Devising an integrated procedure for assessing fragmentation effects

A N Yasyreva², L V Poluyan¹, E S Guryev¹

¹Science and Engineering Centre "Reliability and Safety of Large Systems and Machines", Ural Branch, Russian Academy of Sciences, Studencheskaya, 54-A,Yekaterinburg 620049, Russia
²Department of Computer-Aided Design of Construction Facilities, Ural Federal University named after the first President of Russia B.N.Yeltsin, Mira, 19, Yekaterinburg 620002, Russia

E-mail: sec@wekt.ru

Abstract. The paper presents a comparative analysis of Russian and foreign investigations in fragmentation effects and methods for assessing parameters of fragments formed by explosions of the equipment used for storing hazardous substances. Based on the results of the analysis, a conclusion was made as to the necessity of developing an integrated procedure for assessing fragmentation effects. The procedure is to be implemented as an ordered systematized algorithm comprising the analyzed methods for calculating individual parameters of fragments. The procedure devised was tested during the accident at the «Cosmo Oil» petroleum refinery in Japan, on March 11, 2011. Practical relevance of the procedure proposed is justified by the calculation results agreeing with the accident events.

1. Introduction
Accidents at petrochemical plants, especially those related to damages in tank farms designed for storing huge amounts of fire-and-explosion-hazard substances, cause tremendous property damages and losses of life. Fragment dispersion contributes a lot to the great number of accident victims, property and facilities damage and occurrence of “domino” effects in case of natural disasters, industrial accidents and catastrophes. An analytical review of scientific investigations [1-8] devoted to the problem of assessing fragmentation effects shows that mostly foreign scientists are deeply involved in this research (Figure 1) [9].

![Research percentage ratio](image_url)

Figure 1. Analysis results of the research in fragmentation effects.
Figure 1 shows the statistics based on the analysis of papers devoted to the problem of fragmentation effects, which have been published in Russian journals (“Industry safety requirements”, “Risk analysis problems”, “Science and technology for oil and oil products pipeline transportation”, “Scientific and academic problems of civil protection” etc.) and foreign journals (“Loss Prevention in the Process Industries”, “Hazardous Materials”, “International Journal of Impact Engineering”, “Chemical Engineering Transactions” etc.) for the last 7 years.

The analysis of domestic and foreign papers shows that the problem of fragmentation effects has not been given sufficient attention in Russia, whereas foreign researchers have proved that fragmentation effects are the main cause for the “domino” effects occurrence in industrial accidents [10-15]. Besides, there is no well-devised and adequate procedure for assessing fragmentation effects. The papers under consideration present various ways and techniques for calculating separate parameters of fragments. This leads to the necessity of devising a special procedure for a comprehensive assessment of fragmentation effects; the procedure is to forecast the number of possible fragments, to determine their parameters and a probability of the domino effect. It is also imperative to include a chapter on assessing fragmentation effects, using this particular procedure into all domestic instructions for assessing the failure risk at FSUs (of an explosion hazard nature) [1]. Based on the foregoing, the aim of the research was formulated as devising an integrated procedure for assessing fragments’ parameters for explosion hazard objects.

2. Comparative analysis of the existing methods for calculating fragments’ parameters

The techniques to be analyzed are those presented in [16-18]. A comparative analysis of the aforementioned methods for calculating fragments’ parameters is given in Tables 1, 2.

| Application conditions | Kinetic energy method | Baker-Gelfand method | Baum’s method |
|------------------------|-----------------------|----------------------|--------------|
| Unequal fragments      | -                     | -                    | -            |
| Real gas               | +                     | -                    | -            |
| Any type of vessels    | +                     | -                    | -            |
| BLEVE                  | -                     | -                    | +            |

Basing on the comparative analysis, it may be inferred that no existing method used for calculating fragments’ parameters allows assessing fragmentation effects in full measure, as each method for calculating fragments’ parameters allows for a certain number of factors capable of influencing the final result of the comprehensive assessment. Namely, the kinetic energy method allows for the explosion type when the vessel’s fragmentation occurs, the Baker-Gelfand method takes into account the type of the exploded vessel and the number of fragments formed.

The Baum’s method can be applied strictly to expansion processes taking place when explosions occur, and these explosions are accompanied by the BLEVE effects. Thus, it is necessary to determine a value range of fragments’ initial velocities where the lower limit is preset by the kinetic energy method, and the upper limit is specified by the Baum’s method. And the arithmetical average of the calculated initial velocities’ values is to be regarded as the final value of the fragments’ initial velocity. This approach to assessing fragmentation effects enables allowing for as many factors of calculating fragments’ parameters as it is possible.
Table 2. Comparative analysis of existing methods for calculating fragments’ parameters according to the factors considered.

| Application conditions | Kinetic energy method | Baker-Gelfand method | Baum’s method |
|------------------------|-----------------------|----------------------|---------------|
| Fragments’ number, their shape and weight | - | + | - |
| Explosion type | + | + | + |
| Tank type | - | + | - |
| Degree of tank filling | + | + | - |

3. Algorithm of an integrated procedure for assessing fragmentation effects

A comprehensive assessment of fragments’ parameters is implemented in several stages performed sequentially. The assessment is given in Figure 2 [9].

3.1. Primary data acquisition

To calculate the fragment’s initial velocity the following input data are necessary: the explosion type; the vessel’s shape; the vessel’s content; the vessel’s volume, m³; the vessel’s diameter, m; the vessel’s wall thickness, m; the volume of the gas-filled section, m³; the gas weight inside the shell, kg; the internal pressure inside the vessel, Pa; the shell weight, kg; the shell material density, kg/m³; atmospheric pressure, Pa; the specific heat ratio of gases in the vessel; the vessel’s centre-to-“target” distance, m; the liquid temperature, K, when failure; the boiling point in ambient conditions, K; the critical temperature, K. To determine the maximal fragmentation range it is necessary to add the following input data: the shape of the fragment formed; the air density, kg/m³; the lift-drag ratio $C_L/A_L$; $C_D$ is the resistance factor; $C_L$ is the lift factor; $A_D$ is the area in the plane perpendicular to the trajectory, m²; $A_C$ is the area in the plane parallel to the trajectory, m².

3.2. Fragments’ number forecast

Forecasting the number of fragments which a tank is torn into is performed using various ways presented in Table 3 [9].

Table 3. Methods for determining the number of expected fragments formed in explosions of tanks of various types.

| Pragmatic approach | Sphere (area, zone, space) | HST | VST |
|--------------------|---------------------------|-----|-----|
| [4]                | Local weakening: $N = 2$  | Local weakening: $N = 2$ | Overpressure: $N = 2-3$ |
| Local weakening: $N = 2$ | Overpressure: $N = 3$ | |
| Parametric approach [6]: | | |
| ME | $N = -0.425 + 6.115 \cdot 10^{-3}V$ | | |
| CE | $P(N) = e^{(-0.93 - 0.1N - 0.05N^2)}$ | | |
| RR | $P(N) = e^{(-2.16 - 0.97N - 0.24N^2)}$ | | |
| BLEVE | $P(N) = e^{(-0.20 - 0.72N + 0.03N^2)}$ | | |
| RUERS procedure [7] | $N = -3.77 + 0.0096 \cdot V$ | $N = 2$ | $N = 2$ |
Note. The following nomenclature is used in Table 5: \( N \) is the number of fragments formed during the tank explosion; \( P(N) \) is the discrete function of the probability density; ME is a mechanical (physical) explosion; CE is a confined explosion; RR is a run-away reaction; BLEVE is a boiling liquid vapour explosion; HST is a horizontal steel tank; VST is a vertical steel tank; RUERS is the Russian Unified Emergency Rescue Service.

Table 5 compiled by the first author is convenient to use for determining the number of fragments expected during the tank fragmentation (blowout, rupture) in accordance with the type of the vessel and a preferred approach to assessing the fragment number.

3.3. Fragments’ weight assessment
The only way to calculate the fragment’s weight is to use the pragmatic approach depending upon the number of the tank fragments formed, Table 4 [18].
Table 4. Methods for determining the number of fragments expected during explosions of tanks of various types.

| Tank type                     | Fragments’ weight \( M \) | Fragment’s shape          |
|-------------------------------|---------------------------|---------------------------|
| Sphere, 2 fragments           | \( M_v / 2 \)             | hemisphere                |
| Sphere, many fragments        | \( M_v / n_f \)           | plates                    |
| Cylinder, 2 equal pieces      | \( M_v / 2 \)             | half of tank              |
| Cylinder, 2 unequal pieces    | 1 part: \( M_{cap} \)     | cap/hemisphere            |
|                               | Another part: \( M_v - M_{cap} \) | tank with one cap       |
|                               |                           | missing                   |
| Cylinder, 3 unequal pieces    | 2 parts: \( M_{cap} \)     | cap/hemisphere            |
|                               | The 3rd part: \( M_v - 2M_{cap} \) | plate                    |
| Cylinder, many pieces         | 2 parts: \( M_{cap} \)     | cap/hemisphere strip      |
|                               | Other parts: \( (M_v - 2M_{cap}) / (n_f - 2) \) | cap/hemisphere strip    |

Note. The following nomenclature is used in Table 6: \( n_f \) is the number of fragments; \( M_v \) is the tank weight; \( M_{cap} \) is the weight of the cap/hemisphere.

3.4. Calculation of fragment’s initial velocity

The method for assessing the fragment’s initial velocity is chosen using Table 5 which was compiled by the authors, depending upon the type of the assessment required and specific calculation characteristics.

Table 5. Deciding on the method for calculating the fragment’s initial velocity [9].

| Assessment type                              | Type of burst                                           | Method                                           |
|----------------------------------------------|--------------------------------------------------------|--------------------------------------------------|
| Rough assessment, setting the lower limit of | Rough estimate for all types of vessel bursts, except  | Kinetic energy method                           |
| the initial velocity values’ range           | decomposition of energetic materials                    |                                                  |
| Mean interval value                          | Pressure vessel burst                                    | Baker’s and/or Gelfand’s method                  |
| Mean interval value                          | Runaway reaction, internal explosion BLEVE             | Gelfand’s method                                |
| Setting the upper limit of the               |                                                        | Baum’s empirical formula                        |
| initial velocity values’ range               |                                                        |                                                  |
| Checking the calculated value of the        | For high scaled pressures and decomposition of          | Moore empirical relation                        |
| initial velocity                             | energetic materials                                      |                                                  |

3.5. Checking the accuracy of fragment’s initial velocity calculated values

The Moore empirical relation is used for this purpose. If the value of the initial velocity calculated with the help of other methods (those of kinetic energy, Baum, Baker, Gelfand) is greater as compared to that of the initial velocity calculated with the help of the Moore’s empirical relation, then this value is considered to be overestimated and the value calculated by the Moore’s equation is to be taken as the initial velocity value. Otherwise, the mean value of the fragment’s initial velocity is to be calculated. But, typically, with the Moore’s equation being solved, velocities have higher values than their real ones.

3.6. Calculation of the initial velocity’s mean value

As each method for calculating fragments’ initial velocity allows for a certain number of factors, a value range of fragments’ initial velocities is set up; from which the arithmetic mean of calculated values of the fragment’s initial velocities is obtained.

3.7. Calculation of the fragments’ maximal dispersion distance
The maximal distance over which fragments can scatter is determined by gravitation forces and dynamics of the liquid (lifting and resistance). The order of steps to be taken for determining the maximal range of fragments’ dispersion is as follows.

1. The non-dimensional initial velocity is calculated.
2. Using a diagram of the fragment’s non-dimensional initial velocity dependence on the maximal range, the non-dimensional maximal dispersion distance is determined by the value of the non-dimensional velocity.
3. The maximal fragments’ dispersion range is calculated.

3.8. Assessment of fragmentation effects on people/neighbouring objects

3.8.1. Assessment of fragmentation effects on people

Fragmentation effects on people are determined by the Netherland guidance of “Methods for calculating damage” (the “Green book”) [19] by the probit-function (Table 6).

| Factor and its consequences | a  | b  | D          |
|-----------------------------|----|----|------------|
| Fragments from 0.001 up to 0.1 kg weight | –29.6 | 2.1 | m v0 5.115 |
| Fragments from 0.1 up to 4.5 kg weight    | –17.56 | 5.30 | 0.5 m v0 2 |
| Fragments of more than 4.5 kg weight      | –13.19 | 10.54 | v0         |

Note. The following nomenclature is used in Table 8: \( m \) is the fragment’s weight; \( v_0 \) is the fragment’s initial velocity.

On calculating the probit function, a probability of inflicting damage to people is determined.

3.8.2. Assessment of fragmentation effects on buildings, facilities, immobile carrier vehicles

Damaging fragmentation effects on these objects are determined by the procedure presented in the Gazprom 2-2.3-400–2009 Industry Standard [16], Appendix E.

3.9. Rough risk assessment of the domino effect

The paper presents a comprehensive assessment of a domino effect probability by three damage criteria: excessive pressure at the shock wave front, thermal radiation intensity and the fragmentation factor in order to improve the accuracy of forecasting cascading accidents at explosion hazard objects (Table 7, [9]).

| Damage factor | Threshold effect | Damage criterion |
|---------------|------------------|-----------------|
| Excessive pressure | 16 kPa | Probit-function: \( Pr = -42.44 + 4.33 \ln(\Delta Pa) \) |
| Thermal radiation | 50 kW/m² | Probit-function: \( V = 12.54 - 1.847 \cdot \ln(\text{ttf}), \text{ttf} \geq 10 \text{ min} \) at \( \ln(\text{ttf}) = -0.947 \cdot \ln(I) + 8.835 \cdot 10^{-5} \cdot I^{0.032} \) |
| Fragments | 2500 kg / (m · s) | Specific impulse: \( I^* = mV / S \) |

Note. The following nomenclature is used in Table 7: \( \Delta Pa \) is the excessive pressure value, \( Pa \); \( I \) is the amount of thermal radiation received, kW/m²; \( \text{ttf} \) is the time before destruction, s; \( I^* \) is the specific impulse, m is the fragment weight, kg; \( V \) is the fragment velocity, m/s; \( S \) is the fragment’s frontal area (midsection), m².
4. Testing the procedure devised during the accident

4.1. Short review of the accident
There was an earthquake in Japan on March 11, 2011. The earthquake caused a series of explosions at the «Cosmo Oil» petroleum refinery tank farm consisting of spherical tanks which contain liquefied petroleum gas. The tank farm layout is given in Figure 3, [20]. Technical characteristics of spherical tanks and consequences due to these characteristics are given in Table 8, [20].

4.2. Calculation of fragment’s physical parameters
The velocity of a fragment formed during the explosion of spherical tank #363 was calculated using various methods. The results of the calculations made are given in Table 9. The obtained values of maximal fragments’ dispersion marked by various colours were drawn on the map of the FSUs layout in accordance with the colours specified (Figure 4).

As it is stated in [21], fragments flew as far as the territory of “Maruzen Petrochemical” corporation, which testifies that calculations of fragments’ parameters, using the Netherland prescriptive guidance of “Methods for calculating physical effects” [18] agree with the accident events.

All the calculations presented in the paper were made for spherical vessel #363.

![Figure 3. Layout of the LPG vessel area at the refinery at the petroleum refinery: circles denote spherical tanks, numbers under circles show the number of a spherical tank, numbers inside circles indicate the spherical tank’s volume (m³).](image)
### Table 8. Brief description of spherical vessels containing liquefied petroleum gas

| №   | Volume (m$^3$) | Diameter (m) | Lading          | Remarks, damage          |
|-----|----------------|--------------|-----------------|--------------------------|
| #351 | 5000           | 21.2         | Butane          |                          |
| #352 | 5000           | 21.2         | Butane          |                          |
| #361 | 1600           | 14.5         | Butane /Butene  |                          |
| #362 | 1500           | 14.2         | Butane /Butene  |                          |
| #363 | 2000           | 15.6         | Propane         | Destroyed                |
| #364 | 2000           | 15.6         | Water           | Water filled at the earthquake |
| #371 | 1000           | 12.4         | Propane         |                          |
| #372 | 1000           | 12.4         | Propane         |                          |
| #373 | 2000           | 15.6         | Propane         | Destroyed                |
| #374 | 2000           | 15.6         | Propane         | Destroyed, 1$^{st}$ explosion |
| #381 | 1000           | 12.4         | Butane          |                          |
| #382 | 1000           | 12.4         | Butane          | Destroyed                |
| #383 | 2000           | 15.6         | Propane         | Destroyed                |
| #384 | 2000           | 15.6         | Propane         | Destroyed                |
| #391 | 3000           | 17.9         | Propane         |                          |
| #392 | 3000           | 17.9         | Propane         |                          |
| #393 | 3000           | 21.2         | Propane         | Destroyed                |

### Table 9. Results of calculating fragments’ parameters for spherical tank #363 [9].

| Procedure             | [18] | [16] | [17] |
|-----------------------|------|------|------|
| Fragments’ number     | n=2  | n=12 | doesn’t depend | doesn’t depend |
| Initial fragment’s velocity, m/s | 68   | 70   | - | 76 |
| Maximal dispersion distance, m | 200  | 241  | - | 153 |

Figure 4. Fragmentation damaged areas determined by various methods.

4.3. Assessment of fragmentation effects on the neighbouring tanks

The results of assessing fragmentation effects, using the procedure presented in [16] are given in Table 10.
| Fragments’ number | Tank #373 | Tank #362 | Tank #352 |
|------------------|-----------|-----------|-----------|
| Damage degree    | n=2       | n=12      | n=2       |
|                  |           |           | n=12      |
|                  |           |           | n=2       |
|                  |           |           | n=12      |

Note. The following nomenclature is used in Table 10: the black colour denotes complete destruction; the red colour denotes severe damage.

The value of the specific impulse by which a probability of the domino effect is evaluated was 23335 kg / (m · s), accordingly; referring to Table 7, it was determined that the value obtained exceeded the value of the fragmentation threshold effects, whence it follows that the domino effect caused by fragmentation in the tank farm will occur.

5. Conclusion

1. The analysis of papers devoted to the problem of fragmentation effects proved that the problem in question wasn’t given sufficient attention. And it is equally important to note that the Russian researchers are still to get deeper involved in these investigations.

2. On the basis of existing procedures for assessing individual fragments’ parameters an integrated procedure for assessing fragmentation effects was devised and systematized. This procedure enables forecasting the probable number of fragments formed by a tank explosion, using two possible ways for vertical cylinder tanks and three ways for horizontal cylinder and spherical tanks. It also makes it possible to calculate the initial velocity and the maximal range of fragments’ dispersion.

3. To calculate a more accurate value of the initial fragment’s velocity (and the maximal range of fragments’ dispersion), it is imperative to use several methods for this calculation, depending upon the specific features of the accident scenario under consideration and the possibility to apply existing methods of calculation in the course. It is also necessary to determine a value range of the initial velocities from which the mean value is found. Such approach to assessing the fragment’s initial velocity enables taking into account several parameters of an explosion at once, thus, it can be applied to risk assessment of real accidents at FSUs.

4. The verification example allowed finding out that the procedure of the Netherland Committee for the prevention of disasters “Methods for the calculation of physical effects” (the “Yellow Book”) [18], was the most effective in calculating fragments’ parameters as it provided the closest to the real accident results. That is why the methods presented in this guidance form the basis of the integrated procedure [18].

5. The devised procedure for a comprehensive assessment of fragments’ parameters is recommended to use: in solving problems of risk analysis; in devising safety certificates and declarations of safety of FSUs; in making damage control and recovery plans as well as plans for mitigating damages to nature and other types of damages, forecasting costs caused by these damages and fragments’ dispersion; as an additional tool in the “Toxi+Risk” software package in risk assessment of accidents at explosion hazard objects.

References

[1] Gubinelli G, Cozzani V 2009 Assessment of missile hazards: evaluation of the fragment number and drag factors J. of Hazardous Materials 161 pp 439-449

[2] Liu Z Y, Huang P, Xu Y B 2010 Monte-Carlo analysis of the projectile fragments from cylindrical tank boiling liquid expanding vapor explosion accident Combustion, Explosion, and Shock Waves 30 569–576

[3] Sun D, Jiang J, Zhang M, Wang Z, Zhang Y, Yan L, Zhang H, Du X, Zou Y 2017 Investigation on the approach of intercepting fragments generated by vessel explosion using barrier net J. of Loss Prevention in the Process Industries 49 989–996
[4] Keys R A, Clubley S K 2017 Establishing a predictive method for blast induced masonry debris distribution using experimental and numerical methods Engineering Failure Analysis 82 82–91

[5] Verolme E K, Van der Voort M M, Smits R, Weerheijm J, Koh Y H, Kang K W 2018 A method for backward calculation of debris in a post blast scene J. of Loss Prevention in the Process Industries 51 54–64

[6] Andrew K, Prema J, Wimberly D 2019 Review, identification and analysis of local impact of projectile hazards in the LNG industry J. of Loss Prevention in the Process Industries 57 304–319

[7] Djelosevic M, Tepic G 2019 Identification of fragmentation mechanism and risk analysis due to explosion of cylindrical tank Journal of Hazardous Materials 362 17–35

[8] Djelosevic M, Tepic G 2019 Probabilistic simulation model of fragmentation risk J. of Loss Prevention in the Process Industries 60 53–75

[9] Snigireva A N 2019 Master’s dissertation (Yekaterinburg: Federal State Autonomous Educational Institution of Higher Education “Ural Federal University named after the First President of Russia B.N. Yeltsin”) p 129

[10] Nguyen Q B, Mébarki A, Ami Saada R, Mercier F, Reimeringer M 2009 Integrated probabilistic framework for domino effect and risk analysis Advances in Engineering Software 40 892–901

[11] Chen G, Zhu J P, Wu J, Wang G D 2011 Impact of gap and volume of storage tanks on domino effect of explosion fragments Fire Safety Science 20 37–42

[12] Salzano E, Antonioni G, Landucci G, Cozzani V 2013 Domino effects related to explosions in the framework of land use planning Chemical Engineering Transactions 31 787–792

[13] Sun D, Jiang J, Zhang M, Wang Z 2015 Influence of the source size on domino effect risk caused by fragments J. of Loss Prevention in the Process Industries 35 211–223

[14] Sun D, Jiang J, Zhang M, Wang Z, Zhang Y, Cai L 2016 Investigation of multiple domino scenarios caused by fragments J. of Loss Prevention in the Process Industries 40 591–602

[15] Sun D L, Jiang J C, Zhang M G, Wang Z R, Huang G T, Qiao J J 2012 Parametric approach of the domino effect for structural fragments J. of Loss Prevention in the Process Industries 25 114–126

[16] Industry Standard Gazprom 2-2.3-400-2009 2010 Risk analysis methodology for hazardous production facilities of gas producing enterprises Open Joint Stock Company Gazprom (Open Joint-Stock Company Gazprom) p 369

[17] Kozlitin A M, Yakovlev A M 2000 Technogenic emergencies. Forecasting and assessment. Deterministic Methods for Quantifying Technosphere Hazards: A Training Manual (Saratov: SSTU) p 124

[18] Methods for the calculation of physical effects (the “Yellow Book”) 1997 (The Hague SDU Committee for the prevention of disasters) p 870

[19] Methods for the calculation of damage (the “Green Book”) 1990 (Voorburg: Ministry of Social A fairs and Employment) p 337

[20] Li X, Koseki H, Sam Mannan M 2015 Case study: Assessment on large scale LPG BLEVEs in the 2011 Tohoku earthquakes Journal of Loss Prevention in the Process Industries 35 257–266

[21] Chakraborty A, Ibrahim A, Cruz A M 2018 A study of accident investigation methodologies applied to the Natech events during the 2011 Great East Japan earthquake, Japan J. of Loss Prevention in the Process Industries 51 208–222