Assessing the risk for pollution due to abnormal behavior of a hazardous installation

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Abstract: Our current understanding is that since 18th century many of mankind's activities contribute significantly to the changes in the global climate system. The number of hazardous installations in use and their diversity has dramatically increased during the last 60 years. Each of those technological facilities is a potential source of major accidents with huge or catastrophic impacts on the soil, atmosphere, water quality, ecosystems and directly on human health. The paper briefly comments on an approach for addressing the uncertainty about the unacceptable consequences expected from a particular hazardous facility. The first stage of the approach is discussed in a case study. This part of the methodology is capable to search for and rank those likely abnormal situations having high potential to progress further on into major accidents.

Keywords: Hazardous installation, technological risk, major release scenarios.

1. Introduction

The scientific community works systematically more than 20 years to understand and predict dangerous anthropogenetic interference with the climate system (Hansel et al., 2005), (EEA, 2008), (Rohde, R., et al. 2011). Part of these efforts is to identify and reduce the frequencies and magnitudes of accidents at any engineering system (ES).

Nowadays, natural hazards are not the only threats that affect seriously human live and the global climate system. Modern society relies on various fixed and movable facilities as those of process industries, the energy sector, offshore platforms, etc. It also cannot exist without airplanes and various vehicles for land and marine transport. Many of these ES use, produce and store hazardous materials. Both moving vehicles and fixed installations can be responsible for distinct health effects on their personnel, off-site population and various impacts on ecosystems all over the world.

While operating normally, some installations of the energy sector and process industries emit permanently various substances. In general, observing continuously the dangerous substances, which an ES usually releases, we are able to estimate their quantities with increasing degree of certainty. There is no doubt that the effective techniques for capturing of specific substances, escaping permanently from an ES, may be neither simple nor cheap to implement. However, the uncertainty, about the negative effects on human health and the environment due to persistent emissions, can be reduced just by monitoring the daily production rate of given substances. Thus, efficient protection measures against the continuous pollution of air, the soil and waters are easier to implement than against the harmful impacts, which fixed installations and vehicles can give rise to, in case of occasional abnormal behavior.

Since the industrial era (starting about 1750 A.D.), the "capacity" of ES to utilize diverse hazardous substances in civil and military industries enhances from a day to a day. As a result unexpected releases from hazardous installations (HI) will keep occurring. Part of these undesired events may progress to accidents, associated with shocking impacts of various magnitudes, having the potential to damage smaller or larger regions of the Earth. A list of accidents ending in the past with catastrophic health and environmental effects can be too long. The accidents at: Bhopal chemical plant in 1984 (e.g. Khan & Abbas, 1997), Chernobyl NPP in 1986 (see IAEA, 2006), offshore platform Piper Alpha in 1988 (e.g. HSE, 2004) etc. are only small part of those occurred in the recent 25 years all over the world.

Although major accidents at HI rarely happen, due to their huge or catastrophic immediate and long-term consequences, they are rather risk-significant. On the other hand the accident consequences are too diverse and should be assessed in terms of human deaths and injuries, financial losses, ecological damages etc. Actually, the experience shows that accidents can never be entirely prevented. However, implementing different means to reducee the chance for severe consequences is a reasonable strategy for minimizing the resources that should be spent for post accident activities.

Since ionizing radiation exposure damages living cells and the half-life of a number of radioactive elements is thousands of years, living beings must be protected as effectively as possible from the products of nuclear fission. Specific nuclear legislation and design concepts, applying several levels of defensive barriers, redundant safety systems and various types of emergency procedures, guarantee the high safety of every operating Nuclear Power Plant (NPP) unit.

To keep acceptably low the chance for no adverse impacts on human health and the environment, the radioactive substances at every NPP site must stay isolated, by the installed strictly independent defensive barriers, after any abnormal situation no matter how rarely it can occur. Although, the accidents stemming from non-nuclear HI usually cannot lead to extremely long-lasting consequences, the release of some toxic substances may cause both immediate and long-term damages. The Seveso disaster in 1976, in which the surrounding area near Milan was contaminated with tetrachloro dibenzo dioxin, is such an example.

Taking care about high level of safety for the non-nuclear establishments, the EU Council defines in 1996 the Directive 96/82/EC (known as Seveso II). The Seveso II lists many requirements for installations, operating with big amounts of non-nuclear dangerous substances which the legislation of each of the member states should implement. The philosophy of the Seveso II directive is discussed in many works for instance (Hawksley, 1999), (Kirchsteiger, 1999), (Mitchison, et al, 1999), etc.

From 2002 the first edition of the Bulgarian law for "Environmental protection" is in force. Chapter 6 of the law obliges all individuals and organizations, before starting whatever activities, to obtain special assessment specifying their possible impacts on the environment. The chapter 7 of this law directly applies the Seveso II directive to everyone whose activities in the country pose non-nuclear hazards. It specifies that every operator of a large scale facility must classify it as a unit with low or with high risk potential for the environment. The operator of a highly risky installation needs a safety report that should be periodically updated.

The non-nuclear installations of the energy sector usually contain huge amounts of combustible or flammable materials. Some toxic substances also can be present in those ES. Therefore, if something goes wrong in such installations, it is very likely major accidents, associated with release of large quantities of pollutants, eventually to take place.

Section 2 of this paper briefly presents an approach for identifying those zones at a certain site from which accidental scenarios can emerge. That section also discusses the ranking of likely release scenarios by the release rate of specific hazardous substances. Section 3 comments on a simple case study showing how the method can be applied. In section 4 some conclusions are drawn.

2. Generic features of the approach

A hazardous substance is free to escape in all directions from a given hazardous unit after the defensive barriers, installed to isolate it from its close vicinity, have lost their integrity. The first stage of the approach under discussion quantifies the frequency for occurrence of situations that may go forward into major accidents. This stage of the methodology needs suitable inferential methods by which from the available observations the occurrence frequency of the events, leading even rarely to accidents, to be quantified. Once an undesired event has started proper action of certain mitigating systems and emergency procedures must be applied for preventing the progress of accidental phenomena. The success or failure of these means for fighting accidents determines the chance for harming a target region by dangerous substances escaping from the disabled HI. A number of conditional probabilities estimates the chance for success (or failure) of particular accident fighting means to prevent the occurrence of significant consequences. Finally, correcting the occurrence frequency of the initial abnormal event by these conditional probabilities the frequency of huge consequences in the regions around the stricken HI can be quantified.

The paper comments only on some elements of the entire methodology. It very briefly considers the method for quantifying the frequency of initiators of accidents. Actually, the paper focuses on quantifying the chance that the disturbances with a high risk potential can emerge from each part of a hazardous facility.

The frequency for arising into a given zone X of the HI J of accidents whose risk potential is higher than a given threshold can be formally assessed as:

$F_{J\text{-}x} = F_J * P(Ax|F_J)$, where $A_x \equiv (R_x \cap D_x)$

F_J – Occurrence frequency of specific type of accidents in all zones of the installation J of interest. This entity is considered in many references (e.g. Bier & Yi, 1995; Argirov, 1999) etc., and there is no discussion on it here;

$P(A_x \equiv (R_x \cap D_x)|F_J)$ - The chance that the complex event A_x addresses sufficiently well the uncertainty associated with emerging of accidents of a given type in the zone X of the installation J. Probability theory helps for quantifying this chance;

The event A_x specifies those random and deterministic factors that determine the risk potential of abnormal events in whose further progress hazardous substances escape out of the defensive barriers. The symbols R_x and D_x indicate sets (vectors) consisting of the values of the random parameters and the deterministic variables, respectively. Members of both sets can deviate in space and time and can be complexly related logically with each other. A simple case is considered here in which none of the random parameters varies in time t and each of them is also independent from the deterministic variables. Actually, this is a reasonable assumption if the occurring accident is progressing too quickly for the corrective actions by automatics and operators aimed at preventing the accidental phenomena to be successful thus allowing the hazardous substances to bypass the dedicated defensive barriers.

The set R_x includes values of such random factors that identify how those barriers, which are available at the zone X of the installation J, can fail at the time t=0. The initial values of the deterministic variables, D_x [t=0], should be known to predict how the indicators for severity of the potential accidents vary. The symbol D_x [t]| R_x shows that for the zone X the deterministic variables can also depend on anyone of the random parameters.

Due to the assumptions and conventions mentioned above the following relation can be written:

$P((R_x \cap D_x[t])|F_J) = P(R_x|F_J)P(D_x[t]|F_J, R_x)$ (1)

$P(R_x|F_J)$ – Conditional probability specifying the severity of initial disturbances by using a vector of random parameters whose value R_x falls into a particular region of a corresponding hyperspace. This term identifies the vague damaging potential of this fraction of the likely accidents, which for a unit time arise just at the zone X of the facility J. The values of the random parameters identify "holes" in a barrier inducing particular fractions of accidents;

$P(D_x[t]|F_J, R_x)$ – Conditional probability specifying those abnormal events that, after arising from the zone X with the potential identified by the values of R_x and $D_x[0]$, progress later on in such a way that can overcome the rest of the defense barriers. This means that for this fraction of possible accidents as the R_x so the $D_x[0]$ are known to the accuracy of a small region within their hyper-spaces.

In fact, the final consequences are those indicating how severe an accident scenario is. However, while an abnormal situation progresses from stage to a stage its magnitude can be "measured" by using some "intermediate" indicators. For instance, using the release rate of a hazardous substance as an indicator we can find those potential disturbances, which can develop further on into major accidents. Indicators of every stage take their values depending on what has happened in previous stages of the propagation of accidents. The time variation of the indicators, suggesting that major accidents are possible, depends strongly on the $D_x[t]$. On the other hand for similar scenarios the deterministic variables never accept the same values $D_x[t]$ at the time t. The initial values $D_x[0]$ of deterministic factors change from scenario to scenario since the value of every random parameter is predictable only to the accuracy of a certain range. If the sets of values R_x and $D_x[0]$ plus those deterministic laws of nature that govern the evolution of the dominant accidental phenomena are exactly known, then predictions are obtainable by single values. However, this is impossible in the real word because of the uncertainties which both the parameters and the models introduce. Quantifying the indicators the analyst should consider that random factors are inherently vague and also it is not possible to specify exactly the real initial values of all deterministic variables. Since mathematical expressions for deterministic laws of nature more or less adequately approximate but very rarely entirely reproduce the real progress of the phenomena of interest they also contribute to the uncertainty. Being unable to assess with zero error how the indicators vary in space and time, the best we can do is to address the uncertainty which dominant factors introduce in the investigations.

The formal mathematical relations discussed so far suggest that the uncertainty about the indicators, for arising of high risk abnormal situations, can be addressed varying suitably in their hyperspaces the factors, identifying the potential of the zone X, to induce accidents. It is assumed that the values R_x, which the random parameters take initially, stay unchanged while accidents progress. Also, that the initial values, $D_x[0]$, of the deterministic variables can depend on R_x but the opposite is not true.

The approach here presented supposes that the real world accidental scenarios are expressible sufficiently well by the following logical order: $R_x \rightarrow D_x(0) \rightarrow [D_x(t)=f(R_x, D_x(0))] \rightarrow [{}^{I}M_x(t)=f(D_x(t))]$ - the symbol $f(\cdot)$ shows a function of a number of arguments;

- the symbol ${}^{I}M_x(t)$ points out the value taken by the indicator's vectors, given the initial values of the random and deterministic factors are restricted within small regions of their hyperspaces. The components of the matrix:
$M_x(t) \equiv [\ {}^{1}M_x(t),\ 2M_x(t),\ \ldots\ ,\ {}^{Imax}M_x(t)]$ can be calculated altering the values of both type of parameters for all sub-regions they can fall into. (Since I_{max} is usually a big number the analysis is time consuming.)

In order to address the vague potential of the abnormal events, occurring from the zone X of the J, the first step is to define the joint probability distribution – $P_x(R_1, R_2, \dots, R_N|F_J)$, for n=1, 2, …., N, of those N random parameters having dominant contribution. The hyperspace, in which these factors vary, is an ordered N-tuple Cartesian product. An appropriate inferential approach is needed to identify the marginal probability distributions first, and after that their joint probability distribution. Then the likely initial values, $D_x[0]$, which the deterministic variables take into their hyperspace, should be identified. Once the hyperspaces of both types of factors are divided into a reasonable number of sub-regions the components of the matrix $M_x[t]$, are assessable by using corresponding expressions for the deterministic laws of nature. Finally, the fraction of the risk-significant abnormal events can be assessed as the ratio of the number of those values of the matrix $M_x[t]$, which fall outside the safety region of the indicators hyperspace, to the total number of its elements.

There is no more discussion on the generic features of the methodology further in this work. None of the issues related with the model uncertainty are commented on here in order to focus on the methodology's application. Some specific methods that the methodology uses are considered in the next section.

3. Case study

The case specific discussion on the approach

A vertical cylindrical storage tank filled with a liquid flammable fuel is analyzed to identify the land areas around the tank from which huge fires or explosions can occur. Although the tank is no part of an installation processing hazardous substances it is surrounded by other vessels. Thus, at the site in which the tank of study is situated the domino effect is highly possible.

The wall of the vessel is the single barrier separating the fuel form the environment. Therefore, any time when the wall has lost its integrity release scenarios occur and liquid fuel and its vapors will be emitted around the tank. The mass flow rate of fuel through the tank's wall is used as an indicator showing that the wall failures can grow further into huge fires or explosions. The magnitude of velocity through the ruptured place and the cross-section of this hole uniquely determine the mass of fuel released for any given period. The direction of velocity from the hole is also important parameter since contents of both the vulnerable items and the ignition sources in the vicinity of the tank can vary largely from one target area to another. It is well know that the meteorological conditions and local topology dominantly determine how the fuel will disperse first in the air and then onto the land but this stage of accident progression is outside the scope of this work.

The restricted analysis, here presented, aims to identify the most severe release scenarios. The fuel mass that has left the tank for a certain period $[0, t_1]$ is an indicator for those wall's failures, which later on can turn into fires or explosions. The indicator $M[t_1]$ is quantified by the following relations:

$$M[t_1] = \int_0^{t_1} M[t]dt; \quad M[t] = |\mathbf{u[t]}|\rho[t]A_h \qquad (2)$$

where,

$|u[t]|$ - the magnitude of the velocity through the hole at the time t - [m/s];

$\rho[t]$ – the density of the liquid fuel leaving the hole at the moment t – [kg/m^3];

Ah – [m^2] the cross-section of the wall's rupture, specified by a circular hole with the same face.

For this study, R_1 identifies the location on the wall surface in which the tank fails and R_2 is the diameter of a circular hole with cross-section of A_h. (To specify the joint distribution of these two random variables their marginal distributions should be obtained first).

Let us suppose that the tank of study stands on the ground and there is no thermal isolation over its metal wall. The tank height is 3 [m] and its diameter is 1 [m]. Neither chemical reactions nor other sources generate or sink heat into the tank but heat fluxes from the outside make the pressure, the temperature and the fuel properties to fluctuate. The tank has no connection with other vessels or pumps also the fuel inside is under stable static pressure and its temperature is almost the same as the ambient one. Thus, when a rupture arises the static pressure is the force pushing the liquid fuel out of the tank. Later on, due to the loss of fuel, the pressure and the density of fuel inside the tank decrease and the mass flow rate through the hole reduces continuously in the time. (The pressure inside cannot change suddenly due to impacts from other vessels or active components like pumps and valves). After the tank fails the pressure and the density inside will change very slowly as only small holes are assumed possible to occur unexpectedly. When the failure of the tank's wall induces a very mild transient the Bernoulli equation is a suffieciently correct deterministinc law for prediciting the quasi-static change in the pressure of fuel inside. Due to the assumpions listed above, for a short time step the average velocity over the hole's cross-section $u_h[t]$ is assessed as:

$$uh[t] = (h[t]g)^{0.5}; \qquad (3)$$

where,

g – acceleration of gravity [m/s^2];

h[t] – the distance between the free fuel surface in the tank and the center of hole at the time t [m].

Identifying the ranges in the hyperspaces of parameters

To estimate uniquely the fuel mass flow rate through the hole at the given time of t_1 we need the initial values of two deterministic parameters - the temperature behind the hole $T_h[0]$ and the distance h[0]. The initial temperature in the whole tank can be supposed almost the same and equal to $T_h[0]$ but its exact value is uncertain because the varying ambient conditions influence on the state of the fuel inside. For this study we assume that $T_h[0]$ varies in the range [5°, 45°] degrees Celsius. Due to the uncertainty about the exact value of $T_h[0]$ it falls into a larger range than the range in which the $T_h[t]$ varies during the progress of release scenarios. Thus, for the period $t \leq t_1$ $T_h[t]$ is considered a constant equal to $T_h[0]$. The h[0] falls into the range [0, 3] in [m] and it is a function of the random parameter R_1, which is discussed later on.

The following sequential steps are applicable in the inner cycle of the iteration scheme, given the random factors $\{^K R_1,\ ^L R_1\}$ are identified to the accuracy of a small region within their space :

1. The values $^b u_h(t_i)=f(h[t_{i-1}]),\rho[t_{i-1}]=\rho(p_h[t_{i-1}],T_h[0])$, $p_h[t_i]=p_0+g^b h[t_{i-1}]\rho[t_{i-1}]$, for p_0 the atmospheric pressure, and $\Delta^b M[t_i]=^b u_h[t_i]\rho[t_{i-1}](t_i-t_{i-1})A_h$ are assessed at each time step i first;

2. After correcting the fuel mass in the tank by the lost mass of $\Delta^b M[t_i]$ the new value of $^c h[t_i]$ is estimated. Then $^c u_h[t_i]$, $\rho[_{ti}]$, $T_h[t_i]$ and $\Delta^c M[t_i]$ are calculated. The time step is reduced if the difference between $\Delta^b M[t_i]$ and $\Delta^c M[t_i]$ is too large. When the error of lost mass at current time step is acceptably small then $\Delta M[t_i]=\Delta^c M[t_i]$ and the calculation goes on;

3. Since the conjugate space of the deterministic variables for the case study is two-dimensional the indicator should be predicted by combining their initial values at least in four couples. The biggest among the calculated values is used as conservative estimate for the fuel mass lost through a particular area over the wall surface. The maximal value of the indicator can be obtained as:

$$\Delta^m M[t_i]=\max(\Delta^{d,d}M[t_i],\Delta^{d,u}M[t_i],\Delta^{u,d}M[t_i],,\ ^{u,u}M[t_i])$$

The meaning of the above listed symbols is as follows:

$T_h(0)\in[^J T^d,\ ^J T^u]; h(0)\in[^N h^d,\ ^N h^u];\ ^L R_2\in[^L R_2^d,\ ^L R_2^u]$;

$^K \mathbf{R_1}$ is radius vector of the space surface ;

$$\Delta^{d,d}M = f({}^{J}T^{d},\ {}^{N}h^{d},\ {}^{K}\mathbf{R}_1,\ {}^{L}R_2);\ \Delta^{d,u}M = f({}^{J}T^{d},\ {}^{N}h^{u},\ {}^{K}\mathbf{R}_1,\ {}^{L}R_2);$$

$$\Delta^{u,d}M = f({}^{J}T^{u},\ {}^{N}h^{d},\ {}^{K}\mathbf{R}_1,\ {}^{L}R_2);\ \Delta^{u,u}M = f({}^{J}T^{u},\ {}^{N}h^{u},\ {}^{K}\mathbf{R}_1,\ {}^{L}R_2)$$

The range of the initial temperature of fuel in the tank can be divided on two sub-ranges [5°, 25°) and [25°, 45°]. The sub-ranges of the initial distance h[0] depend on the sub-regions on which the random parameter R_1 is divided on.

The outer cycle of the iteration scheme includes sequential visiting of all sub-regions into which the entire hyperspace of random parameters is divided for the case of study.

1. The parameter R_1 should identify so small areas on the entire surface of the tank's wall within which the minimal and the maximal value of the indicator do not differ too much. For the case of study a cylindrical coordinate system is suitable to define the radius vector of any part of the wall surface in which the rupture can arise. Also, the point at which the tank axis crosses the land surface is used as the origin of this coordinate system. In order to identify the values of the radius vector ${}^{K}R_1$, corresponding to the area ${}^{K}A_w$ of the wall surface, two parameters are used - height Y and azimuth angle θ:

$$Y \in (0,3);\ {}^{1}Y \in (0,0.6];\ {}^{2}Y \in (0.6,1.3];\ {}^{3}Y \in (1.3,2.1];\ {}^{4}Y \in (2.1,3)$$
$$\theta \in [0^{\circ},360^{\circ}];\ {}^{1}\theta \in [0^{\circ},60^{\circ}];\ {}^{2}\theta \in [60^{\circ},120^{\circ}];\ {}^{3}\theta \in [120^{\circ},180^{\circ}]$$
$${}^{4}\theta \in [180^{\circ},240^{\circ}];\ {}^{5}\theta \in [240^{\circ},300^{\circ}];\ {}^{6}\theta \in [300^{\circ},360^{\circ}]$$

By using the listed notations it is easy to find that the couple ${}^{3,5}R_1 \equiv \{{}^{3Y},{}^{5}\theta\}$ corresponds to that part of the wall surface for which the Y and the θ falls into the ranges (1.3, 2.1] and (240°, 300°], respectively.

2. The other random parameter the diameter of the hole, specified by the symbol R_2, uniquely identifies the cross-section of the crack location as $A_h = \pi R_2^2$.

A suitable inferential model is required to quantify the marginal distributions of the random factors. Because of the above listed, for the case of interest, at the outer cycle of the iteration scheme 4x6 sub-regions within the conjugate hyperspace of the random parameters should be visited. For each one of those 24 sub-regions the initial values of deterministic parameters are altered at least 4 times and by using the deterministic laws the indicator values varying in time should be found and ranked. The maximal among those 4 figures about the indicator, obtained in the inter cycle of the iteration scheme, specifies the most dangerous release scenario among those emerging from anyone of the specified parts of the tank's wall. The mass of fuel left the tank for the control time t1 shows how likely the given release scenarios are to progress later on into huge fires and explosions. The discussion so far focuses on identifying the significance of release scenarios in terms of deterministic arguments. In the author's opinion the more important question is what is the fraction of release scenarios that for the period t_1 can push out of the tank a fuel mass bigger than given threshold value?

Quantifying the probabilities of the major release scenarios

As it was discussed in section 2 the approach here presented estimates the chance that the possible failures of the tank of study can grow to major releases of hazardous substances. The approach introduces the conditional probabilities $P(D_x[t]|F_J, R_x)$ and $P(R_x|F_J)$. The term $P(D_x[t]|F_J, R_x)$ identifies how probable it is if the rupture has occurred the deterministic variables after falling initially into a certain region of their hyper-space to change later in a particular way, given the random parameters are restricted within a small sub-region of their hyperspace.

For the tank of investigation we should assess the probability of the following complex events:

$$E_{1,1,[1,K2],L} \equiv [{}^{1}T_h[0] \in [5^{\circ},25^{\circ}]) \cap ({}^{1}h[0] \in (2.4,3])] \,|\, ([{}^{1}Y,{}^{K2}\theta],\ {}^{L}R_2]$$
$$E_{2,1,[1,K2],L} \equiv [{}^{2}T_h[0] \in [25^{\circ},45^{\circ}]) \cap ({}^{1}h[0] \in (2.4,3])] \,|\, ([{}^{1}Y,{}^{K2}\theta],\ {}^{L}R_2]$$

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$$E_{1,4,[4,K2],L} \equiv [{}^{1}T_h[0] \in [5^{\circ},25^{\circ}]) \cap ({}^{4}h[0] \in (0,0.9])] \,|\, ([{}^{4}Y,{}^{K2}\theta],\ {}^{L}R_2]$$

$E_{2,4,[4,K2],L} \equiv [{}^2T_h[0] \in [25^o,45^o]) \cap ({}^4h[0] \in (0,0.9])] \mid ([{}^4Y,{}^{K2}\theta], {}^LR_2]$
for K_2 varying from 1 to 6 as first L=1 and then L=2.

We can define the following probabilities:

$P({}^1T_h[0]) = 0.5; \; P({}^2T_h[0]) = 0.5$

The term $P(R_x|F_J)$, that the methodology introduces should specify in the case of study the rupture location on the defensive barrier – the tank's wall for this study.

Since the uncertainty about random parameters is expressed by their joint probability distribution let us suppose that the parameters R_1 and R_2 are independent and the following is true:

$P(R_1 \cap R_2) = P(\mathbf{R_1})P(R_2); \; P(\mathbf{R_1}) = P(\bigcup_{K=1}^{24} {}^K\mathbf{R_1}); \; P(R_2) \approx P({}^1R_2 \cup {}^2R_2)$

The symbol ${}^dR_2$ indicates that value of the hole diameter at which the cumulative distribution is equal to some value c_1 or $P(0 < R_2 \leq {}^dR_2) = c_1$. The symbol ${}^uR_2$ shows the 97.5% quintile of this distribution or $P({}^dR_2 < R_2 \leq {}^uR_2)=0.975-c_1$ and $P(R_2 > {}^uR_2) = 0.025$.

Having no reliable observations about those areas on the tank surface within which the wall's integrity is more often lost, the assumption that rupture is equally likely in each one of the specified 24 parts of the wall surface is a reasonable one or:

$P({}^1\mathbf{R_1}) = ... = P({}^{10}\mathbf{R_1}) = ... = P({}^{20}\mathbf{R_1}) = ... = P({}^{24}\mathbf{R_1}) = 0.04167$

The distribution about the hole's diameter should be identified first, then the values of ${}^dR_2$ and ${}^uR_2$ can be assessed. When there is not enough specific data, as usually the situation is, Bayesian statistics can help. It is capable to combine coherently generic information with the limited data coming from identical units.

Identifying the distribution about the hole's diameter

The Bayesian concept on probability is outside the scope of this paper. Many excellent works as (Robert, C., 2004) and many others are dedicated to the Bayesian approach. A parametric Bayesian model is used to specify the distribution for the entity R_2. This inferential model can obtain the posterior density function about the rupture diameter relating it with both its prior distribution and the likelihood function about the available observations.

$$\pi(\varphi \mid \mathbf{O}) = \frac{\ell(\varphi \mid \mathbf{O})\pi(\varphi)}{\Lambda}, \text{ where } \Lambda = \int \ell(\varphi \mid \mathbf{O})\pi(\varphi)d\varphi \quad (4)$$

$\ell(\varphi \mid O) = p(O \mid \varphi)$ - likelihood function about the evidence $\mathbf{O}$

$\pi(\varphi), \; \pi(\varphi \mid O)$ - prior and postrior density functions

Λ – normalizing constant

$O \equiv [O_G, O_I]$ – a set of more or less relevant observations about the entity R_2;

The set of observations includes generic data, OG, and more relevant data about ruptures of identical tanks - OI. The source of generic information for the study is the (HSE, 2000) and data here used are listed in the appendix. Due to the lack of reliable data for the size of cracks on identical tanks the set $O_I \equiv [2, 5, 10]$ in [mm] is applied in order to show how the inferential model works.

The Bayesian theorem is applied two times. On the first stage the evidence O_G is used to specify the generic posterior distribution. On the second stage the generic posterior distribution is updated by means of the data set O_I coming from identical units. Hierarchical Bayesian models are used on every one of these stages. A huge number of references are dedicated to the theoretical aspects of Bayesian models with hierarchical structure, like (Browne&Draper, 2000), (Gelman&Pardoe, 2006) etc. The application of Bayesian inference at various practical problems is also considered in many works, for example (Esner et al., 2004), (Argirov, 2006) and so on.

The multilevel model used has the following structure:

$\beta \sim \text{gamma}(\alpha_1, \mu_1)$; where α_1, μ_1 are constants

$\sigma \sim \text{uniform}(\alpha_2, \mu_2)$; where α_2, μ_2 are constants

$\pi(\varphi) \equiv \pi(\beta, \sigma)$

$$\ell(\varphi \mid \mathbf{O}_L) \sim \text{Normal}(\beta, \sigma \mid \mathbf{O}_L);\ \text{for } L = G, I \qquad (5)$$

The constants α_1, α_2 , μ_1, μ_2 are chosen in such a manner that the distributed parameters β, σ identify our prior believe about the variability of the hole diameter. Then, under the assumption that the likelihood functions for all separate observations belong to the lognormal family, the parameters β, σ are updated by using first the evidence O_G and then the data O_I. Although, the hierarchical model here presented is not the best one, it demonstrates well enough how the uncertainty about the entity R_2 is addressed.

The computer code WinBUGS (Spiegelhalter et al., 2003), (Woodward, 2005) is used to solve this multilevel inferential model. The generic prior, the generic posterior and the tank specific posterior density functions are presented on figures 1, 2 and 3 respectively. Some characteristics of these distributions are listed in table 1. Table 1 shows that as far as the evidence O is relevant to our case we can be 97.5% sure that the hole's diameter is smaller than 14.5 mm.

Therefore, we can specify that $P(0 < R_2 \leq 8.44)=0.75$, $P(8.44 < R_2 \leq 14.5)=0.225$ and $P(R_2 > 14.5)=0.025$.

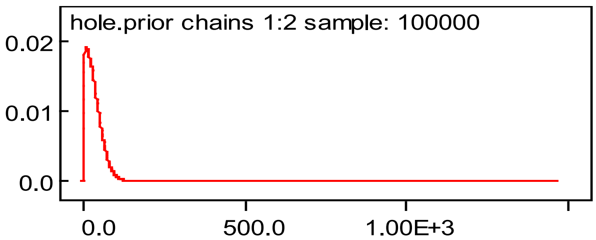

Fig. 1. Generic prior distribution

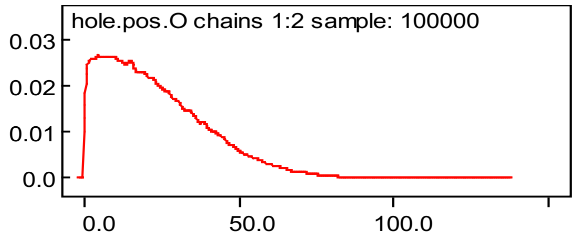

Fig. 2. Generic posterior (specific prior) distribution

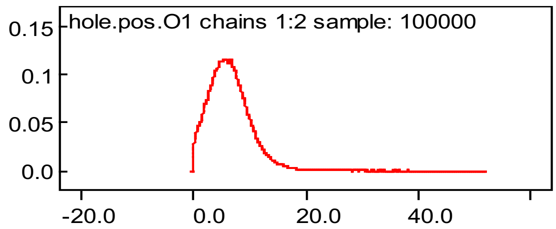

Fig. 3. Specific posterior distribution

Table 1: Distributions about the diameter of the hole

Distribution about the hole diameter in [mm]	2.5%	50%	75%	97.5%
Generic prior (hole.prior)	1.29	27.4	46.6	104.3
Specific prior (hole.pos.O)	0.95	19.8	33.2	63.2
Specific posterior (hole.pos.O1)	0.66	6.04	8.44	14.5

Quantitative characteristics of the release scenarios

For the tank of investigation it is easy to figure out that the bigger accidental release rates are associated with a sub-area of its wall that is closest to the ground. These parts of the wall surface are analyzed by the following events:

$$E_{1,1,[1,K2],L} \equiv ({}^1T_h[0] \in [5^\circ, 25^\circ]) \cap ({}^1h[0] \in (2.4, 3]) \mid ([{}^1Y, {}^{K2}\theta], {}^L R_2)$$
$$E_{2,1,[1,K2],L} \equiv ({}^2T_h[0] \in [25^\circ, 45^\circ]) \cap ({}^2h[0] \in (2.4, 3]) \mid ([{}^2Y, {}^{K2}\theta], {}^L R_2)$$

for K_2 varying from 1 to 6 as first L=1 and then L=2.

All of these events, consider release scenarios for which the parameter h[0] varies in the range

[2.4, 3] in [m] and the velocity $u_h[0]$ falls in the rage [4.86, 5.42] in [m/s].

The events $E_{1,1[1,K2],1}$ and $E_{2,1[1,K2],1}$ represent the random occurrence of ruptures in the tank wall with equivalent diameter smaller than 8.44 [mm]. For both events the value of A_h is smaller than $2.24x10^{-4}$ [m^2] and the chance that it is true is about 0.75 - P(0<R2<8.44)=0.75. The couple of events $E_{1,1[1,K2],2}$ and $E_{2,1[1,K2],2}$ identifies release scenarios for which the value of A_h is in the range [$2.24x10^{-4}$, $6.61x10^{-4}$) and also P(8.44<R2<14.5)=0.225. The chance for random occurring raptures with cross-section of about $6.61x10^{-4}$ [m^2] and above is no more than 0.025.

Let us assume that the tank contains flammable methanol at pressure of 1.3 [bar] whose density and the specified temperatures are: $\rho[5^o]=805.1$, $\rho[25^o]=786.4$ and $\rho[45^o]=767.4$ [kg/s], respectively. Having in mind all listed figures we can conclude that the maximal mass flow rate of interest from the tank at the t=0 is 2.88 [kg/s]. Thus, for the study the following is true:

$$P(E_{1,1,[1,K2],2} \cup E_{2,1,[1,K2],2}) = P(\bigcup_{K2=1}^{6} E_{1,1,[1,K2],2}) + P(\bigcup_{K2=1}^{6} E_{2,1,[1,K2],2}) = 0.0563$$

$$P(\bigcup_{K2=1}^{6} E_{1,1,[1,K2],2}) = P(5^o < T_h[0]) < 25^o)P(\bigcup_{1}^{6} {}^{1,K2} R_1)P(8.44 < R_2 < 14.5)$$

$$P(\bigcup_{K2=1}^{6} E_{2,1,[1,K2],2}) = P(25^o < T_h[0]) < 45^o)P(\bigcup_{1}^{6} {}^{1,K2} R_1)P(8.44 < R_2 < 14.5)$$

$$P(T_h[0]) < 25^o) = P(25 < T_h[0]) < 45^o) = 0,5;$$

$$P(\bigcup_{1}^{6} {}^{1,K2} R_1) = 0.25; \; P(8.44 < R_2 < 14.5) = 0.225$$

Thus, no more than about 2.25% of the expected release scenarios may originate with release rate bigger than 2.88 [kg/s]. A fraction of 5.63% of all scenarios is associated with an initial mass release rate varying in the range [0.835, 2.88] [kg/s]. For the tank of study the remaining release scenarios occur with mass flow rate smaller than the figure of 2.88 [kg/s].

4. Conclusions

The paper suggests that the possible impacts on the global climate system due to accidental releases of dangerous substances should be quantified and taken into account. Since the magnitude of such releases is associated with huge uncertainty, specific methodology is required. An easy for implementing in practice approach capable to “measure” the potential of release scenarios to progress further into major accidents, is presented. This methodology allows the fraction of those scenarios which can affect badly certain target land areas, situated in particular directions from a hazardous unit, to be identified. The part of the approach presented in this work is applicable to search for those zones over a defensive barrier, separating hazardous substances from their surroundings, within which risk significant release scenarios can emerge. The information, that even the first stage of the approach here presented finds, can help in ranking by quantitative criteria the areas, in the surroundings of a hazardous unit, which may be polluted seriously. By predicting conservatively the most likely amounts of dangerous substance entering in certain regions around the failed unit the uncertainty about the consequences of likely accidents for people and the environment can be reduced.

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Appendix

Generic evidence - OG for failures of units operating with liquids (based on HSE, 2000)

No (year)	System	Equivalent hole [mm]
1 (92-93)	Utilities Oil; Heat transfer Oil	3
2 (93-94)	Gas Compressor lubricating Oil	25
3 (93-94)	Gas Compressor lubricating Oil	1
4 (92-94)	Gas Compressor lubricating Oil	1
5 (93-94)	Condensate methanol	50.8
6 (93-94)	Processing Methanol	20.4
7 (93-94)	Dehydration of Glycol	10
8 (93-94)	Dehydration of Glycol	12.7
9 (93-94)	Power gen. turbine, Diesel released	6.7
10 (93-94)	Utilities, Oil, diesel	25.4
11 (93-94)	Utilities, Heat transfer oil	9.53
12 (93-94)	Power gen. turbine, Oil released	1.0
13 (93-94)	Separation, Oil test	12.7
14 (93-94)	Flare, Condensate released	76.2
15 (93-94)	Processing, LPG released	12.7
16 (94-95)	Export, Oil released	1.0
17 (94-95)	Gas Compression, Lub. Oil released	12.7
18 (94-95)	Gas Compression, Lub. Oil released	1.0
19 (94-95)	Gas Compression, Lub. Oil released	1.0
20 (94-95)	Gas Compression, Lub. Oil released	1.0
21 (94-95)	Processing, Glycol released	2.0
22 (94-95)	Dehydration of Glycol	1.0
23 (94-95)	Dehydration of Glycol	1.0
24 (94-95)	Dehydration of Glycol	1.0
25 (94-95)	Power Gen. turbine, Diesel released	5.0
26 (94-95)	Utilities Oil, Heat transfer Oil	1.0
27 (94-95)	Utilities Oil, Heat transfer Oil	1.8
28 (94-95)	Utilities Oil, jet fuel	1.0
29 (94-95)	Power Gen. turbine, Diesel released	11.8
30 (94-95)	Power Gen. turbine, Diesel released	11.8
31 (94-95)	Power Gen. turbine, Oil released	25.4
32 (94-95)	Treatment of (H2S/CO2), Condensate	25.4
33 (95-96)	Gas Compression, Lub. Oil released	1.0
34 (95-96)	Gas Compression, Lub. Oil released	2.7
35 (95-96)	Dehydration of Glycol	1.0
36 (95-96)	Power Gen. turbine, Diesel released	1.0
37 (95-96)	Utilities, Diesel released	2.3
38 (95-96)	Heat transfer Lub. Oil released	1.0
39 (95-96)	Heat transfer Lub. Oil released	38.1
40 (96-97)	Export Lubrication Oil	1.0
41 (96-97)	Power Gen. turbine Lub. Oil released	5.4
42 (96-97)	Power Gen. turbine, Diesel released	1.0
43 (96-97)	Utilities, Diesel released	1.0
44 (96-97)	Utilities, Diesel released	1.0
45 (96-97)	Utilities, Diesel released	12.7
46 (96-97)	Utilities, Diesel released	12.7
47 (96-97)	Utilities, Diesel released	12.7
48 (96-97)	Utilities, Diesel released	1.0
49 (96-97)	Utilities, Diesel released	1.0
50 (96-97)	Utilities, Diesel released	1.0
51 (96-97)	Import, Condensate released	1.0
52 (97-98)	Utilities, Diesel released	1.0
53 (97-98)	Utilities, Diesel released	3.0
54 (97-98)	Utilities, Diesel released	1.0
55 (98-99)	Gas Compression, Lub. Oil released	5.0
56 (98-99)	Dehydration of Glycol	1.0
57 (98-99)	Power Gen. turbine, Lub Oil released	1.0
58 (98-99)	Power Gen. turbine, Lub Oil released	1.0
59 (98-99)	Power Gen. turbine, Lub Oil released	5.0
60 (98-99)	Power Gen. turbine, Oil released	3.2
61 (98-99)	Power Gen. turbine, Lub Oil released	1.0
62 (98-99)	Utilities, Diesel released	1.0
63 (98-99)	Utilities, Diesel released	1.0
64 (98-99)	Utilities, Diesel released	1.0
65 (99-00)	Utilities, Diesel released	1.4
66 (99-00)	Utilities, Diesel released	1.0
67 (99-00)	Utilities, Diesel released	1.4
68 (99-00)	Power Gen. turbine, Lub Oil released	1.9

ценивая Риск Загрязнения из-за Ненормального Поведения Опасной Установки

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Резюме: Наше нынешнее понимание, заключается в том, что с 18-го века многие виды деятельности человека способствуют многозначительно изменениям в глобальной климатической системе. Количество опасных установок в использовании и их разнообразие резко увеличилось в течение последних 60 лет. Каждый из этих технологических объектов является потенциальным источником крупных несчастных случаев, с огромными или катастрофическими воздействиями на почву, атмосферу, качество воды, экосистемы и непосредственно на здоровье человека. В статье кратко комментируется подход к решению неопределенности в отношении неприемлемых последствий которые ожидаются от особенного опасного объекта. Первый этап подхода обсуждается в исследовании конкретного случая (кейс стади). Эта часть методологии способна искать и классифицировать те, вероятно, ненормальные ситуации с высоким потенциалом к дальнему прогрессу в несчастных случаях.

Ключевые слова: Опасные установки, технологический риск, сценарии основного выпуска.