# Risk Assessment of Buried Natural Gas Pipelines. Critical Aspects of Event Tree Analysis

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The safety aspects of pipelines conveying hazardous materials are not included neither under the umbrella of Seveso Directives aiming at preventing major accidents at industrial facilities, nor in other EU legislation such as the Pressure Equipment Directive (PED). A review of relevant past accidents can provide statistical evidence on the extent to which pipelines present a risk potentially comparable to that of Seveso installations and on the degree to which the pipeline hazards are adequately controlled. Starting from evidence that in the last decades, the international natural gas market has been growing at a very high rate and continues to exhibit an increasing trend, in this paper we focus on consequences deriving from accidents on high pressure buried Natural Gas Pipelines (NGP) and related probabilities of the various outcomes. The paper focuses on a novel Event Tree framework, to overcome the limitations of the amply applied over-conservative IP UKOOA approach. In order to evidence the capability of the approach, the use of refined PET is exemplified by means of a real case-study of a high pressure buried NG pipeline, contrasting the actual results with those obtained by conventional methods, in terms of evolving scenario probability and damage. Conclusions are drawn about the effective application of the framework within risk assessment and related uncertainties in pipeline accident modelling.

## 1. Introduction

Owing to the new knowledge about environmental problems and the creation of the necessary transmission pipelines, in the last 40 years, the situation has changed and nowadays Natural Gas (NG) is ranking the third place in world energy consumption and has the best growth perspective between the fossil sources. Since the 70's world NG consumption has increased by more than 34 times, growing from 100 billion cubic meters to 3424 billion in 2013. The use of pipelines for NG transport to industry and domestic consumers represents a worldwide mode of distribution and the total length of pipelines is steadily increasing, thus enhancing the risk of relevant accidental scenarios. As an illustrative example, European total gas pipeline length has constantly increased reaching in 2013, the total length of 14,3727 km against 13,5211 km in 2013 (ECIG, 2015).

### 1.1 Pipeline accident statistics

The occurrence of the failure of a pipeline can be due to a number of different causes such as external interferences, corrosion, material or construction defects, hot tap made by error; ground movement; other causes, such as fatigue, operational and maintenance errors. Over the last 20 years, interest of integrity managers has been focused in failures and damage mainly related to the following conditions: stress Corrosion Cracking (SCC); Electrical Resistance Welding (ERW) and old repairs; lack of materials identification; lack of data on operating conditions; increase in population around pre-existing pipelines. Pipeline aging is a common item in Europe and resulted in notable accidents (e.g. Vairo et al., 2017), with potential high environmental impact in case of proximity with sensitive areas (Vairo et al., 2017). Some of the main gas distribution pipelines are more than 50 years old: integrity issues of these aged pipelines are related not only to material problems such as low toughness and in-service damage, but also to the way demographic expansion has affected conditions in some metropolitan areas. The usually uncontrolled increase in dwelling

around (and sometimes along) the right of way has influenced integrity requirements for operators of gas pipelines in various ways (Otegui, 2014):

- reduced acceptable risk of blowouts and other failures: this is a serious burden for integrity teams, especially in suburban areas where most of the pipelines are un-piggable;
- increased consequences of failures in gas treating and compression plants, due to increased production requirements and space constraints;
- increased risk of third party damage: notably;
- changes in soil conditions.

Dealing with expected frequency based on historical statistical analysis, different values can be calculated, as exemplified by Hill, 1992 who obtained over the time span 1983-1991 figures of $5.8 \cdot 10^{-4}$ and $7.4 \cdot 10^{-4}$ [ev/km/y] referred to the overall pipeline accidents and respectively based on data by CONCAWE (European Oil Company Organization for Environment, Health and Safety) and US-DOT. Crude oil and oil products are the main fluids extensively conveyed in European networks and as detailed in the following, different fire scenarios may result from the failure of a flammable material pipeline, whereas only for liquid releases it is considered pool fire scenario (Palazzi et al., 2017). Leak sizes range from pinholes up to hole sizes which represent critical or unstable defects for particular pipeline parameters. Unstable defects result in ruptures. A rupture release is a full bore, double-ended break or equivalent from which gas is released into a crater from both sections of pipe. In relative terms, the problem of HazMat pipeline risk assessment does not come with hazard analysis, or the estimation of failure frequency, but with the calculation of the consequences (Palazzi et al., 2014). In most cases, the rupture scenario will dominate the risk from Natural Gas pipelines. Usually, failure frequency data is quoted for the sum of all hole sizes, and these should be classified into specific hole sizes to permit the development of the risk assessment. To determine the range of hole sizes to be considered in the consequence assessment, the hole size which gives an equivalent outflow to the critical length of an axial defect for specific pipeline parameters should be determined. Critical defect length and equivalent hole diameter applies to external interference where axial, crack-like defects can occur; the equivalent hole sizes which relate to such defects do not apply to rounded punctures or stable holes due to corrosion or material and construction defects. The maximum possible hole size in high pressure gas pipelines is limited to the critical defect size. According to US DOT (2010) the immediate causes of NG pipeline failures are connected to corrosion (28%), construction material failure (23%), followed by excavation damages with a percentage of 20%. A limited sample of relevant NG pipeline accidents occurred in the USA, Canada and the EU, for which detailed accident reports are available from various sources (HSE, 2000), were thoroughly analyzed with following considerations on major events and immediate causes:

- rupture was the common type of failure occurred for all the cases;
- 54% cases were characterized by immediate ignition and the other 38.5% by delayed ignition. In one case ignition timing is unknown;
- 38,5% cases of failure were caused by corrosion generally localized in the bottom part of the pipe, 31% of cases characterized by third-part damage, 23% of cases by failure of girth weld and one case of hydrogen stress cracking;
- vertical jet fire has occurred in all the cases, only in one case a grounded jet fire or trench fire has been reported. In two cases the shaped of the jet was unknown;
- fireball has occurred in 31% of the cases but for two of them it was considered only as probable;
- flash fire has occurred only in one case.

## 2. Pipeline risk assessment

A bow-tie diagram centred on the critical event (see Figure 1) allows obtaining a qualitative description of major events resulting from a Natural Gas release from a buried pipeline and relevant preventive barriers. Design and procedural weaknesses can be identified in the left-hand side and probabilities of the various outcomes from an accidental event can be determined. The right-hand side is to be designed according to an event tree analysis (ETA) illustrating all possible final major hazard phenomena resulting from the critical event, considering whether installed safety barriers are functioning or not and additional/contributing factors. ETA can be used to identify all potential scenarios and sequences in a complex system following a step-by-step inductive logic chain:

- identification and definition of a relevant initiating event that may give rise to unwanted consequences;
- event tree construction;
- description of the potential resulting accident sequences;
- determination of the frequency of the accidental event and the (conditional) probabilities of ET branches;
- calculation of the probabilities/frequencies for the final outcomes or scenarios.
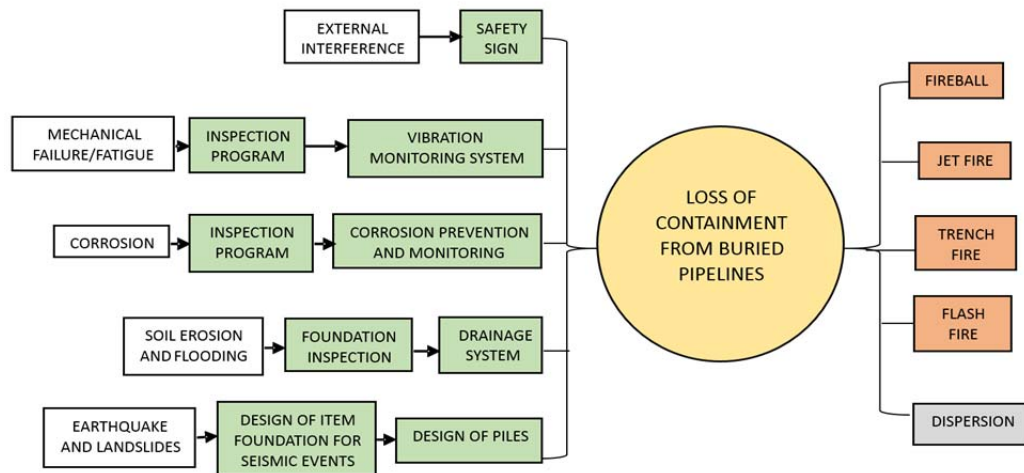
*Figure 1: Bow-tie showing major events from natural gas LOC in buried pipelines and preventive barriers*

In the following, a brand-new ETA is presented by a critical crossover with IP-UKOOA (2006) and HSE (2015) methods, to attain a more detailed description of all the possible outcomes and of the relative probabilities.

### 2.1 ETA development

The development of the novel PETA depicted in Figure 2 mainly relies on failure frequencies obtained EGIG report, which considers different values depending on the size of the failure.

The overall ignition probability is derived from the "look-up" correlations according to IP-UKOOA scheme:

$$y = 10^{mlog_{10}(x)+c} \tag{1}$$

where y is the ignition probability, x is the mass release rate (kg/s), m is the gradient of the correlation and c is the y-axis "offset" of the correlation. Such a definition allows the application of the model to a wider range of release cases, including full-bore, leaks and pinhole. Release rate shall be assessed with dedicated models and the risk analyst based on the specific project requirements can select relevant level of detail.

The second branch of the ETA is characterized by the additional choice between obstructed or unobstructed release, starting from HSE (2015) and allowing a more specific representation of the accidental scenario evolution. The corresponding value depends on the size of the release because actually for ruptures the unobstructed probability is 0.63, while for obstructed release is 0.37. Instead, for leaks the unobstructed probability is 0.25 and consequently, the obstructed probability is 0.75. Obviously, the likelihood of an obstructed or unobstructed release depends on the type of damage on the pipeline. If the damage derives from an external interference, the unobstructed release will be more probable while if the damage will be caused by corrosion, the release will be generally obstructed. The third branch of the ETA deals with the immediate ignition probability. In HSE report (2015), it is suggested a default conditional immediate ignition probability of 0.15. This probability can be modified by considering two parameters: $P_{AI}$= autoignition potential depending upon actual T and AIT; $P_{SD}$= potential for static discharge related to MIE and release energy for released material (defined as $P^{1/3}$). The immediate ignition probability can be written as follows:

$$P_{immediate\ ignition} = P_{AI} + P_{SD} \tag{2} \qquad P_{immediate\ ignition} = \left[1 - 5000e^{-9,5\left(\frac{T}{AIT}\right)}\right] + \left[\frac{0,0024P^{1/3}}{MIE^{2/3}}\right] \tag{3}$$

where: T and AIT [°F], P [psig], MIE [mJ] and the limiting values are: $T_{MIN}$= 0°F;
if T/AIT<0.9 then $P_{AI}$= 0; if T/AIT>1.2 then $P_{AI}$=1

When T< AIT + 93.3°C than it will occur a delayed ignition with P $_{immediate\ ignition}$< 0.98.

Such an approach allows for a more specific calculation of immediate ignition conditional probability when compared to the IP-UKOOA, where only very general values (mainly based on risk analyst judgment) are provided. Finally, the last branch deals with the difference between delayed local and delayed remote ignition probability. HSE-UK formula used to calculate the delayed local ignition probability is based on limited experimental observations and a number of relevant parameters are to be defined based on expert judgment and are still affected by a large degree of uncertainty (Pesce et al., 2012).
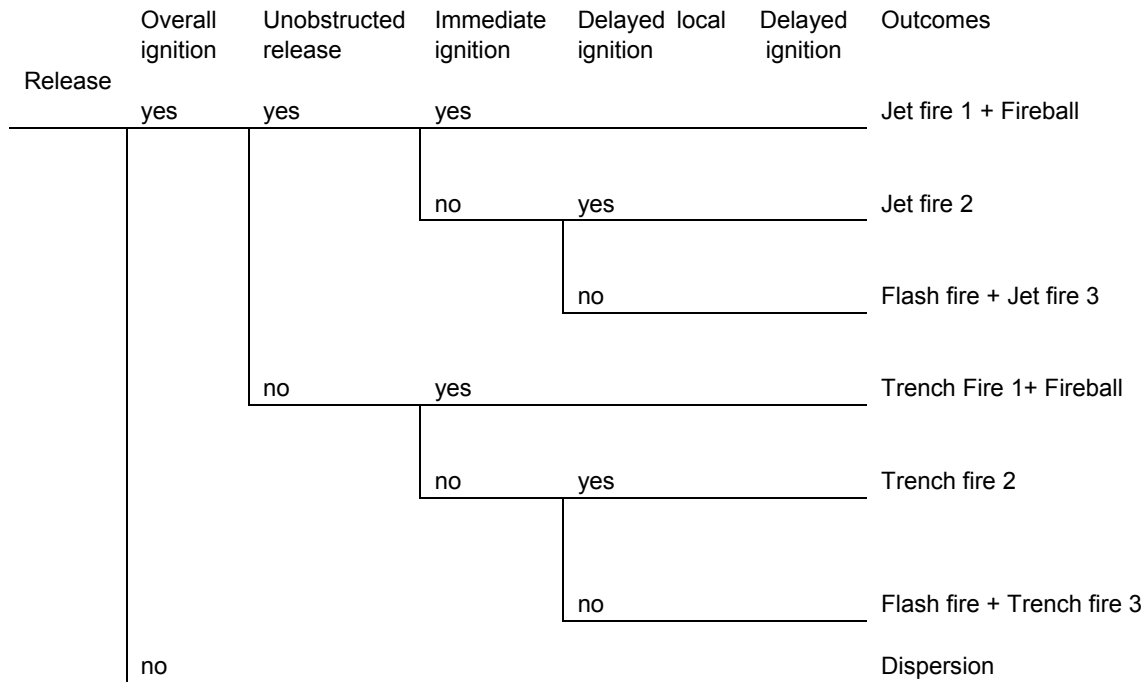
| | Overall ignition | Unobstructed release | Immediate ignition | Delayed local ignition | Delayed ignition | Outcomes |
|---|---|---|---|---|---|---|

Release

yes / yes / yes → Jet fire 1 + Fireball

no / yes → Jet fire 2

no → Flash fire + Jet fire 3

no / yes → Trench Fire 1+ Fireball

no / yes → Trench fire 2

no → Flash fire + Trench fire 3

no → Dispersion

*Figure 2: Buried natural gas pipeline ETA obtained according to the outlined framework*

It is common practice considering remote delayed ignition probability equal zero because during a NG high pressure release initially the cloud cools significantly during the expansion process so that local ignition of the cold, dense cloud is possible. Further downwind, buoyant behaviour becomes apparent so ignition by remote ignition sources at ground level is not possible and flash fires are usually excluded (HSE, 2015). This approach would lead to the exclusion of the flash fire event from the final outcomes taxonomy. However, although very infrequent, flash fire has been observed at least once in the accident reports analysed: in order to solve this issue, the relationship developed by Kletz (1977) and accounting for the total released mass from a pipeline was assumed to assess the delayed remote ignition probability.

In order to respect the evidence that in the proposed event tree the value of the overall ignition probability must be equal to the sum of the immediate and delayed ignition probability, the following equation applies:

$$P_{IGN} = P_{immediate} + P_{delayed} \qquad (4)$$

Delayed ignition probability can be defined as follows:

$$P_{IGN} = P_{immediate} + P_{local} + P_{remote} \qquad (5)$$

The value of the conditional ignition probabilities can be expressed as:

$$\overline{P_{immediate}} = \frac{P_{immediate}}{P_{IGN}} \qquad (6)$$

$$\overline{P_{local}} = \frac{P_{local}}{P_{delayed}} = \frac{P_{local}}{1 - P_{immediate}} = \frac{P_{local}}{1 - \overline{P_{immediate}} P_{IGN}} \qquad (7)$$

$$\overline{P_{remote}} = \frac{P_{remote}}{1 - \overline{P_{immediate}} P_{IGN}} \qquad (8) \qquad\qquad \overline{P_{local}} = 1 - \frac{P_{remote}}{1 - \overline{P_{immediate}} P_{IGN}} \qquad (9)$$

where $\overline{P_{immediate}}$ is the conditional probability of immediate ignition given the ignition, $\overline{P_{local}}$ is the conditional probability of local delayed ignition given the delayed ignition ($1 - P_{immediate}$) and $\overline{P_{remote}}$ is the conditional probability of remote delayed ignition given the delayed ignition.

All the conditional probabilities to be input in the event tree can be therefore calculated defining two input values, namely the conditional immediate ignition probability provided by the HSE-UK report and the delayed remote ignition probability (flash fire probability) obtained from Kletz correlations.

**2.2 Methodology**

Following the Event Tree structure previously outlined, the first input term considered is the failure frequency derived from the EGIG report. Then, the overall ignition probability is calculated using the IP-UKOOA model starting from Eq. (1). If the release is ignited, the second branch of the event tree requires the calculation of immediate ignition probability, which is obtained by Eqs. (2) and (3) with their boundary conditions, assuming in the given case that T/AIT is approximately 0.1. In the following section, we present and critically discuss the results obtained for the three cases considered with the new P ETA and draw relevant implications for QRA.

## 3. Applicative case-study

In this section, the new Event Tree, developed making a crossover between IP-UKOOA and HSE data is applied to a real buried Natural Gas transport pipeline and compared with the results for the various outcomes obtained by the conventional IP-UKOOA method. The worked example is based on following design data of a NG pipeline: operating pressure 44 Barg; total length 374 km; nominal diameter 24 inch; flow rate 26 kg s$^{-1}$; total NG volume equal to 10,7989 m$^3$. We considered three LOC sizes, namely ¼", 4" and full-bore. Tables 1 summarizes the calculated values for the discharge flow rates, the discharge time and the release frequency for buried NG pipelines for the three considered LOCs according to the modified ETA.

*Table 1: Discharge flow rate, discharge time and release frequency for the given LOCs*

| Hole size | Discharge flow rate [kg/s] | Discharge time [min] | Release frequency [ev/km/y] |
|---|---|---|---|
| ¼" | 0.2 | >60 | $4.38*10^{-5}$ |
| 4" | 56 | >60 | $4.68*10^{-5}$ |
| Full bore | 1102 | 19 | $1.97*10^{-5}$ |

Table 2 summarizes the results obtained by the two frameworks, considering Jet fire and Flash-fire scenarios respectively in terms of threshold radiation distances and hazardous concentration distances.

*Table 2: Results for buried NG pipeline considering Jet fire and Flash fire scenarios following two ETA models*

| | JET FIRE | | | | | FLASH FIRE | |
|---|---|---|---|---|---|---|---|
| | Radiation distance [m] | | | | | Concentration distance [m] | |
| | 3 [kW/m$^2$] | 5 [kW/m$^2$] | 7.5 [kW/m$^2$] | 12 [kW/m$^2$] | 37.5 [kW/m$^2$] | LFL | LFL/2 |
| **Old ETA** | | | | | | | |
| ¼" U | 10 | 8 | 7 | 6 | 4 | - | - |
| ¼" O | 3 | 2 | 2 | 0 | 0 | - | - |
| 4" U | 87 | 66 | 53 | 31 | 0 | - | - |
| 4" O | 94 | 74 | 62 | 46 | 31 | 286 | 441 |
| FB | 160 | 132 | 116 | 93 | 59 | 586 | 925 |
| **New PETA** | | | | | | | |
| ¼" U | 7 | 5 | 5 | 4 | 2 | - | - |
| ¼" O | 3 | 2 | 2 | 0 | 0 | - | - |
| 4" U | 87 | 66 | 53 | 31 | 0 | - | - |
| 4" O | 94 | 74 | 62 | 46 | 31 | 286 | 441 |
| FB U1 | 368 | 281 | 228 | 142 | 0 | - | - |
| FB O1 | 160 | 132 | 116 | 93 | 59 | - | - |
| FB U2 | 263 | 200 | 162 | 99 | 0 | - | - |
| FB O2 | 160 | 132 | 116 | 93 | 59 | - | - |
| FB U3 | 176 | 134 | 109 | 66 | 0 | - | - |
| FB O3 | 160 | 132 | 116 | 93 | 59 | - | - |
| FB FFU | - | - | - | - | - | 37 | 38 |
| FB FFO | - | - | - | - | - | 586 | 926 |

The results calculated for the three considered LOCs according to the novel Pipeline Event Tree Analysis (PETA), all of them expressed as functions of the hole size are summarized in Table 3.

Even if the modified PETA approach clearly needs further verification on the trustworthiness of the results, mainly by accident statistical elaborations and systematic uncertainty assessment with suitable factors (e.g. Milazzo et al., 2015), the following preliminary considerations can be outlined for buried NG pipeline:
• minor leak (¼"): the frequencies for both ETAs are the same and radiation distances are comparable. In the new ETA, flash fire is assumed as negligible with respect to the results from IP-UKOOA ETA;
• medium LOC (4"): jet fire frequencies have the same order of magnitude and radiation distances while flash fire frequency according to the modified model, results three orders of magnitude lower;
• full-bore case: considering the sum for all the jet fire cases in the new PETA, jet fire frequency is of the same order of magnitude of the IP-UKOOA ETA. With the new PETA the obstructed jet fires implies similar severity. The radiation distances for unobstructed cases result to be longer at lower thermal radiation levels but the threshold value of 37.5 kW/m$^2$ is never attained. The radiation distances for obstructed flash fire are the same for both cases, while for the unobstructed are negligible. The event frequency for flash fires are one order of magnitude lower for the developed PETA when compared to the IP-UKOOA one.

*Table 3: Outcomes values obtained with new ETA for the buried Natural Gas transport pipeline*

| Hole size | Fireball and JF 1 | JF 2 | FF and JF 3 | TF 1 and Fireball | TF 2 | FF and TF 3 | Dispersion |
|---|---|---|---|---|---|---|---|
| ¼" | 8.9E-13 | 1.3E-08 | 1.3E-11 | 2.7E-12 | 3.9E-08 | 3.9E-11 | 4.37E-05 |
| 4" | 1.1E-10 | 2.3E-07 | 2.3E-10 | 6.2E-11 | 1.4E-07 | 1.4E-10 | 4.64E-05 |
| Full bore | 7.04E-07 | 9.99E-06 | 1.05E-06 | 4.13E-07 | 5.87E-06 | 6.19E-07 | 0 |

## 4. Conclusions

The focus of this paper is a critical discussion on pipeline ETA accounting for a comprehensive description of possible consequences from accidents on high-pressure buried Natural Gas pipelines. The newly developed Pipeline Event Tree (PET) allows a better quantitative description of the ignition taxonomy considering on a statistical basis, immediate, delayed local and remote ignition probability. The framework, allowing to quantitatively assessing the distinction between delayed local and remote ignition probability, can be used as an effective tool for pipeline RA, using the predicted results confidently for practical applications.

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