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Assessing external explosions and their probabilities

Keywords

external explosion, explosion pressure waves, Monte Carlo simulation, probabilistic safety assessment

Abstract

External hazards such as explosions can be safety significant contributors to the risk in case of operation of industrial plants. The procedure to assess external hazard explosion pressure waves within probabilistic safety assessment starts with a screening procedure in order to determine scope and content of the assessment. The second step is to choose an appropriate approach in case that a full scope analysis has to be performed. Several methods can be applied to evaluate the probability of occurrence of an external explosion event. The presented results indicate that the probability of occurrence of external explosion pressure waves can be successfully assessed by means of the Monte Carlo simulation, in particular in difficult site-specific conditions.

1. Introduction

Internal hazards such as fire and external hazards (e.g. aircraft crash, flooding, explosion) can be safety significant contributors to the risk in case of nuclear power plant operation because such hazards have the potential to simultaneously to trigger initiating events and reduce the level of redundancy by damaging redundant systems or their supporting systems. Methods to analyse existing plants systematically regarding the adequacy of their existing protection against hazards can be deterministic as well as probabilistic.

This paper deals with the assessment of external explosion pressure waves and the calculation of their probabilities at the plant under consideration.

However, although some part of this paper is correlated to the application with respect to nuclear power plants, the same approach could be applied for other industrial plants.

The assessment of external hazards requires detailed knowledge of natural processes, along with plant and site layout. In contrast with almost all internal hazards, external hazards can simultaneously affect the whole facility, including back up safety systems and non-safety systems alike. In addition, the potential for widespread failures and hindrances to human intervention can occur. For multi-facility sites this makes the situation even more complex and it requires appropriate interface arrangements to deal with the potential effects on several facilities.

An explosion is a rapid and abrupt energy release, which produces a pressure wave and/or shock wave. A pressure wave has a certain pressure rise time, whereas a shock wave has zero pressure rise time. As a result of the pressure and/or shock wave, an explosion is always audible. Explosions can be classified into a number of types (see *Figure 1*).

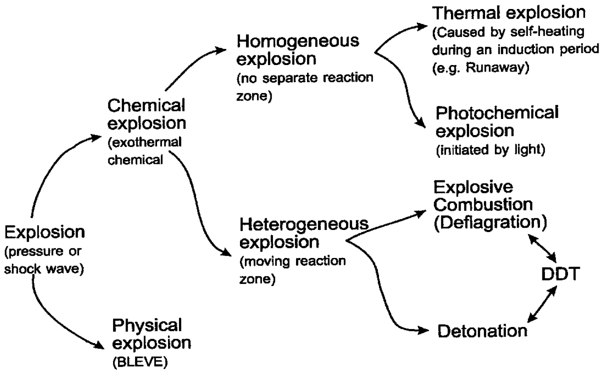

Figure 1. Types of explosions

Explosion is used broadly to mean any chemical reaction between solids, liquids, vapours or gases which may cause a substantial rise in pressure, possibly to impulse loads, fire or heat. An explosion can take the form of a deflagration or a detonation.

The most common type of chemical explosion is the heterogeneous explosion.

In heterogeneous explosions, a propagating reactive front clearly separates the non-reacted materials from the reaction products. The reaction front, usually called the reaction zone or flame (front), moves through the explosive mixture as the explosion occurs. In this zone the strongly exothermic reactions occur. Heterogeneous explosions are divided into two types: deflagrations and detonations.

In deflagrations, the reaction zone travels through the explosive mass at subsonic speed, while the propagation mechanism is heat transfer (by conduction, radiation and convection). Reaction zone propagation velocities (flame speeds) of deflagrations may vary over a wide range and so do the corresponding explosion pressures.

In some instances, accelerating deflagrations show a deflagration-to-detonation transition (DDT) as shown in *Figure 1*.

The major characteristic of a detonation is its extremely high speed: the explosion zone moves at a supersonic speed. While, for deflagrations the flame speeds are low (typically one to several hundreds of metres per second), detonation flame speeds in air can easily reach one to two kilometres per second. The propagation mechanism of a detonation is an extremely rapid and sharp compression occurring in a shock wave. In contrast to a reversible adiabatic compression, shock compression occurs irreversibly (non-isotropic), due to the extreme rapidity with which it occurs. Both types of explosion pressure waves (caused by detonation of liquids or solid explosives or air-gas mixtures and such pressure waves caused by deflagrations of only air-gas mixtures) have to be taken into account in the safety assessment of the plant under consideration.

The first step of the assessment is a screening procedure in order to determine scope and content of the assessment to be performed, the second step is to propose an appropriate approach for those cases where a full scope analysis has to be performed.

In the latter case methods which can be applied to evaluate the probability of occurrence of an external explosion event are, e.g., fault tree analysis, event tree analysis and Monte Carlo simulation.

The presented results show that the probability of occurrence of external explosion pressure waves can be successfully assessed by means of the Monte Carlo simulation.

2. Guidance on assessing external events

Since October 2005, a revised guideline [4] as well as revised and extended supporting technical documents (see [6] and [7]) are issued in Germany which describe the methods and data to be used in performing probabilistic safety assessment in the frame of comprehensive safety reviews. In these documents, probabilistic considerations of aircraft crash, external flooding, earthquake and explosion pressure waves are required. Also on international level, new recommendations regarding external hazards including explosions pressure waves are recently issued (see, e. g., [12] to [14]). The safety assessment should demonstrate that threats from external hazards are either removed, minimised or tolerated. This may be done by showing that safety related plant buildings and equipment are designed to meet appropriate performance criteria against the postulated external hazard, and by the provision of safety systems which respond to mitigate the effects of fault sequences.

Explosion pressure waves with relevance to the site can be caused by shipping, fabrication, storage and reloading of explosive materials in closer distances to a nuclear power plant or another industrial plant with a high hazard potential (e. g., process industry). This leads to different types of risky situations which have to be assessed within a probabilistic safety assessment:

1. the explosive material is available as a stationary source in the neighbourhood of the plant under consideration (e.g., a storage or a fabrication facility).
2. the explosive material is mobile, i.e. it is shipped in close distance to the plant on the road, by train or on ships along a river or the sea nearby.

In the latter case, the situation is not stable and changes with the varying distances. Moreover, the transport way could be a straight line or a bent which has to be addressed in the calculations (see [11] for a straight road and [3] for a bent river). Usually, a uniformly distributed accident probability is assumed along the transport way. However, in reality the accident probability may increase in junctions or confluences and – in case of rivers and roads – in curves or strictures. Such on example is explained in section 5 in more detail.

Accidents with explosive material are not only theoretical considerations but happen in reality, sometimes with catastrophic consequences. One extremely severe transportation accident took place in June 2009 in Viareggio which resulted in comprehensive safety evaluations [17]. Although no industrial plant was damaged in this accident, the potential explosion severity is visible. The accident followed the derailment of a train carrying 14 tank cars of liquefied petroleum gas. The first tank car was punctured after the derailment releasing its entire content that ignited causing an extended and severe flash-fire that set on fire several houses and lead to 31 fatalities.

A more recent accident happened in January 2011 on the river Rhine in Germany, fortunately without any environmental consequences. However, a ship capsized and blocked for many weeks the river for other transportation but, in particular, had the potential to lead to an explosion because – in addition to 2400 tons mainly of sulphuric acid – one tank also contained water and hydrogen.

3. Screening process

In a first step, the important areas of the plant are divided into the three classes A, B and C for the analysis of explosion pressure waves to reflect the degree of protection against the impact by the explosion pressure waves. These classes are the same as for the consideration of aircraft crashes [1].

Class A contains systems, where in case of their damages a hazard state directly arises or where an initiating event may occur which cannot be controlled by the emergency cooling system. Class B contains systems where in case of their damages a hazard state not directly arises, but where an initiating event may occur which is controlled by the emergency cooling system. Class C contains these safety systems needed for core cooling.

Typical examples of these different classes are [2]:

A: e.g. primary circuit,
B: e.g. turbine building,
C: separated emergency building.

Basic idea in case of explosion pressure waves is a prescribed check if the frequency of core damage states is less than 1E-07 per year for the plant under consideration. This is the case when

- the total occurrence frequency of the event "explosion pressure wave" (i.e. the sum of all contributions from detonation and deflagration) is determined to be less than 1E-05 per year,
- the building of classes A and C are designed against the load assumptions shown in *Figure 2*,
- the safety distances according to the BMI guideline [8] are fulfilled, based on the formula (1):

$$R = 8m \cdot \sqrt[3]{\frac{L}{kg}} \qquad (1)$$

with

R = safety distance (in m) of the place where the explosive gas is handled from to the respective plant which should be larger than 100 m, and
L = assumed mass of the explosive material (in kg).

It should be noticed that the total mass to be assumed depends on the type of explosive material.

For the case that the prerequisites of this prescribed check are met, no further probabilistic considerations are necessary.

Otherwise the procedure has to be in accordance with the graded process of evidence regarding explosion pressure waves as presented in *Table 1*.

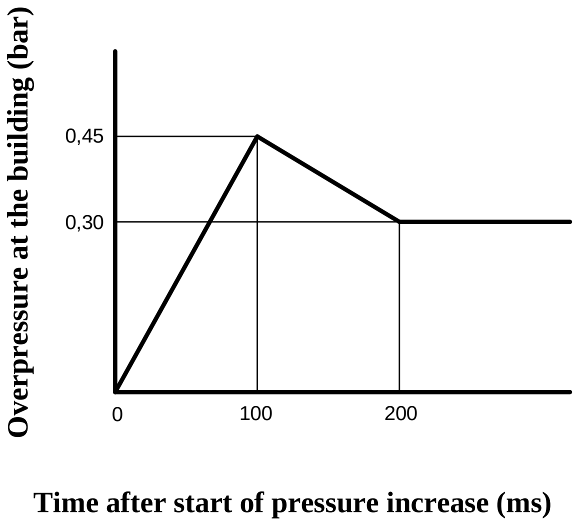

Figure 2. Pressure behaviour at the building for a single pressure wave according to [8]

Table 1. The graded process of analysing explosion pressure waves.

Criteria	Extent of analysis
Occurrence frequency <1E-05 per year Classes A and C are designed according to load assumptions and safety distances determined in length l_R according to [8]	Verification using the prescribed check
Not fulfilled Fulfilled	Conservative estimation of occurrence frequency
Not fulfilled Not fulfilled	Detailed probabilistic safety analysis

4. Methods as recommended in the German PSA document for nuclear power plants

4.1 Introduction

The German PSA document on methods [6] describes the approaches to be used in the probabilistic safety assessment which have to be performed in the frame of comprehensive safety reviews of nuclear power plants.

One part of this approach is dedicated to the screening process already explained in section 2, the further parts of this document deal in more detail with the occurrence frequency of explosion pressure waves taking into account the site-specific situation, sources of possible explosion pressure waves in the surrounding of the plant, and the procedure for the calculation of occurrence frequencies of accidents during transportation of explosive material by ships, trains or trucks and of accidents of stationary plants near the plant under consideration.

4.2 Assessment

In case that the plant buildings classified as A and C are designed according to the BMI guideline [8] and the safety margins regarding distance and mass of the explosive material are kept, it can be assumed that in the most unfavourable case of an explosion pressure wave event

- no event is initiated which directly leads to a hazard state,
- due to the event explosion pressure wave a system failure occurs in the class B and an initiating event is initiated which can be controlled by the emergency cooling system as designed,
- the emergency cooling system is protected against the effects of the event explosion pressure wave.

In the most unfavourable case, a loss of offsite power with destruction of the secondary plant parts (main heat sink, feed water supply) can be assumed, which occurs with the total occurrence frequency of the event explosion pressure wave. It is assumed for simplifying the analysis that together with the occurrence of this event those systems which are outside of the classes A and C fail.

For the calculation of the frequency of the hazard state, resulting from explosion pressure waves, this initiating event and the incident-controlling functions of the emergency cooling system (stochastic non-availabilities) are to be modelled and quantified in an event tree (or using another appropriate method).

The frequency of the event explosion pressure wave to be chosen is the sum of all contributions of the events detonation and deflagration, as far as they can lead to an hazardous state of the plant, resulting from accidents during transportation procedures or the operation of stationary plants in the surrounding of the plant under consideration.

The occurrence frequency of a detonation is several orders of magnitude lower compared with a deflagration [9]. As far as the distance of the area where the deflagration started has a distance larger than 100 m from the plant under consideration (see safety margins in accordance with [8]), no endangerment of the plant buildings has to be assumed.

The deflagration pressure of max. 10 bar drops over 100 m around a factor 1E04, so that within the power station pressure values within the range of the wind pressures are reached.

In case of explosive gas air mixtures (combustible gases with air; inflammable steams, e.g. also of liquid gas, with air) clouds can be appear and a drifting of these clouds from the place where the accident happened into the direction of the plant is possible. In this situation the deflagration can take place in the area of the plant buildings. The approach applied for this case is described in the following equation [9]:

$$H_{E,GLG} = H_{U,GLG} \cdot W_M \cdot W_D \cdot W_Z \qquad (2)$$

with

$H_{E,GLG}$	Annual frequency of an explosion pressure wave by gas air mixtures in the surroundings of the nuclear power plant,
$H_{U,GLG}$	Annual frequency of accidents with combustible gas in the surroundings of the nuclear power plant,
W_M	Conditional probability for the development of an explosive gas air mixture in case of an accident with combustible gas,
W_D	Conditional probability for drifting the gas air mixture to the nuclear power plant (as a result of temporal averaging of the arising wind directions),
W_Z	Conditional probability of the ignition at the area of the plant.

In a more detailed verification the assumptions introduced can be replaced by plant-specific proofs, considering the different effects of the determined explosion pressure waves.

In the case of a deviation from the BMI guideline [8] partial results of the total occurrence frequency of the event arise which contribute directly to the frequency of the hazard states. These contributions are to be determined by a differentiated view of the assigned explosion pressure waves and their effects.

5. Monte Carlo Simulation

5.1. Application

The following application is a case study that represents the evaluation of the probability of occurrence of an external explosion pressure wave that takes place near a plant. The probability of occurrence is assessed on the condition that an accident with combustible gas already occurred. The application is not restricted to a special field of industry; plants of process industry might be in the focus as well as nuclear power plants. It is assumed that the external explosion pressure wave is initiated by an accident of a gas-tanker that carries explosive liquids on a river.

Although the application is described in a generalized way, it incorporates several elements that are typical in order to assess the impact of explosion pressure waves: accident, wind direction, wind speed and ignition.

It should be noticed that the events, boundary conditions and parameters given in Figure 3 to 6 and Tables 2 and 3 are only example values and do not represent conditions of any specific application.

5.1.1. Plant environment

The plant and its environment are depicted in *Figure 3*. The length l_S of the section of interest is 4800m and the width w_S is 1800m. The river is subdivided into 7 subsections; each subsection is characterised by an individual length, width and gas-tanker accident frequency.

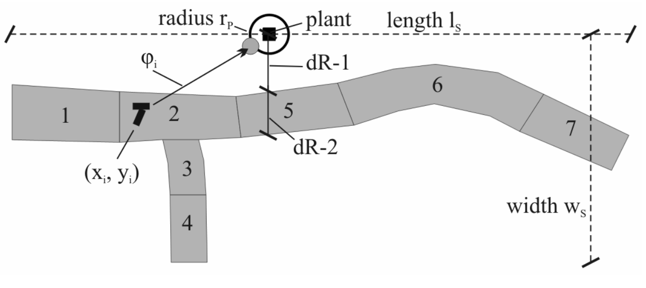

Figure 3. Plant environment and hazardous scenario

The vertical distance between the plant and the river is between 440m (dR-1) and 780m (dR-2). In the given application ships can reach every location at the river. An accident at the river-coordinate (x_i, y_i) may cause the development of explosive gas mixture.

Depending on the wind direction φ_i the cloud of gas mixture can drift to the plant. An ignition of the gas mixture close to the plant (within the radius r_P) is in the focus of this study.

All relevant application parameters of *Figure 3* are given in *Table 2*.

Table 2. Relevant application parameters

Description	Parameters
length l_S	4800m
width w_S	1800m
distance [dR-1, dR-2]	[440m, 780m]
radius r_P	150m
plant	100m·100m

5.1.2. Assumptions

The case study depends on the following assumptions:

- Empirical-distributed accident probability depending on the subsection of the river on condition that the accident already occurred. It is assumed, that the accident frequency is higher in sections with confluences or curves than in straight river-sections.
- Uniformly-distributed accident-coordinate (x_i, y_i) on condition that the accident occurred in the river-section i.
- The development of explosive gas mixture occurs with fixed probability w_G.
- Empirical-distributed wind direction.
- Empirical-distributed wind speed.
- Exponentially-distributed ignition probability depending on the time.
- An explosion within the radius r_P around the plant is in the focus of this study.

The parameters and distribution models are given in *Figures 4* to 6 and *Table 3*.

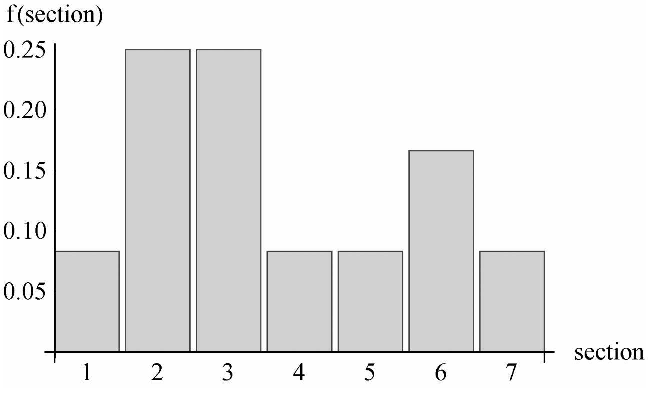

Figure 4. Empirical accident river-section frequencies

Table 3. Parameters and distribution models

Description	Distribution	Parameters
accident river-section	empirical	-----
accident (x, y)-coordinate	U(a, b)	depending on river-section
development of explosive gas mixture	fixed probability	0,3
wind direction φ	empirical	-----
wind speed v_W	empirical	-----
time τ to ignition	Exp(λ)	Exp(0,01 s^{-1})

5.2. Basics

5.2.1. Monte Carlo Simulation

Detailed basics of the Monte Carlo simulation like random sampling, estimators and biasing techniques are specified for example in [5] and [15]. In [3], [10] and [11] the Monte Carlo simulation has been applied and verified successfully in order to estimate the probability of external explosion pressure waves.

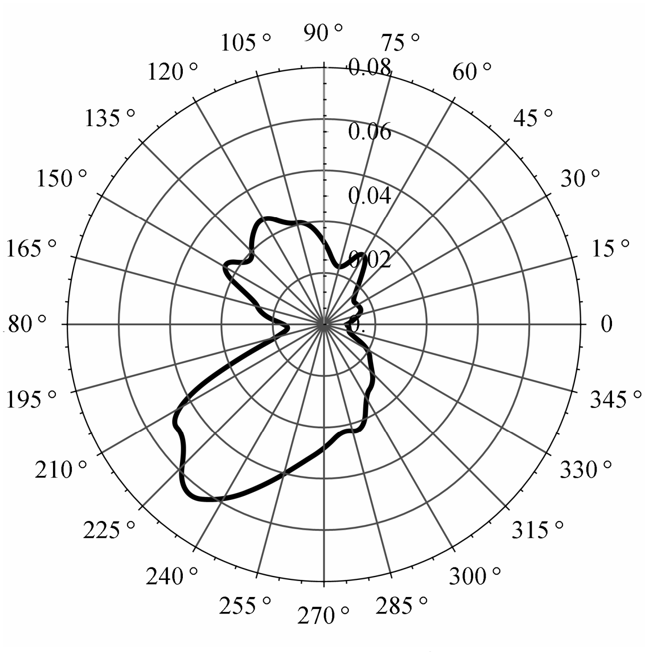

Figure 5. Empirical wind-direction frequencies

5.2.2. Distribution models in use

The pdf of the uniform distribution U(a, b) with the parameters a < b is given by

$$f(x) = \frac{1}{b-a} \text{ for } a \le x \le b. \tag{3}$$

The pdf of the exponential distribution exp(λ) with the parameter λ > 0 is given by

$$f(x) = \lambda \cdot \exp(-\lambda \cdot x) \text{ for } x \ge 0. \tag{4}$$

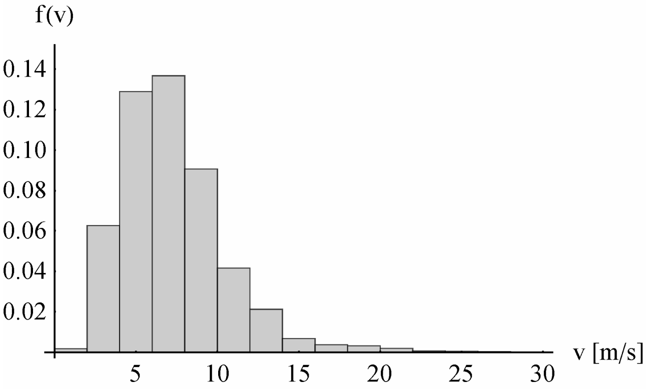

Figure 6. Empirical wind-speed frequencies

5.2.3. Estimators in use

As the last event estimator (lee) [16] is used to predict the probability of an event (e.g. an explosion event), the observed frequency of explosions within the radius r_P is determined. The sample mean probability is

$$\hat{P}_E = \frac{1}{N} \cdot \sum_{i=1}^{N} P_E(i) \tag{5}$$

where $P_E\ (i) \in \{0, 1\}$ and N = number of trials.

An alternative method is to compute the theoretical probability of an explosion event within the radius r_P in each scenario the wind direction will move the explosive gas mixture to the plant. The advantage over the lee is that each scenario gives a contribution to the probability of occurrence. By analogy with transport theory, this procedure is called free flight estimator (ffe) [16]. Depending on the accident coordinate (x_i, y_i), the wind direction φ_i and the wind speed v_{Wi} in trial i, the probability of an explosion event within the radius r_P is given by

$$\begin{aligned} P_E(x_i, \varphi_i) &= \exp(-\lambda \cdot 1/v_{Wi} \cdot d_1(x_i, \varphi_i)) \\ &\quad - \exp(-\lambda \cdot 1/v_{Wi} \cdot d_2(x_i, \varphi_i)) \end{aligned} \tag{6}$$

where $d_1(x, \varphi)$ and $d_2(x, \varphi)$ are the distances between the accident coordinate and the intersection of the wind direction and the plant area with radius r_P.

The intersection coordinates (x_I, y_I) of the wind direction φ_i and the plant area with radius r_P are determined by means of

$$x_I^2 + (y_i + \tan(\varphi_i) \cdot (x_I - x_i))^2 = r_P^2 \tag{7}$$

and

$$y_I = (y_i + \tan(\varphi_i)\cdot(x_I - x_i))^2 . \tag{8}$$

The sample mean probability is

$$\hat{P}_E = \frac{1}{N}\cdot\sum_{i=1}^{N} P_E(x_i, \varphi_i) \tag{9}$$

where N = number of trials.

5.3. Analysis

The MCS is performed by means of the last event estimator and the free flight estimator.

The algorithm to model and solve the problem is based on the German Probabilistic PSA guideline [4] and the supporting technical document on PSA methods [6].

The MCS depends on a sequence of single events:

- accident river-section: empirical-distributed (*Figure. 4*),
- accident (x, y)-coordinate: uniformly-distributed on condition that the accident occurred in the river-section i,
- development of explosive gas mixture: fixed probability (0,3),
- wind-direction φ: empirical-distributed (see *Figure 5*),
- wind-speed v_W: empirical-distributed (see *Figure 6*),
- time τ to ignition: Exp(0,01 s^{-1})-distributed.

5.4. Results

The results of the MCS are evaluated on the condition that the accident already occurred.

In order to assess the frequency of occurrence of an external explosion event the frequency of accidents with combustible gas has to be considered. It should be noticed, that the results for the frequency of occurrence of an external explosion event will be several magnitudes lower than the results for the conditional explosion event probability given in this paper.

Different ranges of conditional explosion-probability P_E are depicted in *Figure 7* and *Figure 8*. Areas with higher gray-level intensity represent higher conditional explosion-probability. In order to compare the results to the conditional explosion event probability P_E close to the plant (within the radius r_P) the results in *Figure 8* are normalised on the plant area $\pi\cdot r_P^2$.

The number of trials, the simulation time and the results like mean value and variance are listed in *Table 4*.

Figure 7 and *Figure 8* indicate that the conditional explosion event probability decreases as the distance to the river (place of the assumed accident) increases. This is due to the exponentially distributed ignition probability which depends on the time or the distance to the accident.

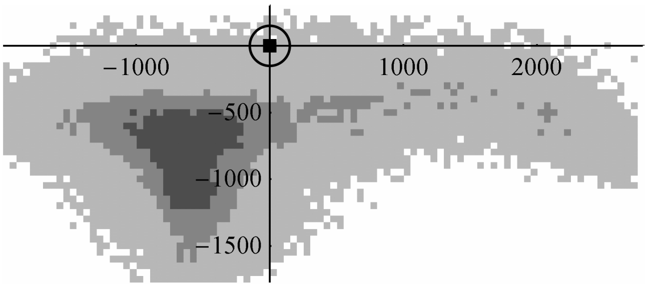

Figure 7. Ranges of conditional explosion event probability P_E – normalised on 1m^2

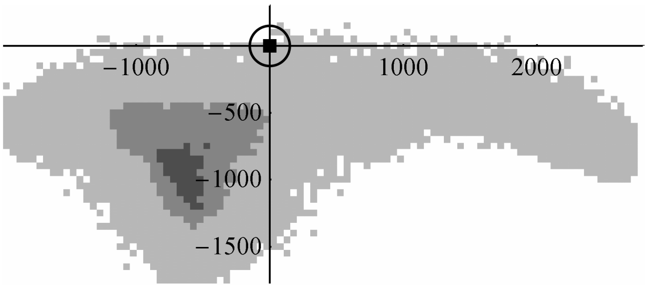

Figure 8. Ranges of conditional explosion event probability P_E – normalised on the plant area $\pi\cdot r_P^2$

Table 4. Conditional probability of an explosion event within the plant area with radius r_P

Method	Trials	Time	Mean	Variance
analog MCS - lee	1E06	60.7s	1.21E-03	1.20E-03
analog MCS - ffe	1E06	65.1s	1.23E-03	1.13E-04

Close to the river-sections 2 and 3 the conditional explosion event probability increases, this is due to the higher accident frequency in these sections combined with the specific wind-direction frequencies.

As the different Monte Carlo methods given in Table 4 are compared it can be found out, that both solutions fit a mean about 1,2E-03 which verifies the results as well as the adopted different Monte Carlo algorithms.

If the variance is regarded, the Monte Carlo simulation in combination with the free flight estimator is the most efficient approach.

6. Concluding Remarks

6.1. Countermeasures to avoid or mitigate the adverse effects of external explosions

Knowledge of the explosion characteristics and the structural impact on buildings of the respective plant is necessary to determine the appropriate countermeasures in order to ensure a safe operation of the plant. However, fundamental changes of the plant under consideration are mainly possible only during the design and construction phase. In case of a plant already operating since several years, the implementation of effective countermeasures is much more difficult or even not possible.

On the one hand, comprehensive calculations can be performed to show that existing assumptions in the calculation provided for the licensing of the plant have been very conservative.

On the other hand, organizational and technical provisions can be taken to reduce the occurrence of an external explosion pressure wave at the plant.

One organizational possibility is to interdict the transport of explosive material, e.g. on a road, in the neighbourhood of the plant. Another solution is to close the road for transit traffic such that the road is only leading to the plant.

One technical countermeasure to reduce the explosion frequency on site is the installation of an automatic ignition system placed at a save distance from the site. An assessment has been performed for such an installation which showed that – if the igniters are correctly designed and installed – the shock wave impact after an ignition on the buildings will be limited and will not cause any structural damage.

6.2. Modelling of external explosions and potential for improvements of the methods

The evaluation of external hazards in relation to nuclear power plant design is traditionally considered as a two-step process. The detailed evaluation is preceded by a screening phase where potential scenarios are identified. Many scenarios are screened out on the basis of different criteria, such as distance from the site, probability of occurrence, expected consequence on the plant, or because their effects on the plant are expected to be enveloped by some others. Typically, explosion pressure waves are part of the probabilistic safety assessment as in case of comprehensive periodic safety reviews.

In the German safety guidance documents [6] the screening process for the explosion events is explicitly described. The classes of buildings with respect to their protection are the same as for the aircraft crash assessments. Since the updated PSA guideline has been issued in 2005 also requiring the assessment of external events, first practical experience in performing and reviewing the external PSAs are available and will be used for a revision of the guideline which is scheduled to start next year. One topic is the assessment of the conditional probability of the occurrence of external explosion pressure wave and the discussion of appropriate methods according to the state of art.

The procedure and methods applied are used for the evaluation of external explosion pressure waves with respect to nuclear power plants. However, they can also be applied to other types of industrial plants.

The presented case study and its results (Figures 7 to *8* and *Table 4*) in the second part of this paper indicate that the conditional probability of occurrence of external explosion pressure waves in consideration of realistic conditions (accident frequency depending on environmental conditions, wind direction & wind speed) can be successfully assessed by means of the MCS.

As a next step the assessment of explosion events should be extended to include much more realistic boundary conditions:

- the extent of the hazard and the explosive gas mixture,
- ignition probability that depends on environmental conditions.

Different ignition models are discussed in [18]. The applied model should be more realistic like the applied exponentially-distributed ignition model; moreover the applicability to integrate the new ignition model into Monte Carlo algorithm should be given.

References

[1] Berg, H.P. (2005). Screening procedures for the probabilistic analyses of internal and external hazards. *Proc. of the 9th International Conference on Structural Safety and Reliability (ICOSSAR 2005),* Rome, 3663 – 3670.

[2] Berg, H.P. (2010). Aircraft crash onto a nuclear power plant. *Journal of Polish Safety and Reliability Association,* SSARS 2010, Vol. 1, 27 - 34.

[3] Berg, H.P. & Hauschild, J. (2010). Probabilistic assessment of external explosion pressure waves. *Proc. of the 8th International Probabilistic Workshop,* Szczecin, November 2010, 27 – 39.

[4] Bundesamt für Strahlenschutz. (2005). *Safety Codes and Guides – Translations. Safety Review for Nuclear Power Plants pursuant to § 19a of the Atomic Energy Act - Guide on Probabilistic Safety Analysis*. Salzgitter: BfS, August 2005.

[5] Dubi, A. (2000). *Monte Carlo Applications in Systems Engineering*. New York: John Wiley & Sons.

[6] Facharbeitskreis Probabilistische Sicherheitsanalyse für Kernkraftwerke. (2005). *Methoden zur probabilistischen Sicherheitsanalyse für Kernkraftwerke, Stand: August 2005.* BfS-SCHR-37/05, Salzgitter: BfS, October 2005 (published *in German*).

[7] Facharbeitskreis Probabilistische Sicherheitsanalyse für Kernkraftwerke. (2005). *Daten zur probabilistischen Sicherheitsanalyse für Kernkraftwerk*e, *Stand: August 2005.* BfS-SCHR-38/05, Salzgitter: BfS, October 2005 (published *in German*).

[8] Federal Minister of the Interior (Bundesminister des Innern – BMI). (1976). *Richtlinie für den Schutz von Kernkraftwerken gegen Druckwellen aus chemischen Reaktionen durch Auslegung der Kernkraftwerke hinsichtlich ihrer Festigkeit und induzierter Schwingungen sowie durch Sicherheitsabstände.* BAnz Nr. 179, Sept. 1976.

[9] Federal Minister for Research and Development. (1990). *Deutsche Risikostudie Kernkraftwerke, Phase B, Fachband 4: Einwirkungen von außen (einschließlich anlageninterner Brände).* Köln: Verlag TÜV Rheinland GmbH, (published *in German*).

[10] Hauschild, J. & Andernacht, M. (2009). Monte Carlo simulation for the estimation of external explosion event probability. *Proc. of ESREL`09*, Prague, Balkema, 2139-2142.

[11] Hauschild, J. & Andernacht, M. (2010). *Monte Carlo Simulation for modelling & analysing external explosion event probability. Proc. of ESREL`10*, Rhodes, Balkema, 985-989.

[12] International Atomic Energy Agency. (2010). *Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants.* IAEA Safety Standards Series No. SSG-3, Vienna.

[13] International Atomic Energy Agency. (2003). *External Events Excluding Earthquakes in the Design of Nuclear Power Plants.* IAEA Safety Standards Series No. NS-G-1.5, Vienna.

[14] International Atomic Energy Agency. (2009). *Safety Assessment for Facilities and Activities, General Safety Requirements.* IAEA Safety Standards Series No. GSR Part 4, Vienna.

[15] Marseguerra, M. & Zio, E. (2002). Basics of the Monte Carlo Method with Application to System Reliability. *Serving Life-Long Learning*, Hagen.

[16] Marseguerra, M. et al. (1998). A concept paper on dynamic reliability via Monte Carlo simulation. *Mathematics and Computers in Simulation 47*, 27 – 39.

[17] Pontiggia, M. et al. (2010). Safety of LPG rail transportation in the perspective of the Viareggio accident. *Proc. of ESREL`10*, Rhodes, Balkema, 1872 – 1880.

[18] Schalau, B. et al. (2009). Berechnung der Zündwahrscheinlichkeit freigesetzter brennbarer Stoffe im Rahmen einer quantitativen Risikoanalyse. *Technische Überwachung*, Nr. 9, 35-40 (published *in German*).