Djelosevic & Tepic, 2018).

3. The Domino Effect

In terms of production facilities and particularly refineries, it is necessary to focus (in terms of transport and production processes) on storage capacities. The storage capacities consisting of the tanks of different types, sizes and shapes are used for the permanent or temporary storage of different classes of dangerous substances (oil and oil derivatives, gas, high-pressure liquids, various corrosive substances, etc.). When an accident occurs in the production/processing or storage facilities, the physical effects of that particular accident very often lead to a damage to another surrounding equipment. Taking this into account, a relatively small incident can be said to have the ability to escalate into an event causing a damage to a much larger surface and leading to far severer consequences; in practice, it is called a domino effect. Such effects are usually created and caused by the physical effects of primary accidents, such as (Chen et al. 2012):

- overpressure,
- fragments (impact fragments)
- thermal radiation, and
- heat flux.

Darbra et al. (2010) analyzed 225 accidents with the consequences of the domino effect in the processing, storage and transport plants in the period since 1961. On this occasion, the following aspects were analyzed: the accident scenario, the type of the accidents, the class/type of the substance, the causes and the consequences, as well as the most frequent accidents sequences. The analysis established the fact that the most common causes were: the external losses of 31% and the mechanical errors of 29%. Even 35% of the domino-effect accidents happened in the storage area, whereas 28% of them occurred in the processing plants. The flammable substances included 89% of the accidents, most of which were LPG. In the largest number of the cases, the damaged equipment has no ability to resist, thus leading to a leakage and a loss of hazardous material and additional scenarios:

a) explosion → fire (27.6%),
b) fire → explosion (27.5%), and
c) fire → explosion (17.8%).

The definitions of a domino effect contain the following three concepts (Cozzani et al. 2006), (Antonioni et al. 2009), (Nguyen et al. 2014):

1. a “primary” event (fire, an explosion) that occurs in a certain unit;
2. the propagation of the accident towards one unit or a larger number of units or plants, in which “secondary” accidents are triggered as a result of the primary event;
3. an “escalation” effect leading to a general increase in consequences, with such secondary accidents being severer than the primary one.

The oil and chemical industry include many flammable and explosive chemicals for production and storage, and manufacturing processes are performed at high temperatures or high pressures. There are many different pieces of pressure equipment in industrial plants, such as tanks (cylindrical, elliptical, and torispherical) containing gas (LPG) or high-pressure liquids. When it reaches a critical level of high pressure, overheating or mechanical stress, the tank can suddenly explode and generate many fragments (one or more, depending on the critical pressure, the crack propagation, the type of the material and the connection of the basic mechanical components) that pose a threat to another equipment or other adjacent tanks. So, the fragments caused by the explosion of the tank have an effect on other tanks, and this effect is reflected in a partial or complete breakdown and/or damage to adjacent tanks and equipment. Fragments are of different shapes, sizes, initial speeds, and initial departure angles (horizontal and vertical). According to the INERIS expert reports, a typical explosion (BLEVE) of a cylindrical tank creates a limited number of massive fragments, mainly two or three, and very rarely more than four or five.

4. The Probability of a Domino Effect

The accidents characterized by an explosion of process equipment in an installation are usually followed by a sequential sequence of events (a domino effect); so, in order to analyze risk, it is necessary to know the probability of the occurrence of the primary and secondary events of the observed accident chain. In this context, the probability of the occurrence of a domino effect requires the knowledge of the probabilistic probabilities of the consequent-causal events of one cycle of the emergency chain. The probability of producing a domino effect is presented by (1), if the primary and secondary events are marked as PD and SD, respectively.

$$P(PD \cap SD) = P(PD) \cdot P(SD \mid PD) \quad (1)$$

As is known from the theory of probability, the formulation (6.10) shows that the realization of a secondary event is dependent on the realization of the primary event that is the first in an accidental chain. The primary event is an independent event in an accidental sequence and has the role of linking multiple sequential events into a unique accidental chain. The conditional likelihood of the occurrence of a secondary event, provided that the outcome of the primary one is completely certain, has the following form:

$$P(SD|PD) = \frac{P(PD \cap SD)}{P(PD)} \tag{2}$$

It is important to point out the fact that the analysis of a domino effect in research studies is based on a conceptual misinterpretation since it interprets the probability of an accidental sequence without the probabilistic probability of primary and secondary events. In this way, the independence of events in an accidental chain is established, which is contrary to logical and mathematical principles. The basic risk factor for a hazard that can be the generator of a domino effect encompasses the probability of its occurrence and, therefore, great attention is paid to this phenomenon for this very reason.

The occurrence of a chemical accident during the technological process in the industrial plant for the production (processing) of hazardous substances is illustrated by the principle of the Bajes network. In order to simplify the considered illustration, that there are only two causes in the occurrence of the accident, namely the human factor and the unreliability of equipment, will be assumed.

The variables representing the human factor and the reliability of equipment are indicated by *HU* (Human Factor) and *RE* (Reliability of Equipment), respectively. Assign an expert assessment of the potential causes of a chemical accident due to *HU* and *RE* the following probabilities: $P(HU = yes) = p$ or $P(RE = no) = q$, respectively. If chemical accidents are marked as *ChmA*, and if it is supposed that a) the organized HU behavior is in accordance with the prescribed procedure, and that b) the embedded process equipment works reliably, then the technological process takes place normally without any hint of a possible accident and the same is valid: $P(CA = yes \mid HU = no, RE = yes) = 0$. However, the probability of the occurrence of an accident due to unreliable process equipment reads as follows: $P(CA = no, RE = no) = ½$. Since *HU* manages the work of the technological process, any significant deviation from the procedure of working with dangerous substances inevitably leads to the occurrence of an accident. This may be a result of unintentional omissions due to the irresponsibility of *HU* (the management or direct executors) and the preplanned organized activities in the form of sabotage, regardless of the motives for such actions. The probability of the occurrence of an accident, if caused by the harmful effects of *HU*, regardless of the degree of the reliability of process equipment, is as follows:

$P(CA = yes \mid HU = yes, RE = yes) = 1$ and $P(CA = yes \mid HU = yes, RE = no) = 1$.

The probability of the occurrence of an accident may be expressed based on the previous analysis by applying the following equation:

$$\begin{aligned} P(CA = yes) &= \sum_{HU,RE} P(CA = yes, HU, RE) \\ &= \sum_{HU,RE} P(CA = yes \mid HU, RE) \cdot P(HU \mid RE) \cdot P(RE) \\ &= \sum_{HU,RE} P(CA = yes \mid HU, RE) \cdot P(HU) \cdot P(RE) \end{aligned} \tag{3}$$

where $P(HU \mid RE) = P(HU)$ as a consequence of the assumption of the independence of HU and RE events. Then, after developing the sum of (3), the following equation is obtained:

$$\begin{aligned}P(CA=yes)=\ &P(CA=yes\mid HU=no,RE=no)\cdot P(HU=no)\cdot P(RE=no)+\\&P(CA=yes\mid HU=yes,RE=no)\cdot P(HU=yes)\cdot P(RE=no)+\\&P(CA=yes\mid HU=no,RE=yes)\cdot P(HU=no)\cdot P(RE=yes)+\\&P(CA=yes\mid HU=yes,RE=yes)\cdot P(HU=yes)\cdot P(RE=yes)\end{aligned} \tag{4}$$

$$\begin{aligned}P(CA=yes)&=\frac{1}{2}\cdot(1-p)\cdot q+1\cdot p\cdot q+0\cdot(1-p)\cdot(1-q)+1\cdot p\cdot(1-q)\\&=\frac{1}{2}\cdot q\cdot(1-p)+q\end{aligned} \tag{5}$$

where p and q represent, respectively:

the probability that the cause of the accident (*CA*) will be the human factor (*HU* = *yes*): $p = P(HU = yes)$, and the probability that *CA* will be equipment unreliability (*RE* = *no*): $q = P(RE = no)$.

These probabilities are a result of an expert assessment and can be obtained on the basis of statistical monitoring for *HU*, or according to the analysis of the reliability of process equipment in the real conditions of exploitation for *RE*. Adopting, for example, that p = 0.10 and q = 0.15, the probability of *ChmA* has the value $P(CA) = ½·q·(1\text{-}p)+q$ = ½·0.10·(1-0.10)+0.15=0.195.

The obtained probability $P(CA)$ = 0.195 represents the "*a priori*" probability of a chemical accident (CA) before observing any evidence.

$$\begin{aligned}P(HU=yes\mid CA=yes)&=\sum_{RE}P(HU=yes,RE\mid CA=yes)\\&=\sum_{RE}\frac{P(CA=yes\mid HU=yes,RE)P(HU=yes)P(RE)}{P(CA=yes)}\end{aligned} \tag{6}$$

$$\begin{aligned}P(RE=no\mid CA=yes)&=\sum_{HU}P(HU,RE=no\mid CA=yes)\\&=\sum_{HU}\frac{P(CA=yes\mid HU,RE=no)P(HU)P(RE=no)}{P(CA=yes)}\end{aligned} \tag{7}$$

By developing the sum in (6) and (7), and by replacing the concrete probability values, the following equation is obtained:

$$\begin{aligned}P(HU=yes\mid CA=yes)&=\frac{1\cdot p\cdot(1-q)+1\cdot p\cdot q}{\frac{1}{2}\cdot q\cdot(1-p)+q}=\frac{2}{3-p}\\&=\frac{2}{3-0{,}10}=0{,}689\end{aligned} \tag{8}$$

$$\begin{aligned}P(RE=no\mid CA=yes)&=\frac{1\cdot p\cdot q+\frac{1}{2}\cdot(1-p)\cdot q}{\frac{1}{2}\cdot q\cdot(1-p)+q}=\frac{1+p}{3-p}\\&=\frac{1+0{,}10}{3-0{,}10}=0{,}379\end{aligned} \tag{9}$$

5. Theoretical Analysis of a Tank

Horizontal cylindrical tanks for TNG storage are responsible technical systems designed according to EN 13445-3 (EN 13445-3:2014). The projected exploitation characteristics and the achieved quality of production are checked by testing the tank according to EN 13445-5 (EN 13445-5:2014). The two-axis stress state of the tank indicates the longitudinal and radial deformation of the shell. The analysis of the stress state of the tank is an integral part of the design activities in terms of fulfilling exploitation requirements. A typical shape of the horizontal cylindrical tank discussed in the continuation of this paper is presented in Fig. 2. The construction of the tank consists of the supports (item 1), the cylinder segments (items 2-5), the elliptical end caps (item 6), and the lifting lugs (item 7). The tank is supplied with the filling and discharging system (FDT), the measure and control system (MCS), the inspection hatch (IH), and the safety valve (SV). The empty tank mass is 12.3 t and provides storage of up to 50 m^3 of TNG.

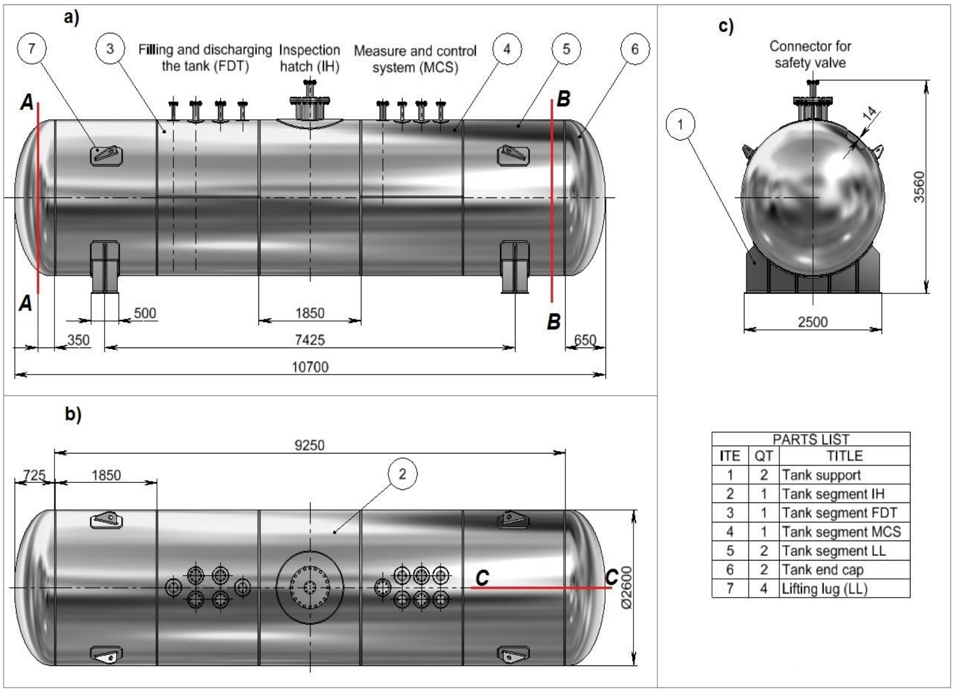

Figure 1. A horizontal cylindrical tank with the elliptical end caps according to DIN 28013

Horizontal cylindrical tanks have three critical cross-sections (Figure 1). The A-A critical cross-section is characteristic of tanks with torispherical end caps, whereas elliptical end caps influence the tank fracture at the B-B cross-section (Figure 1a). The fracture along the C-C cross-section exclusively occurs in tanks with spherical end caps (Figure 1b). The wall thickness of the tank is constant δ = 14 mm (Figure 1c). This condition is of great importance in the fragmentation model for the assessment of the initial velocity.

The critical zone of the tank in Fig. 1 corresponds to the passage of the cylinder into the elliptical end cap (B-B cross-section).

The critical zones of the cylindrical tank are estimated according to (10) and (11), derived from the basis of the substrate in (Ciarlet, 2000).

$$\sigma_{x,\max} = \sigma_x(x = 0.082m) = \left[1 + 0.292685 \cdot \left(\frac{D}{2h}\right)^2\right] \cdot \frac{D}{4} \cdot \frac{p}{\delta} \approx 100 \cdot p \qquad (10)$$

$$\sigma_{\theta,\max} = \sigma_\theta(x = 0.195m) = \left[1 + 0.031418 \cdot \left(\frac{D}{2h}\right)^2\right] \cdot \frac{D}{2} \cdot \frac{p}{\delta} \approx 104 \cdot p \qquad (11)$$

Authoritative stress for dimensioning the pressure vessel is given by (11). Permissible tress for the S355J2G3 (the tank material) is 195.83 MPa. The maximum operating pressure according to (11) is 1.88 MPa, whereas EN 13445-3 prescribes 2.12 MPa. The operating pressure of the LPG storage tank ranges from 16.4 to 16.9 bars (which is an average of 16.7 bars). Rationally designed tanks are characterized by a minimum difference $\sigma_{x,\max}$ and $\sigma_{\theta,\max}$, which is achieved by a D/2h ratio.

In the case under consideration, D/2h = 2; so, it follows $\sigma_{\theta,\max}/\sigma_{x,\max}$ = 4%. The critical zone is conditioned by the criterion (D/2h) = 2.086. The critical zone 1 is considered only if the tank head is elliptical. Then, it is always (D/2h) < 2; so, fragmentation is most often followed by the separation of the end cap from the tank cylinder due to the expansion of the fracture lines by circumference ($\sigma_\theta > \sigma_x$). The critical zone 3 dominates when $\sigma_\theta < \sigma_x$ (the hemisphere head); otherwise, the B-B cross-section is authoritative (Fig. 2). The estimation of critical zones according to (10) and (11) is limited to the generation of a smaller number of fragments due to the BLEVE effect.

The real stress of the tank varies between (10) and (11) due to the axial asymmetry. Therefore, the fragmentation of the tank generally requires the identification of real stress through software structural analysis. Figure 2 shows the critical areas of a cylindrical tank.

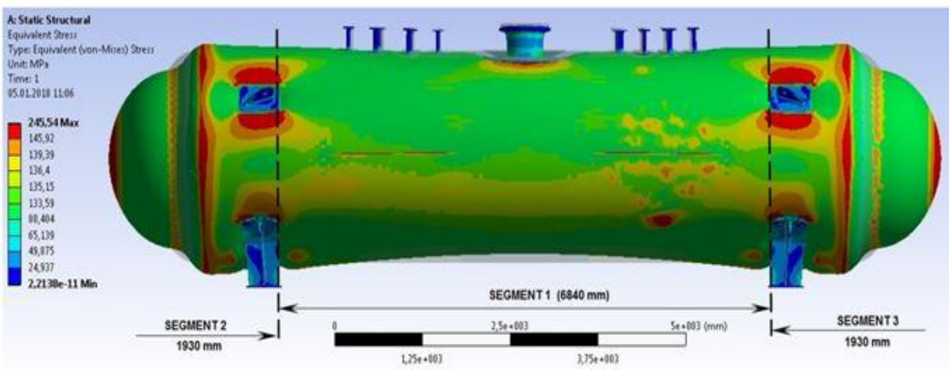

Figure 2. The software simulation of the critical zones of the tank (the pressure of 16.7 MPa)

When the crack spreads faster than the leakage of the fluid/liquid, an explosion of the tank occurs, where fragments are created, the size and velocity of which depend on the type of the cracks, i.e. the brittleness and flexibility of the material. The fragments projected due to the explosion of the tank can affect and damage adjacent objects and tanks in their surroundings. If these affected objects are, for example, pressurized containers, there is a risk that an explosion will occur, which would produce another set of projectiles/fragments. Such fragments can affect other devices and generate next explosions, thus leading to a scenario known as the “domino effect” (Ciarlet, 2000), (Cozzani et al. 2007), (Hauptmanns, 2001a), (Hauptmanns, 2001b), (Khan & Abbasi, 2001a), (Khan & Abbasi, 2001b), (Khan & Abbasi, 2001c), (Cozzani et al. 2009).

According to (Cozzani et al. 2007), (Baum, 1998a), (Baum, 1999b), (Baum, 2001c), (Cozzani, et al. 2006), when speaking about the reliability of industrial facilities and plants under possible explosions, it is necessary to observe and include the following development steps:

1. the analysis of conditional sources – the identification of the potentials of the plants/objects in which an explosion may occur, the knowledge of the conditions that may initiate/lead to an explosion, as well as the knowledge of the geometric dimensions, shapes, speed and frequency of the angles of the caused/generated projectiles;

2. the analysis of the influential term – the knowledge of the conditions that may cause/create the influence of other plants/facilities, the knowledge of the mechanical and geometric properties of the affected targets, the knowledge of impacts such as perforations or a partial penetration/break, as well as a possible creation of a new set of projectiles as a result of the failure/malfunction or explosion of the affected object/tank; and

3. the assessment of the reliability of the plants and facilities, and the consequences of the same.

Risk analysis in industrial plants often considers that random explosions generate the given categories and forms of structural fragments (Fig.3), i.e. standardize projectiles, the speed of which depends on the arbitrary ratio of the total energy. In addition, a detailed analysis is needed to assess the risk of the impact and the mechanical damage that may occur on the surrounding facilities and/or tanks.

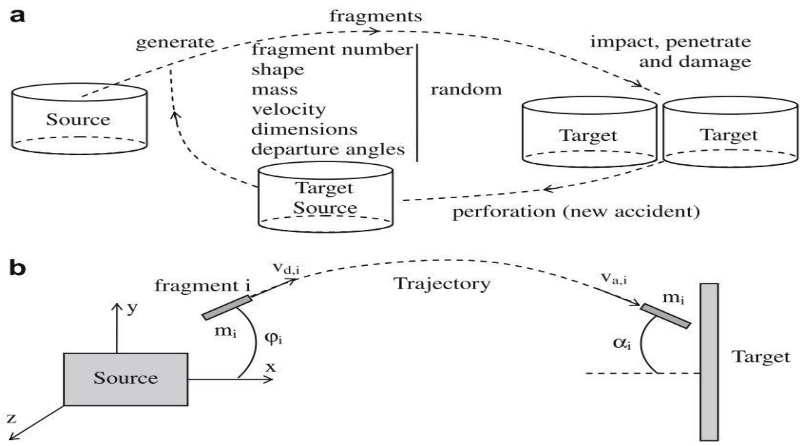

Figure 3. The projectile penetration, a residual resisting target thickness and the domino effect, a) a global view, b) a bi-dimensional model (Nguyen et al. 2009)

Fragments can be generated by various characteristics, such as the geometric shapes and dimensions, mass, velocity, and angles of the projection. If fragments affect the target (another tank), they can penetrate either completely or partially. The generated fragment penetrates partially or completely the second tank, which can cause an explosion of the adjacent tank (Fig.3).

Sophisticated mechanical models are necessary or may be required in order to analyze these dynamic effects and their consequences. Earlier reports (Gubinelli et al. 2004), (Yu, & Guan, 2016) show that there are generally three forms of generated fragments after industrial accidents or tank explosions, namely cylindrical, half-sphere, or plate (Fig.4).

In addition, the valve parts, as well as the tubular parts, may also be transformed into cylindrical shapes during the explosion. Obviously, the impact of a fragment may occur with any value of the angle between the fragment and the target, i.e. the second tank.

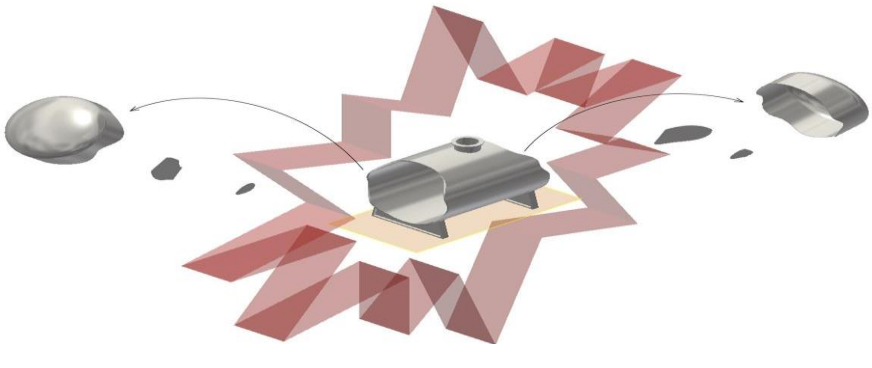

Figure 4. An illustration of fragmentation after a tank explosion

The equation of the motion of the generated fragments is presented below.

The vector form of the equation of motion of the fragment with mass m_{fr} and velocity v_{fr} is (Mébarki et al., 2009) is as follows:

$$m_{fr} \cdot \frac{d\vec{v}_{fr}}{dt} = \vec{W}_D + \vec{W}_L + \vec{G} \tag{12}$$

The force of air resistance in the fragment flight is as follows:

$$\vec{W}_D = -\left(\frac{1}{2}\rho_v C_D A_D v_{fr}\right) \cdot \vec{v}_{fr} \tag{13}$$

The lift force of the fragment in flight is as follows:

$$\vec{W}_L = -\left(\frac{1}{2}\rho_v C_L A_L v_{fr}\right) \cdot \vec{v}_{fr} \tag{14}$$

6. Conclusion

Critical infrastructures play a key role in the normal performance of economies and society. Many hazardous industrial activities provide society with indispensable goods and services. Some of these activities are considered as particularly critical, such as refining, oil and gas transport and distribution, or the production of rare specialty chemicals due to their criticality for ensuring human wellbeing and the smooth functioning of society. Over the past decades, the quantity and diversity of the critical infrastructure have grown rapidly and the interdependence between them has steadily increased. Therefore, an increasing number of the basic services depend on the continuous performance of one, two or more critical infrastructures, such as electricity and water supply, communications, etc.

Observing and reviewing the extreme events that have taken place over the past two decades have revealed that, although the interdependence between critical infrastructures is rapidly rising and becoming more complex, yet there is a huge gap between an increased risk and the actual readiness of the critical infrastructure to respond to extreme events such as accidents. It is also necessary to note that in addition to mechanical and technical causes, there are the external causes of accidents, i.e. natural disasters (e.g. earthquakes, tsunamis, etc.) that need to be analyzed given the fact their consequences are not negligible (e.g. Fukushima 2011).

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