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Assessment of missile hazards: Identification of reference fragmentation patterns

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ABSTRACT

Industrial accidents involving fragment projection were investigated. The analysis of fracture mechanics fundamentals allowed the exploration of the relations between the fracture characteristics and the final event leading to equipment collapse. Reference fragmentation patterns were defined on the basis of the geometrical characteristics of the categories of process vessels that are more frequently involved in fragmentation accidents. Primary scenarios leading to fragment projection were correlated to specific fragmentation patterns. A database reporting a detailed analysis of more than 140 vessel fragmentation events provided the data needed to support and validate the approach. The available data also allowed the calculation of the expected probability of fragment projection following vessel fragmentation, and the probability of the alternative fragmentation patterns with respect to the different accidental scenarios, based on the observed frequencies over the available data set.

1. Introduction

The catastrophic failure of process and storage vessels may result in the projection of fragments at relevant distances [1,2]. Several accidental scenarios, such as physical and confined explosions, boiling liquid expanding vapor explosions (BLEVEs), and runaway reactions may cause fragment projection [3–6]. The hazard due to fragment projection is well known [1,2], and comprehensive reviews are reported in the literature [7–10]. Besides the possible injuries or fatalities that may be caused to plant personnel and to population, the projection of fragments is among the more important causes of domino effects in industrial accidents [5,6]. Projection distances may be very high, and projected fragments are capable of generating secondary accidents at relevant distances from the primary scenario. Thus, safety distance criteria and preventive actions to avoid domino effect may hardly be applied [6,11,12].

In this framework, quantitative risk analysis (QRA) may provide useful criteria for the assessment of the risk caused by fragment projection, based on the assessment of consequences and expected frequencies [13–15]. However, a well-accepted and validated comprehensive approach to the quantitative assessment of risk caused by fragment projection is still missing. In particular, the estimation of the expected frequencies of domino scenarios caused by equipment fragmentation requires the availability of a reliable model for the assessment of fragments impact probabilities on a given target. Procedures based on a direct statistic analysis of post-accident data were proposed for the estimation of fragment impact probability, as well as for maximum fragment flight distance assessment [7,16]. More recently, comprehensive ballistic methodologies for the calculation of the impact probabilities of a fragment were developed [17–20], mainly derived from the fundamental approach to fragment trajectory analysis proposed by Baker et al. [10]. However, the results of these more advanced methodologies rely on the assessment of reliable ranges and/or probability distribution functions for the initial projection parameters (e.g. initial fragment velocity, number, mass and energy of fragments, fragment drag factor, etc.). These parameters are mainly dependent on the characteristics of the vessel that undergoes the fragmentation and on the scenario causing the vessel fragmentation [11]. In this framework, further investigations are required to assess the dependence of the relevant geometrical parameters of the fragments (number, shape, mass and drag factor) on the characteristics of the vessel and on the scenario causing the vessel fragmentation. The few previous publications available on this issue were mainly oriented to the analysis of pressurized liquefied gas vessels fragmentation due to fired BLEVEs [7,8,21,22].

Thus, a comprehensive approach to the quantitative assessment of risk caused by fragment projection is still missing, although several important studies are available mainly on fragment projection distances and on the assessment of impact probabilities.

The present study was dedicated to the analysis of the possible correlation among the vessel geometry, the accidental scenario causing vessel fragmentation and the shape and number of

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fragments generated. A database reporting data on accidental events involving the fragmentation of more than 140 vessels was developed. The analysis of the available past accident data suggested the presence of preferential fragmentation modes, depending on the accidental scenario and the vessel shape. The concept of “fragmentation pattern”, introduced by Holden, Westin and Reeves [7,8,21,22], was revised and further developed, also in the light of fracture mechanics fundamentals. Reference fragmentation patterns were defined and used to analyze and classify the fragmentation modes experienced in past accidents. The final aim of the analysis was the development of a limited set of credible fragmentation patterns for the assessment of the expected number, shape and drag factor of fragments generated in different accidental scenarios. The observed probabilities of each fragmentation pattern were also investigated.

It is worth mentioning that the present study was carried out within a more general research project, aiming at developing a comprehensive and systematic methodology for the quantitative assessment of fragment damage probability in the framework of quantitative risk analysis and of domino effect assessment [11,19,23].

2. Methods

2.1. Database of fragmentation accidents

The starting point of the present study was the retrieval of data on past accidents in which at least one equipment item underwent a catastrophic failure and/or caused the formation and the projection of fragments. In order to use past accident data to understand the possible fragmentation modes of process equipment and to relate them to the primary scenario causing the fragmentation, a detailed description of the event is needed. In particular, data are required on the following issues:

1. primary event leading to vessel fragmentation
2. type of vessel undergoing the fragmentation
3. data on vessel geometry and material (including data on wall thickness, vessel operating and design pressure)
4. number of the projected fragments
5. shape and geometrical data of the projected fragments
6. vessel fragmentation mode
7. distance and position of the projected fragments

Past accidents databases usually do not report accident case histories with such detail. Thus, more specific sources of information were sought out and a specific database was developed in order to retrieve and organize the available information on past accident data. Table 1 shows the original data sources for the 121 different accidental events included in the database. Two previous important studies, those of Holden [8] and Westin [21], were the source of 68 of the 121 accident files. The other records were obtained from scientific journals, including the Loss Prevention Bulletin, from miscellaneous open sources, or from professionals involved in accident investigations. The screening of the available data on accident location and date allowed the identification of multiple records and the integration of the information reported by the different sources on the same event.

Table 1
Sources of past accident data

Source	Number of events
Scientific journals	37
MARS database [24]	2
NTSB online reports [25]	8
Westin report [21]	35
Holden report [8]	33
Other	6
Total	121

Obviously not all the available files on past accidents reported all the data listed above. In particular, the information on fragment or on vessel geometry was not complete for some accidental events (e.g. in some reports data were missing on the fragment weight, the vessel thickness or the vessel material). When needed, these data were estimated introducing few assumptions: (i) the material was supposed to have the characteristics of AISI 316 stainless steel; (ii) in the case of pressurized vessels, the thickness was assumed as that calculated by the ASME VIII standards; and (iii) fragment mass was calculated on the basis of vessel thickness and of fragment shape. It must be remarked that these assumptions were introduced only in a limited number of cases, if needed to complete the accident analysis.

A further information that is usually not included in the past accident reports is the mode of vessel fragmentation, that will be defined in the following as the vessel “fragmentation pattern”. Fragmentation patterns usually are not discussed in standard accidental reports, although Holden [8] and Westin [21] defined a number of standard fragmentation modes and tried to identify which of them could apply to the events considered in their studies. However, since these data were missing for all the other accident records, it was decided to include in the database only the available information on vessel fragmentation, on the number and on the geometry of the projected fragments.

The data were organized generating three different data sheets for each accidental event, reporting, respectively, the data on the accidental event, on the fragmented vessel and on the fragments projected.

2.2. Analysis of the past accident database

The past accidents database was used to gather information on several issues concerning fragmentation events. In particular the following data were extracted:

- data on the primary scenarios leading to vessel fragmentation
- data on vessels categories involved in fragmentation accidents
- data on fragmentation patterns, including number and shape of fragments

These are discussed in Sections 3 and 4. The available data on the number of vessel fragmentation accidents experiencing different fragmentation patterns also allowed the estimation of observational probability data on the expected fragmentation patterns. These are reported in Section 5.

3. Accidental scenarios leading to fragment projection

3.1. Primary scenarios involving vessel fragmentation

The availability of an extended database of fragmentation accidents made possible the investigation of several issues concerning this category of accidents. In particular, the starting point of this study was the analysis of the different types of accidental scenarios resulting in the projection of missiles, also in order to identify the equipment categories more likely to undergo fragmentation.

Table 2 shows the results obtained from the analysis of past accident data. In the table, a short definition of each category of scenarios that caused the projection of fragments in at

Table 2
Scenarios leading to missile projection

Primary scenario	Description	Number of events
Fired BLEVE	Catastrophic failure of a vessel containing a liquid at temperature above its boiling temperature at atmospheric pressure, due to an external fire.	116
Unfired BLEVE	Sudden loss of containment of a vessel containing a liquid at temperature above its boiling temperature at atmospheric pressure, not due to an external fire.	22
Physical explosion	Catastrophic failure of a vessels containing a compressed gas phase and/or a non-boiling liquid, due to an internal pressure increase not caused by fire or chemical reactions. Possible causes: overfilling, corrosion, etc.	19
Confined explosion	Catastrophic vessel failure due to an internal pressure increase caused by the unwanted combustion of gases, vapours, or dust inside the vessel.	19
Runaway reaction	Catastrophic vessel failure due to an internal pressure increase caused by the loss of control of a chemical reaction.	11

least one of the accidental events recorded in the database is provided.

As shown in the table, unfired BLEVEs and physical explosions (as defined in Table 2) were considered separately, due to the different amount of energy available for fragment projection in these scenarios.

Table 2 also reports the number of events recorded in the database for each of the different scenarios. The table shows that a significant number of events were recorded for all the scenarios considered, although BLEVE resulted as the more frequent scenario leading to fragment projection. The higher number of events involving BLEVEs with respect to those due to confined explosion and runaway is on one hand related to the fact that BLEVE events are not limited to process plants but may take place also as a consequence of transportation accidents (as a matter of fact, all the events included in the report of Westin [21] concern transportation accidents). Moreover, BLEVE accidents are usually more severe, and thus are more frequently reported in sources of past accident data, than less severe scenarios.

3.2. Vessel categories involved in fragmentation scenarios

Table 3 reports a short description of the vessel categories involved in at least one of the accidental events reported in the database. The table also shows the number of events involving missile projection reported for each of the defined vessel categories. The total number of vessels is different from the total number of accidents reported in the database, since in several accidents the fragmentation of more than one vessel is reported.

As expected, Table 3 shows that pressurized cylindrical vessels are the vessel category more frequently involved in this type of accidents, since this type of vessels is the more frequently used for the storage of liquefied compressed gases.

In the case of atmospheric vessels, overpressure was caused mainly by physical explosions, confined explosions and runaway reactions. All these scenarios lead to an internal pressure exceeding design pressure and to fragment projection, even if the absolute pressure at the moment of vessel failure was lower than in pressurized vessels. This is confirmed by the lower projection energy of the fragments, that are usually projected to distances about one order of magnitude lower (10–100 m) than in the case of pressurized vessel fragmentation.

Table 4 shows the number of events recorded for each combination between the above defined primary events and the different vessel categories identified. The table points out the presence of correlations between the accidental scenario and the type of vessel that is likely to undergo fragmentation leading to missile projection. The observed correlations are possibly caused by the different hazards of the process operations for which the different categories of vessels are usually employed. As a matter of fact, BLEVE events leading to vessel fragmentation mainly affect cylindrical and spherical pressurized tanks, used for liquefied gas storage. On the other hand, atmospheric vessels including cone roof tanks are likely to undergo fragmentation accidents mainly due to mechanical and confined explosions, or to runaway reactions.

In a QRA framework, the simple correlations shown in Table 4 may be used as a starting point to identify the equipment items that should be considered as a credible source of missiles, suggesting the more likely categories of accidental scenarios that may involve fragment projection for the different categories of vessels.

4. Analysis of vessel fragmentation patterns

4.1. Expected fragmentation patterns on the basis of fracture mechanics fundamentals

The geometry and the number of projected fragments derive from the fragmentation mode of the vessel involved in the primary accident, also indicated as fragmentation pattern in the present approach. The fragmentation pattern of a vessel is a consequence of crack formation and propagation due to a too high internal vessel pressure.

The mechanism by which cracks propagate is an important factor that may affect the equipment failure mode. The fundamentals of crack formation and propagation in metallic shells are well known and extensively described in several authoritative publications. A discussion of these issues is out of the scope of the present

Table 3
Categories of vessels involved in fragment projection accidents

Primary vessel type	Number of events	Range of vessel volumes (m^3)	Range of vessel design pressures (bar)
Horizontal cylindrical atmospheric vessel	3	50–100	Atmospheric[a]
Vertical cylindrical atmospheric vessel	10	15–60	Atmospheric[a]
Cone-roof atmospheric tank	5	40–9000	Atmospheric[a]
Other sharp-edged atmospheric equipment	2	50–100	Atmospheric[a]
Horizontal cylindrical pressurized vessels	132	50–300	5–65
Vertical cylindrical pressurized vessels	21	1–1600	10–450
Spherical pressurized vessels	13	700–2400	15–25
Other pressurized vessels	1	n.a.	27[b]

[a] Design pressure for atmospheric vessels is not reported in accident reports, but is usually comprised between 1 and 1.3 bar, while hydraulic test pressure of these vessels is usually between 1.5 and 2 bar.

[b] Recorded burst pressure.

Table 4
Number of accidental events recorded for each combination between primary event and vessel category

Primary vessel type	Primary scenario				
	BLEVE		Physical Explosion	Confined explosion	Runaway reaction
	Fired	Unfired			
Horizontal Cylindrical Atm. Vessels	0	0	1	1	1
Vertical Cylindrical Atm. Vessels	0	0	2	6	2
Cone-Roof Atmospheric Tanks	0	0	1	4	0
Other sharp-edged Atm. equipment	0	0	0	1	0
Horizontal Cylindrical Press. Vessels	100	19	8	0	5
Vertical Cylindrical Press. Vessels	5	1	5	6	4
Spherical Pressurised Vessels	11	2	0	0	0
Other Pressurised Vessels	0	0	0	1	0

Grey cells: likely combinations between primary event and vessel type in missile projection accidents.

study. However, in order to better understand the expected fragmentation patterns of the different category of process vessels following the different explosion scenarios identified in Table 2, few fundamental concepts were briefly recalled in the followings.

It is well known that there are two basic failure modes: brittle fracture and ductile fracture [26]. A brittle fracture may be roughly defined as a fracture in which there is no evident plastic deformation at the crack tip or crack front [26]. Generally a high toughness material tends to undergo ductile fracture behaviour while a low toughness material is prone to a brittle fracture behaviour. However, Fig. 1 shows that the material toughness increases with the temperature and decreases with the loading rate. Thus, the likelihood of a brittle fracture is increased by low temperatures and high loading rates.

Although in metallic materials plastic deformation always occurs in front of the advancing crack, it has been demonstrated that also in these materials the energy required for the crack growth during brittle fracture is constant [27]. The typical propagation rate of a brittle fracture is of about 600–800 m/s [26,28]. The comparison of these values with the acoustic velocity of gases at ambient temperature (about 400 m/s), that may be assumed as a reference value of the outflow rate of the vessel content from the cracks, suggests that for brittle fracture the vessels depressurization during fracture propagation is not credible. Thus, during brittle fracture vessel internal pressure is almost constant and crack arrest is not credible. Moreover, if the stress value due to internal pressure is sufficiently high, the fracture can branch. In particular, crack branching is credible during confined explosions or runaway reactions, since in these scenarios the internal pressure may increase even after crack initiation. Crack branching may result in the fragmentation of a vessel into a large number of pieces.

On the other hand, ductile fracture is associated with large plastic deformations at the crack front or crack tip [26]. In a ductile fracture, the crack growth requires energy for the formation of a new plastic zone at the tip of the advancing crack. This should be

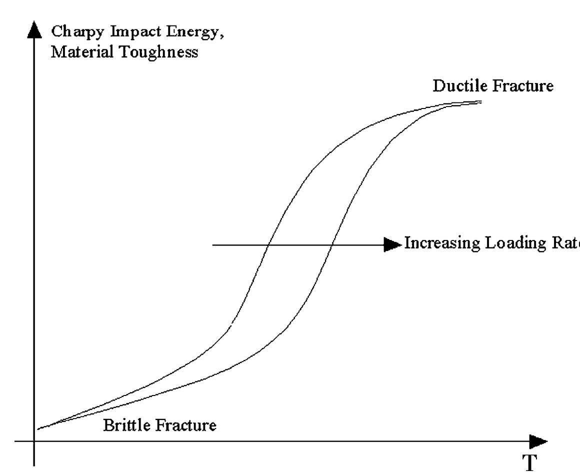

Fig. 1. Likelihood of the type of fracture with respect to loading rate, temperature and material toughness.

Table 5
Relations between the type of the primary scenario, the fracture mechanics and the fragmentation characteristics

Primary scenario	Acronym	Load parameters	Fracture mechanics and dynamics	Fragmentation properties
Fired BLEVE	BLEVE(F)	Low dP/dt and low dσ/dt	Ductile fracture	Low fragment number
		High wall temperature	Low fracture velocity: possible depressurization after crack initiation No branching	Possible crack arrest (due to depressurization and hot-cold zone transition)
Unfired BLEVE	BLEVE(NF)	Low dP/dt and low dσ/dt	Ductile fracture (plastic deformation at the crack tip)	Low fragment number (high fragment number likely only for ME with very low wall temperature)
Physical explosion	ME	Low wall temperature	Low fracture velocity but higher than BLEVE(F): vessel depressurization not credible. Branching possible only for very low wall temperature	Possible crack arrest for high toughness material (brittle-ductile transition)
Confined explosion	CE	High dP/dt and high dσ/dt Low wall temperature	Brittle fracture High fracture velocity: no vessel depressurization Branching	High fragment number
Runaway reaction	RR(low)	Low dσ/dt; low wall temperature	For “low” pressure increase (depressurization possible, stress increase significantly lower than crack propagation), expected behaviour similar to ME	
	RR(high)	High dσ/dt; low wall temperature	For “high” pressure increase (depressurization not relevant, stress increase comparable to than crack propagation), expected behaviour similar to CE	

added to the energy needed for the initiation, growth and coalescence of voids [26,27,29]. The sum of these two energies is higher than that required for the rupture of the atomic bonds in a brittle fracture. Thus, the branching of ductile fractures is scarcely credible due to the higher energy required by the advancing crack.

The propagation rate of a ductile fracture is of the order of 200 m/s, therefore vessel depressurization may take place during ductile fracture propagation. Thus, two crack arrest mechanisms are credible for ductile fractures: (i) arrest due to stress decrease caused by vessel depressurization, and (ii) arrest due to crack propagation from a hot zone to a cold zone where the material has a higher allowable stress. The latter crack arrest mechanism is of particular relevance in the case of BLEVE due to external fire. In the case of high toughness material, as a low carbon steel or an austenitic stainless steel, a further crack arrest mechanism is due to brittle-ductile transition, fully described elsewhere [26].

Therefore, the actual mechanism of fracture propagation could be influenced by the type of material, the shell thickness, the shell temperature, and the loading rate. Correlating the general features of pressure and thermal load in the different primary scenarios likely to cause vessel fragmentation, it is possible to draw basic information on the expected fracture mechanisms and on the consequent failure modes of the process vessels undergoing the event. Table 5 reports the results of a qualitative analysis performed for the primary scenarios listed in Table 2. The table shows that very simple relations could be drawn between the primary scenario and the expected number of fragments. These were derived considering the likely fracture mechanism and the credibility of crack branching and/or of crack arrest as a consequence of the typical behaviours of the shell loads due to internal pressure and wall temperature during the different scenarios. As shown in the table, a specific fragmentation mechanism and a qualitative evaluation of the fragment number may be associated to each primary scenario likely to cause vessel fragmentation, with the exception of runaway reactions. Ductile fractures resulting in a limited number of fragments are expected to be the prevailing fragmentation mechanism in BLEVEs and in physical explosions. On the other hand, in the case of confined explosions and of runaway reactions, brittle fracture resulting in a high number of fragments is expected, although brittle-ductile transition is possible for high toughness vessels. In the case of runaway reactions very different pressurization rates may take place [30], thus resulting in the different vessel fracture behaviours shown in Table 5.

Important outlines on the mode of fragmentation may be drawn also considering the influence of the vessel shape on the crack propagation. The propagation of a crack on a vessel occurs in a normal direction to that of the maximum stress. Thus in cylindrical shells the cracks tend to start in the axial direction, since the circumferential stress is higher. The fracture may propagate in the circumferential direction only due to stress field changes caused by bends, and to stress intensification areas due to connections or to defects in the material (e.g. weldings). In spherical shells the fracture may start and propagate in any direction, although areas where material defects or stress intensification due to connections are present are those where crack initiation is more likely.

4.2. *Definition of reference fragmentation patterns*

On the basis of the above discussion, it was possible to define a reference set of expected fragmentation patterns. The concept of reference fragmentation pattern was first applied to the analysis of vessel fragmentation by Westin [21], that recognized that a limited number of reference patterns was sufficient to describe the modes of fragmentation of cylindrical vessels containing liquefied petroleum gas (LPG) undergoing BLEVE events. Reference fragmentation patterns were used to classify the observed vessel fragmentation mode also in the work of Holden [8], although also in this case only the fragmentation of horizontal cylindrical vessels subjected to BLEVE was considered. Limited attention was dedicated by these authors to the role of axial cracking, since this mechanism is scarcely relevant in the detachment of fragments during fired BLEVEs.

In the present study, fracture mechanics fundamentals were used to develop a set of reference fragmentation patterns for all the vessel categories listed in Table 3. The reference fragmentation patterns defined in the present study represent a revision and an extension of those introduced by Westin [21] and Holden [8], mainly based on the analysis of both axial and circumferential crack propagation modes on different equipment categories.

Fig. 2 reports a graphical representation of the reference fragmentation patterns identified, that are briefly described in Tables 6 and 7. As shown in Table 6, for cylindrical shells all the possible combinations of axial and circumferential crack propagation were examined. No distinction was made between horizontal and vertical cylindrical vessels.

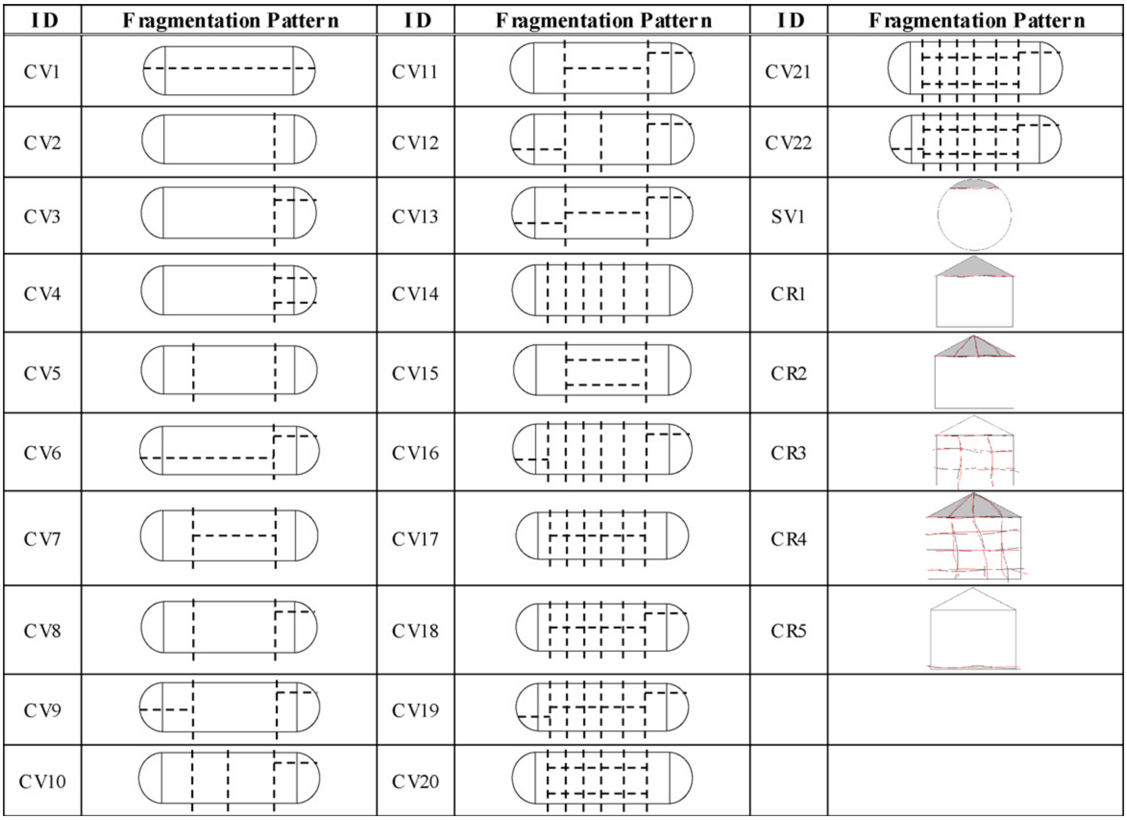

Fig. 2. Graphical representation of the reference fragmentation patterns.

Table 6
Expected FPs for cylindrical vessels

ID	N_F	Fracture description	Notes
CV1	1 or 2	1 AF	The fracture usually starts in the axial direction. The fracture starts to propagate in two opposite direction. If the crack does not arrest and the two tips meet, two fragments are formed. If not (more probable), 1 fragment (the entire vessel) may be projected, but no detached piece is formed No branching and no direction turn (no connections, no defects) should take place to obtain this FP
CV2 CV2’	2	1 CF	The fracture, likely to start in the axial direction, may turn in the circumferential direction due to stress field changes (bending or stress intensification near connections), or to defects. If the axial crack propagates on the tube-end and stops, a flattened tube-end may be generated. In Annex 1, a distinction was made between CV2 FP, yielding 2 tube-ends, and CV2′ FP yielding a tube-end and a flattened tube-end
CV3	3	1 CF + 1 AF on the end	Credible if the fracture starts on a pipe connection or if one of the two tube ends impacts on a near object at the moment of the projection
CV4	>3	1 CF + >2 AF on the end	Credible if the fracture starts on a pipe connection or if one of the two tube ends impact on a near object at the moment of the projection. The axial fractures on the tube-end could arrest originating flattened tube-ends
CV7	3	1 axial fracture + 2 CF	A longitudinal crack may deviate in circumferential direction in zones where a stress concentration (thickness change, supports, pipe connections), defects or weldings are present. It is highly probable that the circumferential cracks are located at the ends
CV11	5	2 CF + 1 axial fracture + 1 AF on the end	See CV7 and CV3. The axial fracture on the tube-end may arrest originating a flattened tube-end
CV13	6	2 CF + 1 axial fractures + 2 AF on the end	See CV7 andCV3. Less probable than CV11. The axial fracture on the tube-end could arrest originating a flattened tube-end
CV18	>3	>2 CF + 1 AF	A longitudinal fracture branches in various points, starting circumferential fractures. Credible only for CE (brittle fracture). Only in brittle fracture a high number of crack surfaces are formed
CV19	>4	>2 CF + 1 AF + 1 AF on the end	See CV18. The axial fracture on the tube-end could arrest originating a flattened tube-end
CV20	>5	>2 CF + 1 AF + 2 AF on the end	See CV18. This FP is a general representation of FPs CV18 to CV20. The axial fracture on the tube-end could arrest originating a flattened tube-end
CV21	>4	>2 CF + >1 AF	See CV18
CV22	>5	>2 CF + >1 AF + 1 AF on the end	See CV18
CV23	>6	>2 CF + >1 AF + 2 AF on the end	See CV20. This could be used as the general representation of FPs CV21 to CV23. The axial fracture on the tube-end could arrest originating a flattened tube-end

N_F: expected number of fragments; AF: axial fracture; CF: circumferential fracture.

Table 7
Expected FPs for spherical vessels and cone roof tanks

ID	N_F	Fracture Description	Notes
SV1	>4	Fractures propagate in various directions	A fracture on a spherical vessels may propagate in all directions because it will be always subjected to the same stress. It is possible to have more than one crack starting point The number of fragments tends to grow with the vessel volume (higher the volume of the sphere, higher the surface area) because there is a higher probability for the fracture to branch
CR1	1 (roof)	Fracture along the roof-shell edge	Highly probable since the edge is a zone of stress concentration
CR2	>2 (pieces of roof)	Fracture along the roof-shell edge and along the roof	As CR1 but the fracture must branch. Unlikely, since the roof generally has a reinforced structure. May be the result of the impact of the roof with the ground after the projection
CR3	>2 (pieces of shell)	Fractures propagate in various directions. On the shell	The fracture starts more probably at roof edge or at the connection of the lateral wall with the basement. Axial fractures may start, but it is highly probable that the depressurization of the vessel will cause the crack arrest and crack branching is unlikely. The fracture may propagate from the roof to the base, but it is unlikely that a fragment may be formed from the lateral wall
CR4	>2	Fractures propagate in various directions. On the shell and on the roof	See CR2 and CR3
CR5	1	Fracture along the base-shell edge	Probable, since the edge is a zone of concentration of stress and a weak part of the vessels. Less probable than CR1, since the fragment mass is so high that an high energy of explosion will be necessary for its projection

N_F: expected number of fragments.

Table 8
Observed number of events for each FP

FP	BLEVE (F)	BLEVE (NF)	ME	CE	RR	All
CV1	5	0	0	0	2	**7**
CV2	46 (16*)	10	6	9	3	**74**
CV3	9	2	0	0	0	**11**
CV4	0	3	0	0	0	**3**
CV5	0	0	0	0	0	**0**
CV6	0	0	0	0	0	**0**
CV7	23	1	1	0	1	**26**
CV8	0	0	0	0	1	**1**
CV9	0	0	0	0	0	**0**
CV10	1	0	0	0	0	**1**
CV11	0	0	1	0	0	**1**
CV12	0	0	0	0	0	**0**
CV13	0	0	0	0	0	**0**
CV14	0	0	0	0	0	**0**
CV15	0	1	0	0	0	**1**
CV16	0	0	0	0	0	**0**
CV17	0	0	0	0	0	**0**
CV18	2	0	0	0	0	**2**
CV19	0	0	0	0	0	**0**
CV20	0	0	0	0	0	**0**
CV21	3	0	0	1	1	**5**
CV22	0	0	1	0	0	**1**
CV23	0	0	0	0	0	**0**
tot CV	89	17	9	10	8	**133**
SV1	11	2	0	0	0	**13**
CR1	0	0	0	3	0	**3**
CR2	0	0	0	0	0	**0**
CR3	0	0	0	0	0	**0**
CR4	0	0	0	0	0	**0**
CR5	0	0	0	0	0	**0**
tot CR	0	0	0	3	0	**3**

Grey cells: unlikely FPs. *CV2′.

Although all the fragmentation patterns shown in Fig. 2 should be considered possible, on the basis of fracture fundamentals it was possible to identify a more limited set of likely fragmentation patterns for each primary scenario listed in Table 2. This was defined taking into account the influence of the vessel shape, fracture initiation, preferred initial location, fracture propagation mechanism, and credibility of branching and arrest mechanisms. The results obtained are shown in Table 8, that reports the likely fragmentation patterns identified in the present analysis for each primary scenario. As shown in the table, in the case of physical explosion, fragmentation patterns resulting in a high number of fragments (CV18–23) were considered likely only in the case of cryogenic vessels. These fragmentation patterns were considered credible also for runaway reactions resulting in a high rate of pressure increase (see Table 5).

It is worth to recall that in the case of cone-roof tanks, only physical explosions, confined explosions and runaway reactions are likely to cause the fragmentation of the equipment, as shown in Table 4. In the case of spherical vessels, only BLEVE events are credible, since these vessels in general are used only for the storage of liquefied pressurized gases.

It is important to remark that the definition of the fragmentation patterns allows the identification of the expected number and of the shapes of the fragments. Table 9 reports the expected shape and number of fragments for some fragmentation patterns. It must be remarked that in the present study the number of fragments should be intended as the final number of parts in which the vessel is fragmented, including the vessel main body. Moreover, only fragments having relevant sizes (more than 2% of empty vessel weight) were considered.

4.3. Analysis of the observed fragmentation patterns

The data collected on past accidents involving vessel fragmentation were used for the validation of the above defined reference fragmentation patterns. The fragmentation accident database was used to identify the actual fragmentation patterns observed in accidental events. In order to carry out this task, it was necessary to analyze the available data on fragment number and shape in the theoretical framework presented above, in order to understand if one of the above defined reference fragmentation patterns could be associated to the vessel failure mode. Only the accidents for which sufficient information was available were considered in the analysis, and account was given to the possibility of fragment rupture following the impact with the ground or with other equipment items.

A first important result of the analysis of accident data is that the vessel fragmentation mode could be associated to one of the above defined reference fragmentation patterns in all the fragmentation events for which enough data were available. Table 8 shows the distribution of the fragmentation patterns obtained from the analysis of the accidental events recorded in the database. The distribution of the events, reported in the table, shows that a quite limited number of different fragmentation patterns (14) were sufficient to describe the fragmentation modes of the 149 vessels analyzed.

Table 8 also reports the distribution of the fragmentation patterns for the different categories of primary scenarios. The table also shows that 141 of the 149 events fall within the set of likely fragmentation patterns defined above. With the available information it was not possible to clearly identify what caused the vessels to fragment by unexpected patterns in 8 events. Possibly, specific factors (as very high pressure increase rates, or the presence bending momentum due to pipe connections, or the influence of the internal structure) played a role. However, it must be remarked that in all these 8 events the unexpected fragmentation patterns could be also explained as the rupture of the cylindrical shell due to an impact following vessel fragmentation and fragment projection.

The analysis of past accident files also allowed the retrieval of data on the number of fragments formed as a consequence of the different fragmentation patterns. The mean number of fragments resulted strongly dependent on vessel category and on the primary scenario causing the fragmentation. Table 9 reports the available data for the different fragmentation patterns. The table also allows a comparison of the actual number of fragments formed with that expected on the basis of the theoretical analysis of the fragmentation patterns reported in Tables 6 and 7. As shown in Table 9, the observed number of fragments resulted always correlated with the expected number of fragments in each fragmentation pattern. Also the observed fragment shape resulted coincident with that expected from the reference fragmentation patterns, although flattened fragments were observed in several cases. In particular, the shell fragments formed in the CV1, CV7 and CV21 fragmentation patterns are usually flattened, possibly due to the impact on the ground following the projection. Moreover, flattened tube end fragments were formed in some fragmentation events following the CV3 pattern. These results are in agreement with those obtained by Birk [31], that reports fragment flattening in several full-scale experimental tests. A further discussion concerning fragment shape and number is reported elsewhere [32].

Table 8 shows that, even if few data are available, spherical vessels and atmospheric cone-roof tanks evidence a single fragmentation mode (SV1 and CR1, respectively). In both cases, the observed fragmentation pattern was among the set of likely reference patterns defined above. It must be also remarked that the accidental events recorded in the database for these vessel categories are mainly related to a single accidental scenario (fired BLEVE for spherical vessels and confined explosion for conical tanks). Thus,

Table 9
Expected and observed number of fragments for each fragmentation pattern

FP	Expected fragment number	Mean observed number of fragments	Fragment shape
CV1	1	1	Cylindrical shell or flattened cylindrical shell
CV2	2	2	Two tube ends (one flattened in the case of CV2′)
CV3	3	3	One tube-end and two parts of tube-end
CV4	>3	4	One tube-end and three parts of tube-end
CV7	3	3	Two tube ends and a flattened shell
CV11	5	5	One tube-end, two parts of tube-end and one flattened shell
CV18	>3	4	Several shell and tube-end parts
CV21	>4	5	Two tube-ends and several shell parts
SV1	>1	8	Parts of spherical shell
CR1	1	1	Cone roof

N_F: number of fragments.

besides the influence of vessel geometry, the presence of a single fragmentation pattern may also depend on the presence of a preferential scenario that caused the vessel fragmentation.

A more complex situation is present for cylindrical vessels, for which a higher number of fragmentation modes was observed (12). For this vessel category, the fragmentation patterns resulted also dependent on the primary scenario. As shown in Table 8, CV2 is the prevailing fragmentation pattern for all the scenarios. In several events (e.g. 16 of the 46 fired BLEVE events), a flattened tube end was formed (CV2′). An important number of events could be associated also to the CV3, CV7 and CV11 reference patterns. In a limited number of events also the CV1 fragmentation pattern was recorded. However, it must be remarked that in the CV1 fragmentation pattern, the axial fracture may stop outside the heated zone of the vessel (in particular in the case of jet fire impingement resulting in a partial wall engulfment) causing only a loss of containment but not fragment projection. Such events may have been under-reported or not described as vessel fragmentation accidents in past accident reports [7].

Thus, the above data show that patterns resulting in the formation of a low number of fragments were the more frequent fragmentation modes for BLEVEs and physical explosions. The observed average number of fragments for cylindrical vessels undergoing a fragmentation is 2 in the case of a BLEVE, and 3 for a physical explosion.

Patterns resulting in a higher number of fragments (CV21) were relevant for events originated by confined explosion and runaway reactions. As expected, the CV22 event recorded for physical explosions involved a cryogenic vessel.

A limited number of events following the CV18 and CV21 fragmentation pattern was observed also in the case of fired BLEVEs. Besides the possible rupture of fragments due to the impact with the ground, the high number of fragments formed in some of these events (up to 9) also suggests the possibility of fragmentation by a brittle fracture mechanism in the cold zones of the vessel wall, outside the section engulfed in the fire.

5. Expected probabilities of fragmentation patterns

5.1. Probability of fragment projection

The analysis of the available data also allowed the estimation of the expected probabilities of fragment projection given vessel fragmentation. The probability of fragment projection given vessel fragmentation is dependent on the probability with which the fracture propagates all over the equipment shell giving origin to at least a single fragment that will be projected away from the equipment. The problem is particularly critical in the case of fired BLEVE scenarios, in which the fracture may stop outside the heated wall area, causing a loss of containment but not vessel fragmentation [33]. If the vessel fragmentation accidents induced by fired BLEVEs reported in the database are examined, a conditional probability of 0.9 is observed for fragment projection following vessel failure. This is in accordance with the findings of Holden and Reeves [7], that report as well a conditional probability of 0.9 for the fragment projection following vessel failure in BLEVE accidents.

No events involving vessel fragmentation without fragment projection are recorded in the database for scenarios different from fired BLEVEs (see Table 3). Although this may be in part a consequence of the criteria used for accident collection, the under-reporting of events involving vessel rupture without fragment projection for causes different from BLEVEs was observed also in previous studies [7]. Thus, on the basis of the discussion concerning the crack propagation mechanism observed for physical explosions and unfired BLEVEs, summarized in Table 5, it seems reasonably conservative to assume for these scenarios a fragment projection probability equal to 0.9, in analogy with that estimated for fired BLEVEs.

Table 10
Probability of fragment generation after initial crack propagation, P_{cp}

Type of primary event	P_{cp}
BLEVE, fired	0.9
BLEVE, unfired	0.9
Physical explosion	0.9
Confined explosion	1
Runaway reactions	1

On the other hand, a conservative value of the fragment projection probability equal to 1 should be assumed in the case of confined explosions and runaway reactions, since in these events the crack arrest is unlikely. Table 10 summarizes the probabilities of fragment projection due to crack propagation estimated in the present study.

5.2. Conditional probability of alternative fragmentation patterns

On the basis of the data reported in Table 8 it was possible to estimate the probability of a given fragmentation pattern to take place in any of the different types of accidental scenario considered for each category of primary vessel. These probabilities were expressed in the following as conditional probabilities of a fragmentation pattern given the vessel fragmentation resulting in fragment projection. The probabilities were calculated as the observed frequencies of the fragmentation pattern of interest on the data set considered.

The results of the analysis evidences that for two equipment categories a single fragmentation pattern was observed: CR1 in the case of cone-roof tanks and SV1 for spherical vessels. Thus, a conditional probability equal to 1 may be assumed for these fragmentation patterns.

In the case of cylindrical vessels, the observed frequencies calculated for the different fragmentation patterns are reported in Table 11. The data on events caused by physical explosions and unfired BLEVEs are presented together in the table, since the only difference between these primary events is the available explosion energy. Few assumptions were introduced to obtain the data reported in Table 11. In particular, the very limited number of events in which unexpected fragmentation patterns were observed were not considered in the analysis, since it was not possible to assess if vessel fragmentation actually followed these unexpected fragmentation patterns or if fragment rupture took place after fragment formation and projection. Thus, it was decided to exclude these accidents in the calculation of the observed frequencies reported in Table 11. Moreover, for BLEVE accidents, the CV1 fragmentation pattern was also excluded, since the probability of fragment projection following this fragmentation pattern was found to be negligible. This may be easily explained, since when this fragmentation pattern takes place, the vessel shell is generally flattened on the ground due to the start of the axial crack in the upper zone of the vessel, where no liquid is in contact with the vessel walls. As a matter of fact, no accidents involving fragment projection following a CV1 fragmentation pattern are reported in the database.

Clearly enough, deriving the expected probabilities from observational data results in reliable probability values only if the number of observed events is sufficiently high. Thus, Table 8, reporting the number of events for each scenario and vessel category, shows that robust probability values were possibly obtained

Table 11
Number of events and observed frequencies (%) of FPs for cylindrical vessels

	BLEVE (F)	ME BLEVE(NF)	CE	RR	Total
Number of Events					
CV1	5	0	0	2	7
CV2	46 (16*)	16	9	3	74
CV3	9	2	0	0	11
CV4	0	3	0	0	3
CV7	23	2	0	1	26
CV11	0	1	0	0	1
CV21	0	0	1	1	2
Total	83	24	10	7	124
Observed Frequency					
CV1	6	0	0	29	6
CV2	55 (19*)	67	90	43	60
CV3	11	8	0	0	9
CV4	0	13	0	0	2
CV7	28	8	0	14	21
CV11	0	4	0	0	1
CV21	0	0	10	14	2
SUM	100	100	100	100	100

* CV2′.

for cylindrical and spherical vessels, while only preliminary figures were estimated for cone-roof tanks, due to the more limited number of case-histories available.

6. Conclusions

An approach was proposed for the assessment of the possible fragmentation modes following the collapse of a process vessel due to a too high internal pressure. A database collecting 121 accidents involving vessel fragmentation and fragment projection in the process industry was developed. Data on the fragmentation of more than 140 vessels were retrieved. The analysis of the database evidenced that a correlation is present among the category of vessel undergoing the fragmentation and the accidental scenario causing vessel rupture. Vessel geometry and fragmentation scenario also influence the fragmentation mode of process equipment. Reference fragmentation patterns were defined on the basis of fracture mechanics fundamentals and of geometrical characteristics of process vessels. The credible fragmentation patterns (1–8, depending on the vessel category) were found to be an important tool to understand the number and the shape of the fragments that may be formed in the collapse of equipment items. The available data also allowed the calculation of the expected probability of fragment projection following vessel fragmentation, and the probability of the alternative fragmentation patterns with respect to the different accidental scenarios, based on observational data.

The results obtained may give important indications on the expected number and shape of fragments generated in the collapse of process and storage vessels. Moreover, the estimation of the probability of fragment projection by alternative fragmentation patterns may be a useful step towards the implementation of detailed models for the calculation of fragment impact probability in a QRA framework.

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