

A review of damages observed after catastrophic events experienced in the mid-stream gas industry compared to consequences modelling tools

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Information about intensity of dangerous phenomena can be deduced from the review of damages observed after accidents. This is done by comparing damages with resistance criteria to heat flux for each type of exposed structure. Accuracy of such data is not the same as experiment and is not good enough to be used as validation for consequence modelling tools, but it helps to estimate the differences between ideally modelled scenarios and real accidents and verify that modelling tools are reasonably conservative. Three modelling tools have been tested (PERSEE, ORDER and PHAST) and have a good agreement with the collected data; PERSEE and ORDER perform slightly better than PHAST because they use dedicated models for underground pipe rupture. Good accuracy of PERSEE confirms the choice of GDF SUEZ and its subsidiaries to perform safety studies with it.

Introduction: Learning from past accidents to improve risk assessment of existing facilities

Using damages reported after accident to compare with consequences modelling software such as PERSEE

Operators of gas infrastructures such as gas pipelines, gas storages, and regasification terminals have to ensure safety for employees as well as third parties in the surroundings of equipments. In order to comply with this commitment (which is a regulatory requirement in many countries), risk analysis are performed to assess the level of risk for a given installation. The general approach of these analyses is to identify hazardous scenarios and to estimate the risk by quantifying both the probability of hazardous phenomena, the intensity of the phenomena (for example heat flux for fire and overpressure after ignition) and the vulnerability of nearby people and equipment.

Intensity of physical phenomenon is calculated using physical and empirical models available in commercial software such as PHAST developed by DNV GL [1], ORDER developed by DNV GL [2], EFFECT developed by TNO [3] or in-house codes such as FRED developed by SHELL [4], or PERSEE developed by GDF SUEZ [5]. These codes can be used to estimate safety distances in case of leakage of pressurized equipments containing flammable gas. Discharge, dispersion, fire and explosion modelling have to be validated against experimental data to ensure an acceptable level of accuracy in consequences assessment. Given the cost of performing full scale experiments of fires and explosions, it is difficult to have validation data for each configuration encountered in the industry.

During the past decades, several major accidents happened in the gas industry. For some of those accidents extensive reports of the damages to the surrounding equipments and buildings have been documented. Data could be used to estimate the intensity of fires that happened during those accidents. Generally, effects due to initial pipe burst or overpressure after ignition are much lower than thermal effects so it is hardly possible to identify the damage due to overpressure and make a dedicated analysis.

The objectives of this study is to review some major accidents in order to estimate the intensity of physical phenomena and to compare those values to the prediction of physical models used to perform risk assessment studies to confirm the level of conservatism of these tools. Reported values from accidents are estimated and have, of course, an associated uncertainty. Indeed flame length are estimated by witnesses, criteria for damage of structure could only approximately linked to radiation level because it also depends of exact the structure of targets and time duration of fires. Best estimates using available information are proposed in this review.

Review of main accidents experienced in the gas industry

A review of the main accidents in the gas industry history has been done to choose the most relevant to perform analysis and comparison. To limit the scope of this study, only gas transmission and gas storage facilities are included in this review. For those kinds of installations, the main hazard is a leakage of a pressurized equipment containing natural gas together with an ignition.

According to the EGIG database (2013) [6], between 1970 and 2013, in Europe, 1249 incidents leading to leakage were reported for the gas transmission network, 56 were ignited, and less than 7 resulted in fatalities. Similarly, for underground gas storage, 14 massive leakages were reported in the various databases and 4 were ignited. Those figures show that accidents involving ignited massive releases in transportation and storage installation are relatively rare.

From the previous database, 44 major accidents have been reviewed which cover a significant part of the overall accidents that occurred in gas transmission network and gas storage facilities. From this list, 10 accidents have been selected in this report that were both representative and sufficiently documented for a more detailed analysis and a comparison with modelling software.

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Presentation of PERSEE software

Since the development of natural gas in the 1950s, GDF SUEZ has earned a reputation as a responsible company. GDF SUEZ has, among other, contributed to major experimental and theoretical studies in the framework of safety international partnerships. This work has enabled the gas industry to enhance the knowledge and the modeling of the physical phenomena linked to high pressure natural gas releases.

Thus the Research & Technologies Division has developed many high-performance and easy-to-use tools over the past twenty years for evaluating the risks and the consequences of accidental discharges of natural gas into open field. These different consequence calculation tools are regularly used by GDF SUEZ and its subsidiaries for evaluating, managing and controlling accidental risks on its industrial installations. This includes drawing up safety studies, and optimizing design and maintenance costs.

Among them, the PERSEE package, developed since 1990 by GDF SUEZ and constantly improved so far, predicts the phenomena associated with a natural gas discharge in a free environment (release flow rate, dispersion plume, thermal radiation…). PERSEE has been validated against more than 100 medium and large scale experiments to ensure the validity of its predictions.

It is then a support for the safety studies carried out on GDF SUEZ and its subsidiaries French transmission network and installations:

- 32000 km of transmission pipelines,
- 12 natural gas underground storages,
- 3 LNG reception terminals (Montoir, Fos Tonkin and Fos Cavaou),
- 26 compressor stations.

To assess the risk of its French transmission network and installations, GDF SUEZ and its subsidiaries evaluate the probability and the consequences of accidental scenarios, mainly loss of containment. For natural gas, consequence evaluations are performed by the PERSEE package in the open field, made up of different physical modules. The present report focuses on the CALDEIRA and the RAYOT modules but a few estimations come from ECHAUF (estimation of damages to a heated pipe) or RISQUES (estimation of damages to heated rails) modules.

Review of some major accidents experienced in the natural gas industry

Key parameters for risk assessment can be deduced with an uncertainty from damages observed after catastrophic events

To perform risk assessment of facilities, several phenomena are estimated by using physical models that need to be validated. The main physical phenomena involved in a leakage of pressurized gas equipments are: discharge of the pipe, gas dispersion, overpressure after ignition and heat radiation.
It is difficult to have information from accidents concerning gas dispersion because natural gas does not have direct effect on the environment. It is also difficult to have information concerning overpressure after ignition because, in free jet ignition, overpressure is usually less intense than heat radiation and damages to nearby structures due to overpressure after ignition cannot be distinguished easily from damages caused by fire. **For those reasons, comparison will be limited to discharge and fire phenomena. Moreover, it must be highlighted that, because of the lack of information, many uncertainties exist in the estimation of key parameters from accidents.**

Velaux (France), 19/10/1977 - Rupture of a transmission pipeline

This accident occurred on the gas pipeline linking Saint-Martin de Crau to Bouc Bel Air, on a place called « Vallon des Brayes » near the Velaux town. A rupture of a 600 mm diameter buried pipeline pressurized at 59 barg happened after an earthmover working nearby had tensioned the pipe. No fatality was recorded.

According to the various reports of the accident ([7], [8] and [9]) the rupture happened at 3:50 PM and ignition at 4:00 PM. Line valve stations were closed at 5:15 PM at Bouc Bel Air (15 km downstream) and at 5:20 PM at La Fare les Oliviers (5 km upstream). Between 5:40 PM and 5:50 PM the fire brigade indicated that all the gas between valve stations was vented and at 6:30 PM all the smaller fires around were extinguished. In this configuration the leakage lasted between 20 min and 30 min after second valve closing. Wind speed was 10 m/s (at 10 m above ground) on average during this day.

Concerning heat radiation, the maximum distance affected by heat flux could be determined by the following information:

- First police forces reached the place of the accident at 4:05 PM and could not approach the flame without protection closer than 400 m. According to [10] this corresponds to a heat flux above 3 kW/m².
- They reported a flame higher than 100 m.
- A nearby railroad was distorted because of thermal radiation on a length of 200 m. An analysis performed in [9] shows that this effect corresponds to a heat flux of about 25 kW/m². Figure 1 shows the railroad after the accident.

Figure 1 Nearby railroad after Velaux accident in 1977

Villepinte (France), 05/10/1985 – Rupture of a transmission pipeline

A buried pipeline connecting Ferolles to Villiers-le-bel was ruptured after the passage of a bulldozer. The pipe (diameter 500 mm, 60 barg) burst over 8 m length. Pieces were propelled several meters high, and a 12 m long crater was formed. The three workers present died from the intense heat radiation.

According to several reports concerning this accident ([11], [12] and [13]), the ruptured occurred at 2:10 PM with immediate ignition of the gas release, line valve station was closed at 2:30 PM at Ferolles (35 km upstream), at 2:50 PM at Villiers-le-Bel (9 km downstream) and at 2:55 PM at Mitry-Mory (5.5 km upstream). Ten minutes later flow rate from the leakage was significantly reduced and at 5:15 PM, fires were completely extinguished. Wind speed was 4 m/s (at 10 m above ground) on average during this day.

Flame behavior and heat radiation were modified because of the presence of obstacles in the jet direction; two inclined jets at 45° (instead of one vertical jet) were observed during this accident (Figure 2 shows the burnt ground after the accident which correspond to two inclined jets). Several information could be compared to models:

- According to witnesses, **flame height was around 60 m**.
- Temperature of the ground has been deduced by analyzing samples in laboratories of the French ceramics company [14].

Colors of samples vary according to the temperature at which this sample is exposed; it is possible to deduce from the ground color a temperature in the range of 300°C and 1300°C. According to those analysis, ground sample in the middle of the "red zone" (at approximately 90 m from the ruptured pipe, the end of the red zone being at 110 m) reached a temperature of 800°C and ground sample in the "dark zone" (at approximately 65 m from the ruptured pipe) reached a temperature of 1300°C.

A simple analytical model of semi-infinite medium with constant properties (thermal conductivity λ, and thermal diffusivity a) exposed to a given heat flux ϕ_0 at an initial temperature T_0, leads to the following formula for surface temperature (detailed calculation is presented in [14]).

$$T = T_0 + \frac{2\varphi_0}{\lambda}\sqrt{\frac{at}{\pi}}$$

This relation can be inverted in order to deduce heat flux from temperature:

$$\varphi_0 = \frac{T - T_0}{\frac{2}{\lambda}\sqrt{\frac{at}{\pi}}}$$

Measurements of thermal conductivity and thermal diffusivity of soil have been done by the Solid Mechanics Laboratory of Ecole Polytechnique [14] : a = 5,15*10^{-7} $m^2.s^{-1}$ and λ =1,42 $W.m^{-1}.K^{-1}$. The previous mention exposure time of 165 min corresponds to the total accident time. As we don't have information regarding decrease of release rate, we made the assumption that the ground was exposed to a constant intense heat flux during a period of 90 min (according to reported timing of valve closing).

With those assumptions we calculate **a heat flux of 13 kW/m² at 90 m** (associated to the 800°C temperature) and **a heat flux of 25 kW/m² at 65 m** (associated to the 1300°C temperature).

Figure 2 Burnt ground after Villepinte accident in 1985

Saint Illiers (France), 20/02/1996 - Rupture of a pipe on a gas storage

An accident happened at the underground storage facility of Saint-Illiers leading to the rupture and the ignition of a pressurized pipe (300 and 400 mm diameters, pressurized at 59 barg). Because of the intense heat radiation, escalation occurred on several nearby pipelines. No fatality was recorded.

According to the different reports concerning this accident ([15], [16]), the sequence of events was

- 5:20 AM : Leakage near an underground valve of approximately 25 000 m3/h,
- 6:23 AM : Ignition of the gas,
- 6:38 AM – 6:41 AM: Rupture of 300 mm diameter pipe and 400 mm diameter pipe by thermal domino effects.
- 7:15 AM: Main fires are extinguished, only small fires still burn

After the accident, observation of damages shows that trees have been burnt in a radius of 60 m. Without precise information about the nature of the wood and if we consider an exposition of 30 min this correspond to the general value of a heat flux of 13 kW/m² according to references found on the subject ([17], [18], [19], [20]).

Figure 3 Image of ruptured pipes after the Saint-Illiers accident in 1996

Edison (USA), 24/03/1994 - Rupture of a transmission pipeline

This accident concerned the rupture of a 600 mm diameter buried natural gas pipeline pressurized at 66 barg at Edison Township, New Jersey, USA. The rupture was caused by a crack which formed in a gouge to the pipe. Heat radiation from the fire ignited several building roofs in a nearby apartment complex. One person died during the accident.

Several reports ([21] and [22]) located the leakage at 48 km downstream from the Lambertville Linden pipeline (which has a length of 72 km). At 11:58 PM the pipe was ruptured, ignition occurred 10 min later, line valve distance closing system wasn't operational and has been closed manually by operators at 2:30 AM (at 15 km upstream and downstream of the incident) at 3:30 AM all the fires were extinguished. Wind speed was 5 m/s (at 10 m above ground) on average during this day.

Firefighters arrived at the place of the accident at 00:10 AM; they reported a flame height of 150 m and were not able to approach the flame closer than 300 m (which corresponds to 5 kW/m² radiation level according to [10] and [23]). The closest wood building to the jet fire was at 240 m and was completely destroyed which indicates a level of heat radiation at this point higher than 13 kW/m² (which corresponds to piloted ignition of wood according to the reference found on the subject ([17], [18], [19], [20])).

Rapid City (Canada), 29/07/1995 - Rupture of a transmission pipeline at a compressor station

An accident occurred on a compressor station near Rapid City (Canada), leading to rupture of two natural gas pipelines (1004 mm and 914 mm diameters pressurized at 61 barg). Little information about fatalities and damages are available.

According to the various reports concerning this accident ([15]), the following sequence of events was:

- 5:42 AM : Rupture of the 1067 mm diameter pipe, gas ignites immediately,
- 6:04 AM : Emergency valve closed 110.96 km upstream and 108.8 km downstream,
- 6:06 AM : Closing of a valve 0.22 km upstream of the rupture zone,
- 6:30 AM : Isolation of the two pipes from the rest of the network,
- 6:34 AM : Rupture of the 914 mm diameter pipe by thermal domino effects,
- 7:42 AM : Flow rate of leakage is reduced because of the venting of the gas contained inside the pipe,
- 12:00 AM -12:30 AM: All fires are extinguished.

Little information is available concerning the length of the flame and the damages due to heat radiation. However, this accident is analyzed in order to compare it with the release modeling tools.

Figure 4 Image of the pipe and damages around the crater after the Rapid City accident in 1995

Ghislenghien (Belgium), 30/07/2004 - Rupture of a transmission pipeline

An accident occurred on a pipeline between Zeebrugge and the Franco-Belgian border, in an industrial area. At about 8:30 AM, a leak was detected by the hissing of the release (gas is not "odorized" at this stage). The pipeline had an internal diameter of 880 mm and a pressure of 72 barg. At 9 AM, an overpressure after ignition, felt several miles around, occurred accompanied by a fireball and rapidly by a jet fire. The fire spread to two neighboring installations that were destroyed (a service station and a construction site). Many people died during the accident.

Several press articles have been collected and analyzed in an internal GDF SUEZ report [24]. According to those elements:

- a flame of 200 m high was observed,
- heat flux of 5 kW/m² was reached 350 m from the crater (damages to windows of the Paranom society, damages to untreated windows are likely to occur at 4,1 kW/m² according to [25]) and a heat flux less than 5 kW/m² was experienced at 400 m (painting of the car wasn't affected by the heat flux) so **we can position the limit of the 5 kW/m² threshold at approximately 370 m** from the crater,
- burnt wooden pallets indicates that a heat flux of at least 25 kW/m² (this corresponds to the threshold for spontaneous combustion of wood according to reference found on the subject ([17], [18], [19], [20])) was reached 130 m away from the ruptured pipe (see Figure 5); moreover, a damaged car was found 170 m away from the crater whose plastics were not burnt (see Figure 6, spontaneous ignition of plastic in cars is likely to occur for heat flux above 25 kW/m² according to [26], [27], [28]) which indicates a heat flux less than 25 kW/m². So **we can position the limit of the 25 kW/m² threshold at approximately 150 m** from the crater.

Wind speed was 2 m/s (at 10 m above ground) on average during this day.

Figure 5 Burnt wooden pallets after the Ghislenghien accident (130 m from rupture)

Figure 6 Damaged car 170 m away from the crater of the Ghislenghien accident

Moss Bluff (USA), 19/08/2004 – Rupture of a well head at a gas storage site

At 4:00 AM, an uncontrolled release of gas followed by a fire broke out on the shaft of a well (500 mm diameter) in salt caverns underground natural gas storage. For 6.5 days, the 170 million cubic meters of natural gas, stored at 120 barg, were released at a high flow rate (28 million cubic meters per day) and burned. The fire extinguished itself by depletion of fuel and a blowout valve was placed on August 26 to return the cavity under control.

Various reports ([29], [30], [31] and [32]) give an overview of the sequence of events during the accident:

- A rupture occurred in the pipe used to evacuated brine from the cavity 83 m before the bottom of the cavity. On Thursday 19th of August 2004, at 4:00 AM, when the water-gas interface reaches the breach, the high pressure gas enters into the brine pipe.
- An Emergency Shut Down (ESD) valve located on the brine pipe immediately closed the valve but the water hammer generated by the moving brine ruptured the 200 mm diameter pipe just before the ESD. This led to an ignited jet fire impinging the ground.
- On Friday 20th of August, at 1:15 AM, after 21 hours of continuous exposition to the jet fire the well head completely separated from the well leading to a vertical jet fire of at least 300 m high.

Figure 7 Fire after complete rupture of the well head in Moss Bluff 20 August 2004

Appomattox (USA), 14/09/2008

Around 7:45 AM, the rupture of a buried pipeline natural gas from the Gulf of Mexico to New York (pressure: 56 bar rel, diameter: 760 mm) followed by ignition of a significant amount of gas led to a massive fire jet near a taxiway and housing. Debris was thrown into the air and flames rose up to 100 m above the ground. No fatality was recorded.

Several information concerning this accident has been collected in an internal GDF SUEZ report [33]. The length of this pipeline is 30 km, the leak occurred 4 km downstream of the first line valve and 16 km upstream of the second line valve. The accident happened at 7:45 AM with ignition few seconds later, the upstream valve was closed 25 min after ignition and the downstream valve was closed 35 min after ignition. 36 min after the valve closing the gas contained in the pipe section was completely vented out.

Concerning thermal effects, flame height has been estimated based on several pictures (for example Figure 8) at around 200 meters high. The limit of the burnt vegetation is 170 m which correspond to a heat flux of 13 kW/m² (according to reference found on the subject ([17], [18], [19], [20])); one bricks house located at 130 m was totally burnt which correspond to a heat flux of 25 kW/m².

Figure 8 Image of the flame taken 2400 m away during Appomattox accident in 2008

Figure 9 Damages to environment just after the Appomattox accident in 2008

Blénod-Lès-Pont-A-Mousson (France), 18/12/2009

Within the property line of a thermal power plant, an ignited gas leakage occurred around 11 AM on a buried pipeline (pressure: 60 barg, diameter: 387 mm). The pipeline had been commissioned four days before the accident to supply a new unit of Gas Combined Cycle (GCC) on the site. One person died during this accident.

An internal report of GDF SUEZ [34] summarizes information collected around this accident. A hole of 40 mm diameter on the pipe occurred at 11:15 AM leading to an instantaneous jet fire at the end of the 2 km long pipeline. Line valve was closed at 1:20 PM and the fire continued to burn until 3:00 PM (so 100 min after valve closing).

The jet fire was inclined at 30° with the ground; the maximal height of the flame was 20 m. Several plastic markers located near the position of the crater were damaged because of the jet fire radiation; levels of heat radiation could be deduced from the damages observed on the plastic. Those markers are made from high density polyethylene (PEHD) which has a general fusion temperature of 135°C. Calculations made by ECHAUF module of PERSEE show that using typical thermal properties of PEHD, this temperature is reached after two hours of exposure for a heat flux of 3 kW/m². Given the nature of damages, heat flux of 5 kW/m² is taken as a threshold for slight damages:

- A marker located 40 m away from the crater was completely destroyed, this correspond to a heat level higher than 13 kW/m² (minimal energy required for spontaneous ignition of plastics according to [35]).
- A marker located 50 m away from the crater was slightly damaged (heat flux higher than 5 kW/m²) and a marker located 60 m away from the crater was not damaged at all (heat flux less than 5 kW/m²).
- From those elements, we can consider the limit of the 13 kW/m² at 45 m and the limit of the 5 kW/m² at 55 m.

Figure 10 Slightly damaged marker

Figure 11 Highly damaged marker

San Bruno (USA), 09/09/2010

The ignited rupture of a buried pipe of 760 mm internal diameter carrying natural gas pressurized at 26 barg caused important damages in a residential suburb of San Francisco located near an airport. Many people died or were seriously injured during this accident. In addition, four firefighters were poisoned by fumes during rescue operations.

Several press articles and information collected by GDF SUEZ have been summarized in an internal report [36]. According to those elements, the rupture occurred at 6:11 PM with immediate ignition, control command of line valve station wasn't operational and 90 min were needed to close manually the valves located 1125 m from both side of the leakage (at 7:20 PM for the upstream valve and at 7:40 PM for the downstream valve). The leakage stopped 5 min after closing of the valves.

A 100 m high flame has been reported (see Figure 12). Analysis of the damages to buildings provides information concerning the heat flux levels during the fire (see Figure 13):

- heat flux level of 13 kW/m² was experienced 150 m away from the crater : wooden houses burnt
- heat flux level of 25 kW/m² reached 100 m: concrete houses not damaged

Wind speed was 10 m/s (at 10 m above ground) on average during this day.

Figure 12 View of the flame during the San Bruno accident 2010

Figure 13 Heat flux distances according to damages during the San Bruno accident 2010

Comparison with modelling tools

Description of modeling tools used for this study

The CALDEIRA (PERSEE) module: flow rate calculation for punctures and ruptures

The gas flow rate from a leak highly depends on the pipeline characteristics (internal pressure, valve closing…) and on the whole size. In case of a rupture, the flow rate quickly decreases with the internal pressure.

The CALDEIRA module assesses the variation of leakage flow rates through two models, one for the punctures and the other one for full-bore ruptures. Two pipeline segments with different diameters can be modeled, and a large range of upstream and downstream boundary conditions ensures a modeling close to real configurations.

The models determine as a function of time and distance along the pipeline, the internal gas density, the internal axial velocity and the internal pressure by solving the state equations and the conservation of mass and momentum. They consider the pipe friction, the gravitational effects (for non-horizontal pipelines) and the gas compressibility. The models also assume 1D isothermal flow. The provided results are the time dependant curves for the flow rate and the internal pressure.

CALDEIRA has been validated with several large-scale experiments on pressurized air or natural gas long pipelines. A comparison has also been carried out with the software Pipeline Studio to further study the influence of valves, pipeline diameters, boundary conditions and leak sizes. In comparison with experimental data, CALDEIRA predicts the flow rate with an accuracy of ± 10 %. CALDEIRA was appraised in 2003 by DNV GL. Considering the model theory and the comparisons with tests, the validity field announced by GDF SUEZ have been confirmed by DNV GL.

The RAYOT (PERSEE) module: flame geometry and heat radiation calculation

When a natural gas plume is ignited, the chemical energy, released by the combustion, is transformed into heat energy. A part of this energy is emitted by radiation. The convection part remains above the flame. The study of the thermal radiation aims to determine the received heat flow on a target (people or structure).
A flame usually produces two types of radiations:

- the visible radiation which corresponds to a light emission,
- the thermal radiation, or infrared radiation, which corresponds to a heat emission.

The PERSEE package includes a module called RAYOT for computation of radiations and flame shape from jet fire with or without flame/ground interaction. For flame without interaction with ground the empirical RAYON sub-model is activated (which is derived from the Chamberlain solid flame model) but when flame/ground interaction is occurring the integral model RAYO_H (which makes use of conservation equation of fluid dynamics) is used. Since no cases simulated in this report have flame/ground interaction, we will focus on the RAYON module in the next paragraph.

The RAYON module calculates the jet fire geometry, the surface emissive power, and the heat radiation with the immediate ignition of a pressurized flammable release. It assumes a steady-state natural gas jet fire (vertical or tilted, subsonic or supersonic) from above or below (with crater formation) ground releases in an open area (no obstacles).

It first calculates the equivalent conditions after the atmospheric expansion for supersonic releases (Birch model). Then, with an enhanced version of the semi-empirical Shell gas jet fire model (Chamberlain model), it assesses the flame geometry and the surface emissive power. The received heat radiation on a target (people or structure) is then set as the product of the view factor, the surface emissive power and the atmospheric transmissivity. The RAYOT module provides a received heat flux isovalues contour line.

This model has been extensively validated with horizontal and vertical jet releases (large-scale experiments). The crater formation is considered for underground pipelines, which modifies the flame geometry described by Chamberlain. In comparison with the experimental data, RAYOT predicts the thermal effects distances within ± 30 %. RAYON was appraised in 2003 by DNV GL. Comparisons with the PHAST software developed by DNV GL show that the results of RAYON are in good agreement.

The THRAIN (ORDER) module: flame geometry and heat radiation calculation for free above ground jets

THRAIN predicts the behavior of turbulent jets in a cross flow or in still air. The model is formulated to be applicable to both combusting and unignited releases. Where the release is non-combusting, the model may be applied to any non-reacting gaseous material, although for combusting releases the model is limited to natural gas, ethylene, propane or butane. This latter restriction arises as the model uses a laminar flamelet library to determine the properties of the combusting mixtures and currently, such libraries are only available for the fuels quoted above. THRAIN is applicable to all free jets and also to horizontal or near-horizontal releases in which the jet interacts with the ground. It may also be used for the interaction of a jet fire with a (smaller) cylindrical obstacle in its path and will calculate the thermal loading to that obstacle.

The model solves a set of simultaneous ordinary differential equations for the total fluxes of mass, momentum in the horizontal, vertical and crosswind directions and mixture fraction. The model uses a one-dimensional formulation of the k-e turbulence model. A laminar flamelet is used for combusting releases to specify the relationship between the mixture fraction and the density, temperature and combustion products in the flow. If the release is combusting, then soot levels are predicted by solving equations for the soot mass fraction and number density. The model steps along the trajectory of the release, starting at the release point and uses a 4th order Runge-Kutta technique to solve the equations described above.

THRAIN has been validated extensively against a wide range of natural gas releases, from sub-sonic laboratory scale to full-scale vents at sonic velocities, including releases interacting with a cylinder. The model has also been compared successfully with data for a wide range of non-combusting releases of materials other than natural gas.

The CRYSTAL (ORDER) module: flame geometry and heat radiation calculation for flame from underground pipeline

Much of the previous published work concerning fire consequence models has been applied to jet fires, flares and buoyant pool fires. Invariably, these models have incorporated a relatively simple representation of the fire source, usually with uniform flow conditions over a circular cross-section. In order to utilize this earlier work, a specific source sub-model has been incorporated in the present model to provide an equivalent circular source, which gives representative predictions of the size and thermal radiation from fires following an underground pipeline failure.

The complex nature of this flow suggests that it is necessary to make simplifying assumptions in order to represent the flow in an appropriate sub-model, concentrating on the dominant bulk phenomena. The physical phenomena that have been incorporated in the source sub-model are:-

1. Entrainment into the jets of gas before they impact on each other or the wall of the crater.
2. Entrainment due to the jets interacting with each other and the walls of the crater.
3. Momentum loss from the jets to the crater walls during jet interaction.

The approach is restricted to circular sources which are compatible with the phenomenological model of jet fires. The approach adopted has been to extend the pseudo diameter model formulated by Birch et al for sonic free jets.

Ordinary differential equations are solved which represent the conservation of mass flux, and the horizontal and vertical components of momentum flux, in any cross-section normal to the curvilinear trajectory of the jet. In common with other integral models of jets in a cross-flow, the total rate of air entrainment into the jet is considered to be made up of a number of components. Two components are introduced in the present model, to represent entrainment associated with the initial jet momentum, in the near-field of the flow, and that associated with the presence of a cross-wind in the far-field. Conservation of chemical species is satisfied by determining values of mean mixture fraction, such that the total flux of mixture fraction in any cross-section of the jet is equal to the source flux of mixture fraction given by the crater source sub-model. These equations are closed via an averaged turbulent viscosity, determined from a one-dimensional k-ε turbulence model, by solution of transport equations for the spatially-averaged turbulence kinetic energy, and it dissipation rate. The final transport equation solved is an equation for the mean mixture fraction variance. This is required as part of the turbulent combustion model implemented. Mean temperatures, gas concentrations and soot volume fractions, that is, the flame structure, computed by the fluid flow and combustion model, are used to calculate radiative fluxes internal to a fire.

The JFSH (PHAST) module : flame geometry and heat radiation calculation for free jet

The JFSH module: flame geometry and heat radiation calculation for free jet. The surface emitter model by Chamberlain, which was later extended by Johnson et al (1994) has been adopted and implemented in the JFSH model [1].

The Chamberlain model, when compared with point of multiple point source models, gives a better physical description of flame behavior by its representation of a flame with a solid body (conical frustum) emitting radiation from its surface.

The first step in estimating flame dimension and orientation involves the calculation of the discharge followed by the post-expansion state of the fluid at ambient pressure. During this calculation, the post-expansion fluid state (i.e. temperature or liquid fraction) plus the post-expansion fluid velocity or expanded radius are determined. Subsequently, the effective calculation of flame length in still air follows, from which other parameters that describe the flame dimension and orientation in space are determined. Using an empirical correlation expressed as a function of the ratio of the wind speed and post-expansion velocity of the escaping fluid, the fraction of heat radiated from the flame is determined. The latter in conjunction with the heat of combustion of the released fluid is employed in estimating the surface emissive power of the flame.

Comparison of collected data with calculation from modeling tools

In this section comparison between the values collected previously and calculation based on physical models is performed. The PERSEE, ORDER and PHAST packages are used to simulate the pre-mentioned accidents in order to compare simulations with the actual results. Simulation of flow rate and leak duration is performed using CALDEIRA (PHAST model relies on different set of boundary conditions and ORDER could not simulate valve closing), simulation of the jet fire is performed using RAYOT, THRAIN, CRYSTAL and JFSH modules.

Comparison of leak duration

Calculations have been done using the CALDEIRA module which simulates leakage on a pressurized pipe with line valve closing. PHAST. Timing of valve closing has been set in agreement with the real closing time reported during the accidents. For all of the simulated accidents the pipe is linked to the rest of the network from both sides; this has been taken into account for the modeling of the flow rate by putting constant pressure source from both sides of the pipe.

Those values are summarized in Table 1. As it can be observed in this table, leak durations calculated by PERSEE are within the range of the reported values for leak duration for all the studied cases.

For the other comparisons, average flow rate between rupture and first valve closure calculated by PERSEE is used as an input parameter for jet fire models (ORDER, PHAST and PERSEE) used in the next section.

Comparison with thermal effects

Calculations have been done using the RAYOT, THRAIN, CRYSTAL and JFSH module which is used to calculate radiation heat transfer and flame shape in case of jet fires. As it can be observed from Table 2 and Table 3 shows calculations are in good agreement with observed flame characteristics and damages.

For PERSEE, most of the values are within a range of +/-30% except in the case of the Villepinte accident (1985) and Saint-Illiers accident (1996). For the Villepinte accident, it should be emphasized that the case could not be properly modeled by any simple software such as PERSEE, PHAST or ORDER because the jet fire was impacting the damaged bulldozer which led to two inclined jets instead of only one vertical jet. However results are still acceptable given the simplicity of the models used (+38% difference between PERSEE and collected data, +41% for ORDER and +37% for PHAST).

The difference observed for the Saint-Illiers accident is mainly due to the simplified approach used for the modeling where we represent the two largest flames (from the 300 mm and the 400 mm diameter pipe) by only one flame with an equivalent flow rate.

Results of the three codes are in a comparable level of accuracy except two points:

- Flame height is generally over-predicted by ORDER, this may be due to the fact that ORDER is using a sophisticated physical model which is sensitive to atmospheric conditions which are not always noted very precisely in the collected information.
- Distances to the 25 kW/m² heat radiation are generally underpredicted by PHAST compared to collected data, which is not the case for PERSEE and ORDER. This may be explained by the fact that ORDER and PERSEE use special models for buried pipeline, whereas PHAST has only one model for jet fires from both underground and above ground equipments. In particular, PHAST calculates a flame lift-off for underground releases although experiments showed that this parameter is highly modified for underground releases (effect of the crater).

It should be noted that a large range of flow rates has been reproduced by the physical models with an acceptable level of accuracy. Indeed, the leak flow rate for the Blenod accident was around 20 Nm^3/s and it was 5560 Nm^3/s during the Moss Bluff accident.

Table 1 Comparison of leak duration (after valve closing) with PERSEE calculation

Date	Place	Internal pipe diameter (mm)	Leak diameter (mm)	Internal pressure (barg)	Length of the pipe (km)	Position of the leak (km)	Upstream line valve (km)	Downstream line valve (km)	Duration of the leak after first valve closing (min)	Duration of leak calculated with PERSEE (min)
19/10/1977	Velaux (France)	582	582	60	41	26	21	41	20-30	24
05/10/1985	Villepinte (France)	484	484	60	44	35	29.5	44	0-10	6
24/03/1994	Edison (USA)	878	878	66	72	48	33	63	0-60	21
29/07/1995	Rapid City (Canada)	1004 and 914	1004 and 914	61	200	100	0	100	330-360	350
09/09/2010	San Bruno (USA)	760	760	26	20	10	8.75	11.25	0-2	2
14/09/2008	Appomattox (USA)	760	760	55..2	30	4	0	20	0-36	27
18/12/2009	Blenod (France)	387	40	60	2	2	0	2	0-120	60

Table 2 Comparison of fire results with the PERSEE, ORDER and PHAST calculations

Date	Lieu	Height of the flame from observation (m)	Height of the flame (m) calculated with			Distances (m) to heat flux 3 kW/m² or 5	Distances (m) to heat flux 3 kW/m² or 5 kW/m²calculated with		
			PERSEE	ORDER	PHAST		PERSEE	ORDER	PHAST
19/10/1977	Velaux (France)	100	100	94	111	< 400	280	260	272
05/10/1985	Villepinte (France)	60	75	86	78	Unknown			
24/03/1994	Edison (USA)	150	160	147	177	< 300	312	282	302
20/02/1996	Saint Illiers (France)	Unknown				Unknown			

30/07/2004	Ghislenghien (Belgium)	175	228	295	251	350-400	367	395	330
19/08/2004	Moss Bluff (USA)	300	298	407	316	Unknown			
09/09/2010	San Bruno (USA)	100	108	102	123	Unknown			
14/09/2008	Appomattox (USA)	200	179	226	196	Unknown			
18/12/2009	Blenod (France)	20	20	18	18	< 60	66	76	67

Table 3 Comparison of fire results with the PERSEE, ORDER and PHAST calculations

Date	Lieu	Distances (m) to heat flux 13 kW/m²	Distances (m) to heat flux 13 kW/m² calculated with			Distances (m) to heat flux 25 kW/m²	Distances (m) to heat flux 25 kW/m² calculated with		
			PERSEE	ORDER	PHAST		PERSEE	ORDER	PHAST
19/10/1977	Velaux (France)	Unknown				≈ 100	94	107	83
05/10/1985	Villepinte (France)	≈ 90	121	127	123	≈ 65	90	85	87
24/03/1994	Edison (USA)	200-240	183	192	160	Unknown			
20/02/1996	Saint Illiers (France)	< 60	88	53	91	Unknown			
30/07/2004	Ghislenghien (Belgium)	Unknown				130-170	112	140	80
19/08/2004	Moss Bluff (USA)	Unknown				Unknown			
09/09/2010	San Bruno (USA)	> 150	150	161	150	< 100	102	113	90
14/09/2008	Appomattox (USA)	≈ 170	204	236	181	> 130	128	147	81
18/12/2009	Blenod (France)	> 40	43	46	41	Unknown			

Conclusion

Various accidents experienced in the gas industry have been reviewed and observed damages have been reported. It is possible to have a relatively accurate estimate of several parameters such as leakage duration, flame height and distances corresponding to a certain level of heat radiation from the flame.

That information is deduced from the observed damages on the structures and to the environment, the testimony of witnesses and photographic evidences. Accuracy of those elements is not as high as experiment but it gives an order of magnitude and a comparison point for modelling.

Models (PERSEE, ORDER and PHAST) tested in this study give results that are in agreement with the collected information for both small jet fires and larges jet fires. **PERSEE and ORDER perform slightly better than PHAST because they use dedicated models for underground pipe rupture. Good accuracy of PERSEE confirms the choice of GDF SUEZ and its subsidiaries to perform safety studies with it.**

It is interesting to see that models perform well for small leaks as well as large leaks up to 5560 Nm^3/s. This gives more confidence in the physical models to be used in order to estimate hazards zones in case of accidents.

During this study it has been noted that it is difficult to have access to information after accidents. More detailed information and thus more precise validation could be obtained by reporting systematically all damages observed around these catastrophic events.

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