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Consequence Analysis: Comparison of Methodologies under API Standard and Commercial Software

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In this study the procedure for conducting the consequence analysis according to API RBI is presented. The guidelines of API methodology are reported in the document API 581. The calculation of consequences was carried out by Inspection Manager tool (IM), thanks to the implementation of RBI analysis in this software developed in a previous work (Vianello et al. 2013), and Phast, a commercial software package for the estimation consequences modelling.

Through the software, two example of quantitative consequence analysis was conducted by taking into account the consequences of releases both of flammable-explosive and toxic compound based on real process operating conditions.

In both methods, the results are determined as an affected impact area and are useful to establish a comparison between the two software, in order to putting out the differences in the calculation of the consequences.

Finally, it is important to highlight that API approach is greatly simplified procedure and the consequence areas calculated using API methodology are not intended to be employed during unit design and other safety purposes, but only to establish a relative risk ranking of equipment items on the basis of risk, in RBI assessment.

1. Introduction

Loss of containment from processing equipment and the subsequent release of hazardous materials may result in damage to surrounding equipment and produce serious injury to personnel, production losses, and undesirable environment impacts.

A Quantitative Risk Assessment (QRA) is a valuable tool for determining the risk derived from the use, handling, transport and storage of dangerous substances (Egidi et al., 1995; Marhavilas et al. 2011; TNO, 1999). QRAs are used to evaluate the potential risk caused by the activity and to provide the competent authorities with relevant information to enable decisions on the acceptability of risk related to developments on site, or around the establishment or transport route.

The calculation of risk is dependent on the determination of a probability of failure combined with the consequence of failure.

Consequence analysis quantifies the vulnerable zones for an incident. Once these zones are identified, the risk analysis suggests measures of mitigation or prevention that can be proposed to eliminate damage to plant and potential injury to personnel. Estimation of vulnerability zone of such an incident plays an important role in preparing a realistic emergency plan.

An error of consequences estimation is directly associated an error to estimated of risk and ultimately the risk reduction requirements.

For these reasons, it is important to determine correctly consequences of a leak or rupture of a component.

The aim of the study is to compare the consequence estimation approach described in the API Standard 581 and the approach used in commercial software, such as Phast (DNV software).

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2. Consequence Analysis calculation procedures

The different approach for the calculation of the consequence of a leak or rupture of a component for use in API RBI and in Phast is described in this paragraph.

The consequence analysis in the Risk-Based Inspection (API RBI) assessment is performed to aid in establishing a ranking of equipment items on the basis of risk and provide a suitable inspection plan in the refining and petrochemical industry.

In API RBI the consequences are calculated using a simplified procedure based on empirical equations and a predefined set of hole sizes that reflects the range of possible outcomes. The results are expressed as an affected impact area in quantitative terms.

In particular, impact area from flammable and explosive substances are calculated using event trees to determine the probabilities of various outcomes, combined with computer modelling to determine the magnitude of the consequence. Consequence areas are quantified based on the effects of thermal radiation and overpressure on surrounding equipment and personnel. Additionally, the cloud dispersion analysis methods are used to quantify the magnitude of flammable release and to determine the extent and duration of personnel exposure toxic release. Toxic consequences are calculated using computer modelling to determine the magnitude of the consequence area as a result of overexposure of personnel to toxic concentrations within a vapour cloud.

Event trees are utilized to assess the probability of each of the various event outcomes and to provide a mechanism for probability-weighting the loss of containment consequences.

Two levels of assessment are available in API RBI methodology for computing the consequence of failure: the former, or Level 1, is a simplistic method to estimate the consequence area for a limited number of representative fluids; the Level 2 is intended to be much more rigorous and can be applied to wider range hazardous fluids.

In Level 1 consequences analysis contains table lookups and graphs that can readily be used to calculated the consequence of releases without the need of specialized consequence modelling software or technique. The simplifying assumptions are listed below:

- The fluid phase upon release can only be either a liquid or a gas, depending on the storage phase and the phase expected to occur upon release to the atmosphere. In general, no consideration is given to the cooling effects of flashing liquid, rainout, jet liquid entrainment or two-phase.
- Fluid properties for representative fluids containing mixtures are based on average value.
- Probabilities of ignition have been pre-determined for each of the representative fluids as a function of temperature, fluid Auto Ignition-Temperature (AIT) and release type. These values are constants, totally independent of the release rate.

This limitations can be overcome by Level 2 consequence analysis may be used in cases where more rigorous calculation are required and the assumptions of the Level 1 are not valid. For example this occurs if the specific fluid is not represented adequately within the list of reference fluid groups provided in the Level 1 or if it is necessary to consider the effects of two-phase releases or BLEVEs. On the other hand, the Level 2 requires a large amount of input data.

In this study is considered the Level 1 consequence analysis procedure as a simplistic method for approximating the consequence area of a hazardous release.

First of all, a representative fluid that most closely matches the fluid contained in the pressurized system being evaluated is selected from the list. Because very few refinery and chemical plant streams are pure materials, the selection of a representative fluid almost always involves making some assumptions.

It is important to note that the flammable consequence results are not highly sensitive to the exact material selected, provided the molecular weights are similar, because air dispersion properties and heat of combustion are similar for all hydrocarbons with similar molecular weights. This is particularly true for straight chain alkanes, but becomes less true as the materials become less saturated or aromatic. If the mixture contains toxic components and a toxic consequence calculation is desired, the choice of reference fluid is still required, even if the toxic component only makes up a small traction of the mixture. Once it has been selected the representative fluid it is necessary to determine its average properties which are dependent on the stored phase of the fluid. In this analysis the only inputs required are basic fluid properties (such as molecular weight, density and ideal gas specific heat ratio, k) and operating conditions. The initial phase of the hazardous material inside the equipment prior to coming into contact with the atmosphere is required to be defined as either liquid or vapour, and the normal boiling point is used in determining the phase of the material following the release.

The second step is the calculation of theoretical release rate that depend upon the physical properties of the material, the initial phase, the process operating conditions and the assigned release hole size.

The correct release rate equation must be chosen, based on the phase of the material when it is inside the equipment item, and its discharge regime (sonic or subsonic), as the material is released. For a two-phase release a conservative assumption is to utilize the liquid release equation, even if it always should be preferred a Level 2 analysis.
Different analytical models and methods are available to estimate the effects of an instantaneous versus a continuous type of release. It is very important to determine the properly release type, because the calculated consequences can differ greatly according the type of analytical model chosen to represent the release.
In API RBI, the release is modelled as one of two following type:

a) *Instantaneous Release (or puff) is one that occurs so rapidly that the fluid disperses as a single large cloud or pool;*
b) *Continuous* Release (or plume) *is one that occurs over a longer period of time, allowing the fluid to disperse in the shape of an elongated ellipse (depending on weather conditions).*

The transition between a continuous release and an instantaneous release in API RBI is defined as release where more than 4,536 kg of fluid mass escapes in less than 3 min.
The third step is the calculation of the consequence areas associated with several event outcomes for release of flammable and toxic fluids.
The flammable and explosive consequences for either component damage and personnel injury are measured in terms of the area affected by the ignition of a release.
The flammable consequence area is determined from a simple polynomial expression that is a function of the release magnitude and the representative fluid.
The consequence equations are presented in the following generic form:

$$\mathrm{CA_n}^{\mathrm{CONT}} = \mathrm{a} \cdot (\mathrm{rate_n})^{\mathrm{b}} \tag{1}$$

$$\mathrm{CA_n}^{\mathrm{INST}} = \mathrm{a} \cdot (\mathrm{mass_n})^{\mathrm{b}} \tag{2}$$

The Equation 1 is used for continuous release and the Equation 2 is used for an instantaneous release. The coefficient *a*, *b* for component damage areas and personnel injury areas, present in the previous equations, are provided for reference fluids. If the release is steady state and continuous, the release rate is used as the input to the consequence analysis; otherwise if the release is instantaneous, the release mass is required into the equation.
An event tree analysis is performed by listing possible events or outcomes and providing estimates for the probabilities of each event. Probabilities of ignition, probabilities of delayed ignition and other probabilities in the Level 1 event tree are selected based on expert for each of the reference fluids, temperature (proximity to the AIT) and release types (i.e. instantaneous or continuous).
These probabilities are constant and independent of release rate or mass.
There are several potential consequence outcomes for any release involving a flammable material and an equation represents the consequence area referred to a particular event outcome; however, a single combined result is determined as the average of all possible consequence outcomes, weighted according to probability. The consequence area for each outcome, computed from Equation 3, is multiplied by the associated event tree probabilities. If the impact criterion uses only a portion of the consequence area (for instance, flash fires use only 25 % of the area within the LFL for equipment damage, see Table 1) include this in the probability equation.
The equation that summarizes the result of the process is as follows:

$$\mathrm{CA_{comb}} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{p_i} \cdot \mathrm{CA_i} \tag{3}$$

To calculate these consequence areas for a particular event outcome (pool fire, VCE, etc.), API method uses threshold limits for thermal radiation (for jet fire, pool fire and fireball) and overpressure, sometimes referred as impact criteria. They are reported in the Table 1.

Table 1: Threshold limits used in API RBI

Parameter	Component damage criteria	Personnel injury criteria
Explosion Overpressure (kPa)	34.5	20.7
Thermal Radiation (kW/m^2)	37.8	12.6
Flash Fire	25 % of the area within the lower flammability limits (LFL) when the cloud is ignited	The LFL Limits of the cloud when ignite

For pool fires, the API RBI method assumes a dike size of 30.5 m by 30.5 m (929 m^2) and estimates the flammable consequences due to a maximum pool fire of that size.
The predicted results using the above threshold limits are intended to produce a relative risk ranking, which, while being considered to be reasonably accurate, are not the highest levels of consequence that could be estimated for a given accident sequence.
The computer modelling necessary to determine consequence areas associated with cloud dispersion (flash fires, VCEs, toxic releases) require specific input regarding meteorological and release conditions. For the Level 1 Consequence Analysis, meteorological conditions representative of the Gulf Coast annual averages are used. The meteorological input assumptions that you have to enter in order to complete the data for this analysis is small, as shown in the Table 2. They are satisfactory for a wide variety of plant conditions.

Table 2: Meteorological input

Parameters	Value
Atmospheric Temperature	21°C
Relative Humidity	75 %
Wind speed	12.9 km/h
Stability Class	D
Surface Roughness Parameter	30.5 mm

A similar procedure is used for determining the consequence associated with releases of toxic chemicals such as hydrogen sulphide, hydrogen fluoride, ammonia or chlorine, that typically contribute to toxic risks for a refinery. Toxic impact areas are based on Probit equations and can be assessed whether the stream is pure or a percentage of a hydrocarbon stream.
The toxic release rate or mass to be used in the toxic consequence analysis is determined based on the mass fraction of the toxic component ($mfract^{tox}$), that is present in the release fluid.

$$\mathrm{rate_n}^{\mathrm{tox}} = \mathrm{mfract}^{\mathrm{tox}} \cdot \mathrm{W_n} \tag{4}$$

$$\mathrm{mass_n}^{\mathrm{tox}} = \mathrm{mfract}^{\mathrm{tox}} \cdot \mathrm{mass_n} \tag{5}$$

For pure toxic fluids, the toxic release rate ($rate_n^{tox}$) is equal to the release rate (W_n) and the toxic release mass ($mass_n^{tox}$) is equal to the release mass ($mass_n$). The toxic consequences areas are calculated through specific equations that depend on toxic fluid and release type. For example, the toxic consequence area for Ammonia and Chlorine are computed using the Equations 6 for continuous release and the Equation 7 for an instantaneous release:

$$\mathrm{CA_{inj,n}}^{\mathrm{tox}} = \mathrm{e} \cdot (\mathrm{rate_n})^{\mathrm{f}} \tag{6}$$

$$\mathrm{CA_{inj,n}}^{\mathrm{tox}} = \mathrm{e} \cdot (\mathrm{mass_n})^{\mathrm{f}} \tag{7}$$

The constants *e* and *f* are functions of the release duration and provided for each toxic fluid.
In the event the release can involve both toxic and flammable outcomes, it is assumed that either the flammable outcome consumes the toxic material, or the toxic materials are dispersed and flammable materials have insignificant consequences. In this case, the probability for the toxic event is the remaining non-ignition frequency for the event (i.e., the probability of safe dispersion).
The calculation of consequences according API RBI approach is carried out by Inspection Manager tool (IM) , thanks to the implementation of RBI analysis in this software developed in a previous study. The number of values that you have to enter in order to complete the data for this model is small; moreover the software allows the insertion of data in a faster way, simplifying the analysis.
At this point it is necessary to conduct the consequence analysis with a software package for the estimation consequences modelling, such as Phast, to establish a comparison between the two methodologies and highlight the potential limitations of the procedure used in API RBI. The modelling of consequences used in the Phast code is in agreement with the equations of the Yellow Book of TNO (TNO). The study carried out by Phast requires a different type of input data for the consequence analysis, such as the definition of the calculation model, discharge material, inventory, operating conditions, weather conditions. The user defines a given hazardous event, selecting the most suitable Model and its own set of values for the input data to represent a particular hazardous event.
Model known as the “Vessel/Pipe Source Model” is selected. It considers the release of material from its storage or process conditions in a vessel or pipe, through all the stages in its dispersion to a harmless

concentration, and it also performs fire, explosion and toxic calculations to obtain representative effect zones for the dispersing cloud.
Model performs dispersion and effects calculations for a release from containment, setting the levels of radiation intensity and concentration on basis the same threshold values adopted in API (see Table 1). The program processes the consequence calculations for Dispersion and Flammable Models and it performs the analysis for specific weather conditions, reported in Table 2.

3. Quantitative examples

The present study considers two quantitative examples to compare the results by two software and put out the differences in the calculation of the consequences.
The types of hazardous event that are selected in the analysis are as follows:

- a leak in a piping containing an inflammable material
- a leak in a piping containing a toxic material

This allows to take into account either the flammable-explosive consequence area and toxic consequence area.
In both cases the quantitative analysis by taking as reference a small leak in a pipeline outgoing from a storage vessels and the release hole diameter is 6.4 mm.
In the first case the pipeline has a diameter equal to 100 mm and the fluid inside is benzene. The phase of benzene at normal operating conditions is liquid and also the phase of fluid at ambient condition after release to atmosphere is liquid. The representative fluid selected is aromatic. The main input data to estimate the consequence area are provided in Table 3.

Table 3: Input data to calculate explosive-flammable consequences for release of benzene

Parameter	Input Field	Value
Material	Discharge material	Benzene
	Inventory	450 kg
Process conditions	Temperature	60°C
	Pressure	2 bar
Location	Elevation	3 m
Scenario	Scenario type	Leak
	Hole diameter	6.4 mm
	Phase Released	Liquid

The release rate calculated by RBI IM and Phast is respectively 0.23 kg/s and 0.38 kg/s.
Subsequently two software compute the damage areas for auto-ignition not likely and continuous release. The outcomes considered are jet fire, pool fire, flash fire and VCE and the consequence areas of each individual event is combined into a single probability weighted empirical equation representing the overall consequence area of the event tree. The final component damage area is 4.8 m^2 for API RBI and 7.5 m^2 for Phast and the final personnel injury damage area is 18 m^2 for API RBI and 36 m^2 for Phast.
The second case considers a gas release from an horizontal pipeline, containing ammonia at saturation conditions and ambient temperature. The toxic release is constituted by pure ammonia.
The rupture is assumed to occur 3 meters from the ground. The dispersion analysis was performed using a saturated liquid at ambient temperature, with liquid being released from a low pressure storage tank. Toxic impact criteria used is for a Probit value of 5.0. For ammonia, set the dispersion concentration of interest to 25 ppm. The Table 4 shows a information needed to conduct the analysis for this equipment.

Table 4: Input data to calculate toxic consequences for release of ammonia

Parameter	Input Field	Value
Material	Discharge material	Ammonia
	Inventory	100 kg
Process conditions	Temperature	20°C
	Pressure	2 bar
Location	Elevation	3 m
Scenario	Scenario type	Leak
	Hole diameter	6.4 mm
	Phase Released	Gas

The release rate calculated by RBI IM and Phast is respectively $1.02 \cdot 10^{-2}$ kg/s and $1.56 \cdot 10^{-2}$ kg/s.
The toxic consequence area associated with continuous release of ammonia is 14.3 m^2 if it is computed using API procedure and 12.3 m^2 using Phast. Through the two software, the quantitative analysis was been conducted and the estimated consequence areas are summarized in the following table.

Table 5: Results for flammable and toxic consequence area

	Flammable Consequence Area	
	API RBI	Phast
Damage component	4.8 m^2	7.5 m^2
Injury personnel	18 m^2	36 m^2
	Toxic Consequence Area	
	API RBI	Phast
Injury personnel	14.3 m^2	12.3 m^2

The results highlights that API RBI approach underestimates the consequences area for release of flammable substance compared to Phast, while for toxic consequence area the values are similar in both cases. It is also interesting to note that the areas for release of benzene calculated by Phast are about twice those determined by RBI IM.
Phast normally gives conservative results in the consequence calculations.

4. Conclusions

The consequence modelling procedure for API RBI is greatly simplified approach to a relatively complex discipline. The input process involves examining a large number of assumptions that are implicit in the procedure, starting the selection of representative fluid and from all the parameters associated with this choice. API RBI consequence analysis includes also a simplified methodology for assigning the effectiveness of various type of detection, mitigation and isolation systems typically used in petrochemical processing plant. These systems affect a release in different ways: some systems reduce magnitude and duration of the release by detecting and isolating the leak; other ones reduce the consequence area by minimizing the chances for ignition or limiting the spread of material. In the present study the impact of these systems on release magnitude and consequence estimation was neglected, according a more conservative approach; hence the theoretical release rate (or mass rate) is used as the input to the analysis and the magnitude of final consequence area is not reduced by a specific factor, depending on the effectiveness of mitigation system.
Finally, it is important to note that the consequences calculated according to the procedures described in API RBI are not intended to be used in a rigorous consequence analysis of a component and if more accurate consequence estimates are needed, the analyst should refer to more rigorous analysis techniques, such as those used in quantitative risk analysis.

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