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Jet Fires: a “Minor” Fire Hazard?

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Jet fires have received only a rather reduced attention as compared to other types of fires; this is probably due to the fact that they are usually much smaller that fireballs, pool fires or tank fires. However, jet fires often occur in areas where there is other equipment and the probability of flames impinging on a pipe or a vessel can be high. Furthermore, due to the turbulence of the phenomenon, the combustion in such fires is very good and high heat fluxes can seriously affect this equipment, thus originating a domino effect which will enlarge the scale of the accident. A historical survey has shown that, of the jet fires reported in accident data bases, 50 % caused another event with severe effects. In 90 % of the domino effect cases there was an explosion, usually of a vessel; this was especially frequent in transportation accidents. In this communication the main features of jet fires are commented: most frequent domino effect sequences, shape and size, thermal behaviour, mathematical modelling.

1. Fire accidents

Fires are the most common major accidents in process plants and in the transportation of hazardous materials. Although it is not easy to determine the respective frequency with which each type of accident occurs, because often the available information is incomplete and in many cases diverse events occur simultaneously, most historical surveys show that fires are the most frequent ones. For example, Planas et al. (1997) found that approximately 47 % of all major accidents involved fire, 40% involved an explosion and in 13 % there was a gas cloud. As for the type of fire, even though in many cases the data bases did not specify this information, these authors found that the most frequent one was pool and tank fire, followed by flash fire and, with a much smaller frequency, jet fire (respective frequencies: 66 %,29 %,5 %).

The damage radius of fire accidents –with the exception of flash fires– is often much shorter than those associated to other major accidents such as explosions or toxic clouds; thus, the dangerous effects of fires, determined by flame engulfment or by the reach of thermal radiation, are usually confined to a relatively reduced area. However, this area often contains thermally sensitive equipment (vessels, pipes) that can be seriously damaged and, thus, become incorporated into the accident via the domino effect. This is the situation in many process or storage plants, with a rather compact layout, and there are many examples of fires which have propagated throughout the plant giving rise to explosions or further fires, thus significantly enlarging the scale of the accident.

Amongst fire accidents, pool and tank fires, together with fireballs, are important because of their size, which can be very large; while fireballs have a very short duration, pool and tank fires can last for many hours. This is why this has been traditionally the type of fire accident which has received most of the attention from the diverse authors that have studied fires.

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2. Jet fires

Instead, jet fires have been analyzed by a much smaller number of authors, probably because of their smaller size. However, although they are usually smaller –even though some large jet fires have also occurred– than pool of flash fires or fireballs, they often occur in dense plants with compact lay-outs, and locally they can be very intense. Jet fires are associated to very high heat fluxes and if they impinge on equipment (e.g., a pipe or a tank) they can originate a catastrophic failure in a very short time.

A well known example of such a situation is the accident that occurred in San Juan Ixhuatepec, Mexico, in 1984: an initial vapour cloud explosion (due to a release of flammable gas during maintenance work) originated diverse LPG jet fires and, after only 69 seconds, the first boiling liquid expanding vapour explosion occurred (Pietersen et al., 1985); a very short exposure time was enough to cause the failure of a pressurized vessel.

While in this accident the jet fires followed a previous explosion, in other cases the gas release has been due to much less significant events such as for example the failure of a gasket or a flange. Once the jet of a flammable material (usually a pressurized gas or a two-phase mixture) is released, two sequences are possible: or the jet is quickly ignited by an electrostatic spark or another ignition source, or a vapour cloud is formed which is a little bit later ignited, the fire flashes back to the leak source and a jet fire is finally originated. As an example, the case analyzed in (USCSHIB, 2008), can be mentioned: following a propane release from a flange, the jet fire flames impinged on diverse pipes, which failed, releasing additional propane jets which were immediately ignited; the fire weakened a structural steel support, leading to the collapse of a column, and affected as well diverse chlorine tanks, ending with a significant fire and a toxic cloud. Other cases could be mentioned in the field of the transportation of flammable materials, when, following a road accident or a derailing, a jet fire from a broken pipe impinged on a tank, originating a further explosion/fireball event.

In these cases, jet fires –even relatively small jets fires– can result eventually in important major accidents. Thus, the knowledge of their main features and mathematical modelling is quite important from the point of view of risk analysis.

3. Jet fires and the domino effect

Even though it is usually accepted that jet fires can be the initiating event of a domino sequence, it is not easy to show this in a quantitative way. The reason is the lack of detailed information on accidents involving fire, as well as the fact that many accidents without any further consequences (no domino effect) probably are not registered in the accident data bases.

Gomez-Mares et al. (2008) performed a survey on 84 accidents involving a jet fire, occurred between 1961 and 2008, both in process or storage plants and in transportation. 44 % of the accidents occurred in transportation, 36 % in process plants, 11 % in loading/unloading operations and 10 % in storage. 25 % of the accidents occurred in the least robust equipment, i.e., in pipes and hoses (see Table 1 and Figure 1).

Table 1: Origin of the accidents involving a jet fire

Specific origin	Number of accidents	Percent of total	Specific origin	Number of accidents	Percent of total
Process plants			Pipework	1	1.2
Pipework	13	15.5	*Transport*		
Process vessels	6	7.1	Rail tanker	15	17.9
Reactor	5	5.9	Road tanker	13	15.5
Unknown	4	4.8	Pipeline	9	10.7
Equipment with flame	1	1.2	*Loading/unloading*		
Heat exchangers	1	1.2	Hose	5	5.9
Storage			Road tanker	2	2.4
Pressurized tanks	6	7.1	Rail tanker	1	1.2
Atmospheric pressure tanks	1	1.2	Pressurized tanks	1	1.2

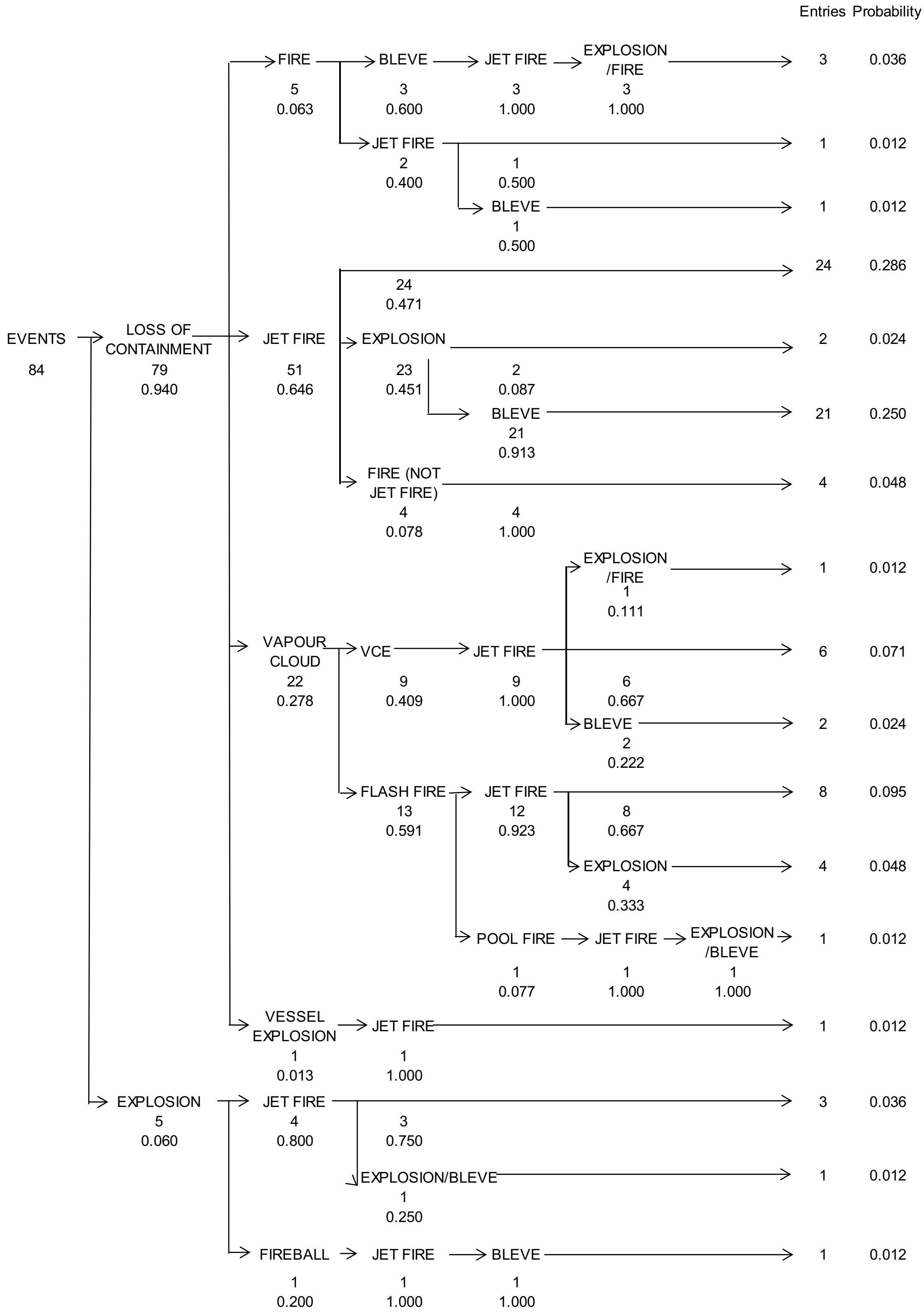

Figure 1: Event tree of a survey on accidents involving a jet fire

As for the type of material involved, the most frequently reported substance was LPG (61 %), followed by hydrogen (12 %) and natural gas and chemicals (10 % each). The most common cause of the accident was mechanical failure (with coupling or flange leakage as the main specific cause), followed by human factor and impact failure; if mechanical failure and human factor were considered together, they accounted for nearly 50 % of the general causes of the accident. In 44 % of the accidents there were 1-10 deaths; however, the majority of casualties were not attributed to the jet fires but to other events of the domino sequence (essentially explosions).

Concerning the diverse domino sequences, they were analyzed by constructing the relative frequency event tree (Figure 1); here, the probability of occurrence is represented for each branch, being obtained from the ratio of the number of accidents to the number of accidents at the previous level.

In 65 % of the cases, the release was ignited by a source –an electrostatic spark or any other type– to form a jet fire. If the jet fire impinged on any other equipment, the probability of an explosion, sometimes a BLEVE, was significant (this happened in 23 cases). If there was no impingement, the jet fire was usually the last step in the accident and was ultimately extinguished. In other cases jet fires were a consequence of a previous explosion. A typical sequence found in transportation begins with the mechanical impact, which generates a leak on a rail car or a tank car, usually in the pipework. The release is then ignited and the jet fire impinges on the tank; the opening of a relief valve provides a new jet fire and sometime later (from a few minutes to several hours) the tank explodes.

The analysis of the different sequences showed that when a jet fire occurs, in approximately 50 % of the cases it will cause another event with severe effects; of course, this percentage should be reduced if it is considered that, in fact, a number of jet fires which did not originate any other accident are not included in accident data bases.

4. Recent work

Diverse experimental studies on jet fires have been carried out in recent years; most of these studies concern either subsonic jet fires or small hydrogen jet flames. Schefer et al. (2006, 2007) reported experimental measurements of hydrogen jet fires, originating from storage pressures up to 413 bar and orifice diameters (d) up to 7.94 mm. Mogi and Horiguchi (2009) studied hydrogen jet fires from d ranging between 0.1 and 4 mm and release pressures up to 400 bar. Proust et al. (2011) investigated hydrogen releases from 900 bar down to 1 bar, with orifices ranging from 1 to 3 mm. It can be seen that these studies involve very small outlet orifice diameters at very high pressures. Royle and Willoughby (2011) studied hydrogen jets with a flame length up to 13 m.

Six horizontal jet fires involving natural gas and a natural gas/hydrogen mixture (~ 24% by volume hydrogen) were obtained by Lowesmith and Hankinson (2011). High pressure gas releases from 20, 35 and 50 mm diameter holes at a gauge pressure of 60 bar, coflowing with the wind, were analyzed. Twenty jet fire experiments were conducted using propane (Palacios et al., 2009; Gómez-Mares et al, 2010). The tests involved vertical releases from up to 43.1 mm diameter holes, with flames lengths up to 10 m. Although a number of experimental works have been performed, it would be useful to include larger orifice diameters and other fuels.

5. Main features

Jet fires can have different orientation (vertical, horizontal, inclined) and can occur in a calm situation or be subjected to the effect of wind (speed and relative orientation); these circumstances will affect their shape. As for their size, it will depend essentially on the outlet orifice diameter and on the mass flow-rate, as well as on wind effect. The thermal features of the flames will depend on the fuel and on its condition. In the next paragraphs these aspects are briefly commented.

5.1 Flame boundary

Jet fires are highly turbulent phenomena; this turbulence, together with the high exit velocity, originates the entrainment of a large amount of air into the jet. The mixing of air with fuel improves significantly the combustion in the jet; therefore, combustion in a jet fire is much better that in a pool fire. This can create a problem, especially with certain fuels (methane, LPG, hydrogen), when defining the exact

contour of the flame, as the flame can be almost transparent and the concept of "visible flame" is difficult to apply when doing experimental work.
Through comparison of visible and infrared images, a temperature of 800 K was selected as the best one to define the flame contour (Palacios and Casal, 2010, 2011). This value is quite close to the Draper point, which is the temperature at which radiation emitted by a heated black body in darkened surroundings becomes visible to the human eye.

5.2 Shape and size

When analyzing the potential effects of a jet fire, a very important aspect is the prediction of the flame shape and length, as they determine the zone in which there can be flame impingement on other equipment. A number of authors have studied this aspect, although many of them have analyzed the behaviour of subsonic or rather small jet fires. However, accidental jet fires are usually momentum-dominated, most of them being sonic jets (for most gases, sonic exit velocity to the atmosphere is reached if the pressure at the fuel source is higher than 1.9 bar abs., which is common in many storage tanks and pipes). A few authors have worked with large sonic fires, which are more representative of real jet fires; some of their results are commented in the next paragraphs.
McCafrey and Evans (1986) studied very large methane jet flames obtained with orifice diameters ranging between 38 and 102 mm; they suggested a general expression which assumes that sonic flame length is 200 times the value of the fictitious exit diameter resulting after the supersonic expansion. Kalghatgi (1983) and Chamberlain (1987) took into account the influence of cross-wind and assumed the shape to be the frustum of a cone; although this shape seems to be more appropriate for a flare than for a high velocity jet fire and, in fact, it was developed for flares, it is often applied to sonic jet fires. However, from Kalghatgi experimental data it can be deduced that at relatively high wind speeds the frustum of a cone becomes almost cylindrical in shape (Mudan and Croce, 1990). Other authors have assumed also a cylindrical shape, based on both experimental and theoretical studies on subsonic jet fires (Schuller et al., 1983; Hustad and Sonju, 1986).

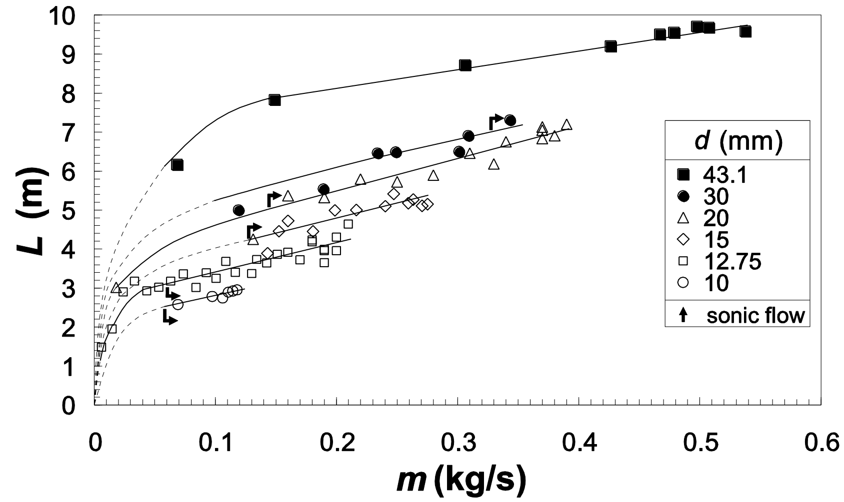

Figure 2: flame length (sonic and subsonic) as a function of fuel mass flow rate.

The length of a jet fire increases with the fuel mass flow rate and the outlet orifice diameter. Figure 2 shows some experimental results obtained with propane, corresponding to six different outlet orifice diameters (Palacios et al., 2009). Different expressions have been suggested to estimate the length of a jet fire, some of them including the overall heat release rate, some others proposing a function of diverse dimensionless numbers.

Another variable that influences the reach of a jet fire is the lift-off distance, i.e. the centerline distance from gas release point to the start of the detached flame. As it happens with flame length, lift-off is a function of jet exit velocity, outlet diameter, and mass flow-rate.

5.3 Flame thermal features

While the main hazard from jet fires is that associated to flames impingement, thermal radiation can also imply a risk at short distances.

Usually the thermal radiation intensity from a jet fire is estimated by applying the solid flame model, with an average value of the flame surface emissive power (E). The value of E will depend on the type and condition of fuel. As stated before, for certain gases the combustion is very good and the flame is almost transparent, the value of E being rather low; however, if the jet fire is fed by two-phase flow instead of by a gas, the quality of the combustion decreases, the flame is much more luminous and the radiation intensity is stronger. Experimental work has shown that there is an axial temperature distribution along the jet fire, giving rise to the existence of three different regions, each one with its own average value of E. In Figure 3 these three regions can be seen, with the highest values of E in the central one.

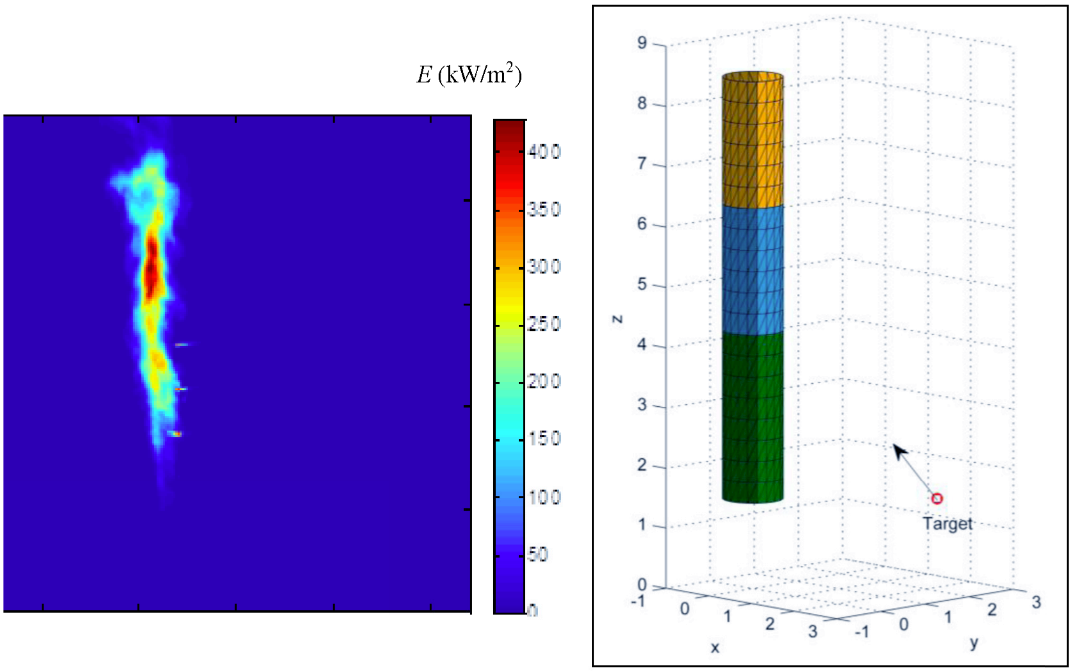

Figure 3: left) infrared image of a jet fire (d = 43.1 mm); the flame temperature distribution has been transformed to a surface emissive power distribution; right) a cylindrical vertical jet fire with the three zones (axis units: m).

Thus, the thermal radiation that reaches a given target can be estimated with the solid flame model by taking into account the sum of the contributions of the three regions (Figure 3) (Palacios et al., 2012), with their respective values of E and of the view factor (three-zone model). However, although this is a better approach to the jet fire phenomenon, in practice it does not imply a significant improvement of accuracy concerning the estimation of the thermal radiation intensity reaching a given target.

The thermal radiation intensity (I) decreases very quickly with the distance from flames. Figure 4 shows the variation of I as a function of the distance from the flame axis, as measured with three radiometers. It can be observed that a few meters are enough to reduce it at values that do not represent any hazard for other equipment.

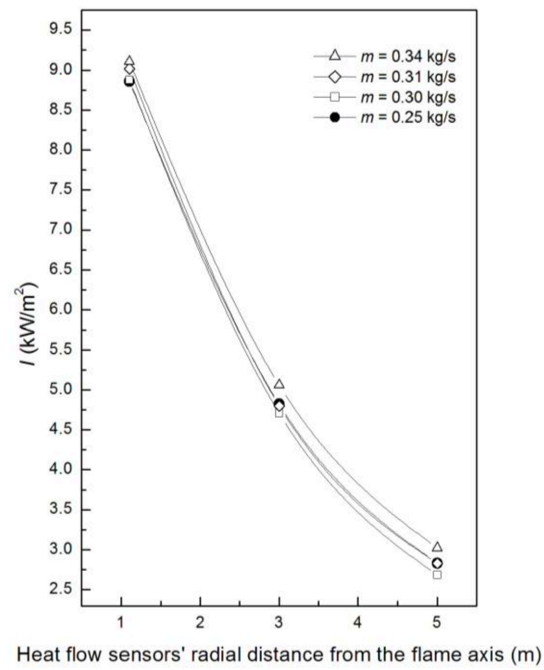

Figure 4: variation of the thermal radiation intensity as a function of the distance from the jet axis for a propane gas jet fire (d = 30 mm).

Therefore, at short distances a thermal hazard can exist even in the absence of impingement, and an accurate prediction is required in this area for the purposes of risk analysis.

5.4 Flame impingement

When jet fire flames impinge on equipment, very high heat fluxes reach the engulfed surface. It is not possible to predict accurately the heat transfer rate, which depends on the fuel, on the size and turbulence of the jet fire, on the region of the jet (middle, tip) which impinges, etc. Diverse approximate values have been proposed in the literature for propane and natural gas; they can be summarized as follows:

- natural gas, sonic jet: 50 – 300 kW/m^2; average: 200 kW/m^2.
- propane (gas) typical value: 300 kW/m^2; propane two-phase flow: 150 – 220 kW/m^2 .
- propane, two-phase flow, low velocity: 50 – 250 kW/m^2 ; average: 150 kW/m^2 .

As for the time to failure, it is also very difficult to predict as it depends on the circumstances, (existence of an insulating layer and condition of this layer): sometimes it has been a few seconds, but it can also be half an hour or more.

6. Conclusions

Even though jet fires are often smaller than other types of fire, they can be very dangerous because of the further accidents that they can originate if there is flame impingement on some equipment or if, due to a short distance, there is a strong radiation. In 50% of the jet fires reported in accident data bases, an additional event with severe effects also occurred. In this case, the failure can occur at any moment from the beginning of the fire, the time to failure being very difficult to be predicted. These accidents can occur in fixed plants or during the transportation of flammable materials.

Although a significant research effort has been made to improve the knowledge on this phenomenon, more research would be required, especially with large sonic jet fires of different fuels, and on the heat fluxes that occur when there is flame impingement.

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