Jet fires and cryogenic spills: How to document extreme industrial incidents

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Introduction:
In industrial plants, such as oil platforms, refineries or onboard vessels carrying fuel, a rupture event of a pipeline could have dramatic consequences, as was demonstrated both in the Piper Alpha and Deepwater Horizon accidents. If surfaces are exposed to extreme conditions, both extreme cold (cryogenic spills) and extreme heat (jet fires), this can affect exposed surfaces, and can cause a domino effect of severe events.

A recent development in the oil and gas sector is the increasing use of Floating Liquefied Natural Gas (FLNG) vessels. These vessels enable mobile gas production sites – a growing need as large gas reservoirs becomes more scarce. Gas production and storage onboard introduces new safety challenges compared to onshore refineries. With a limited volume available, as well as weight limitations onboard the vessels, there is a need to optimize the volume and mass of materials used onboard. This includes materials used to protect production equipment from incidents.

The boiling point of liquid natural gas (LNG) at atmospheric pressure is -162 °C; a cryogenic liquid. LNG is also flammable and could, if ignited, lead to a scenario which includes jet fires (ignited leakages of pressurized gaseous or liquid fuel). Production equipment onboard FLNG vessels and other industrial plants containing flammable, cryogenic compounds therefore need to be protected from both cryogenic spills as well as from jet fires.

It is thus relevant to assess cryogenic spill protection (CSP) materials in terms of jet fire resistance, as this would save costs, weight and volume for end users. Documentation of the performance of a material or structure in case of cryogenic spills or jet fires requires relevant test standards. This paper aims at providing insight into best practice for applied research on CSP and passive fire protection (PFP), focusing on test methods where cryogenic and jet fire testing can be combined. First, background information on CSP and PFP materials, as well as the mechanical properties of steel for the relevant temperature range will be presented. Example documentation from tests performed at RISE Fire Research will be presented, as well as a discussion of lessons learned.

Cryogenic spill and passive fire protection materials

In process plants where the same structures need to be protected against both fire and cryogenic spills there will be a need for combined CSP and PFP materials. Some PFP materials have good insulation properties for both high and low temperatures and will be able to protect efficiently against both cryogenic spills and fires. Other materials insulate well at low temperatures, but deteriorate at high temperatures giving limited protection against fire. There are also materials that are applied as relatively thin and compact layers, and require elevated temperatures to initiate a chemical reaction making the material expand to an insulating and thick protection system.

To give good protection against both cryogenic spills and fires, materials need to maintain their integrity and insulation abilities over a very wide temperature range from close to -200 °C and up to 1300 °C. If the protective material becomes brittle and damaged during the low temperatures it may not behave as intended during a following fire.

Steel properties
On both offshore and onshore industrial plants, the majority of structural elements and process equipment consist mainly of carbon steel. Both

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high and low temperature exposure can change the mechanical properties of the steel, reducing its load carrying capacity and functionality.

To prevent brittle fractures in steel, a CSP protection system should ensure that the structure temperature does not fall below the limit for embrittlement. At the so-called ductile-to-brittle transition temperature, the mechanical properties of the steel changes considerable, going from ductile to brittle [1]. An example of typical ductile to brittle behavior for steel is illustrated in Figure 1. The energy needed to fracture the steel drops over a relatively narrow temperature range. Less impact energy indicates a more brittle behavior. There is no universal lower critical temperature limit for steel as this varies with both grade and quality of the steel, and is dependent on steel thickness and carbon content. However, failure is expected to occur at considerable higher steel temperatures than the temperature of LNG.

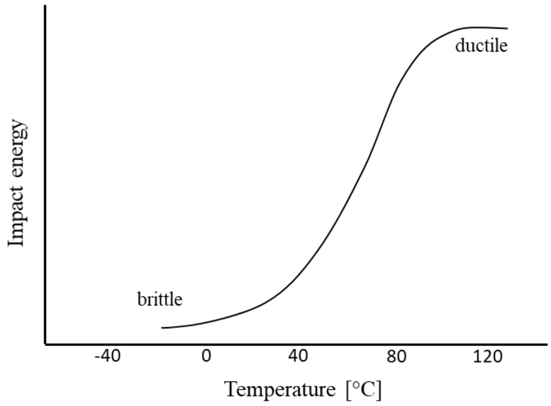


Figure 1 Illustration of the impact energy needed to fracture a steel sample, as function of temperature. The mechanical properties of the steel changes considerable from a ductile to a brittle behavior at a narrow temperature range. The steel becomes brittle at low temperatures. The temperature range and behavior are dependent on grade, quality and thickness of the steel. The figure is inspired by [1].

Steel surface temperatures of 400-600 °C are typically used to indicate failure during jet fire exposure. Increased steel temperature reduces the strength and stiffness of the steel, giving possible deformation and failure [2].

Figure 2 shows an example of effective yield strength of a carbon steel, relative to yield strength at 20 °C, as a function of temperature [3]. A significant decline in yield strength is observed in the 400 °C region. This is the temperature at which this steel element is expected to start to yield, meaning that the strength of the steel declines as the steel structure temperature increases.

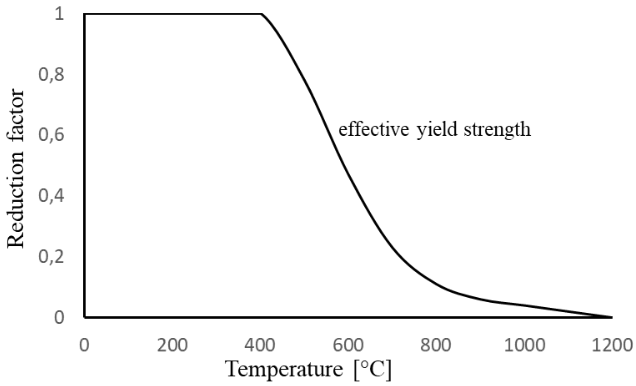


Figure 2: Illustration of effective yield strength, relative to yield strength at 20 °C, for a carbon steel as function of temperature. The effective yield strength of the carbon steel in this example illustrated here declines significantly after reaching 400 °C. The figure is inspired by [3].

Based on the behaviors described above should protection systems be tested towards both extreme cold and heat. This should be done to assure that steel structures do not reach temperatures that affect the mechanical properties in a way that it reduces the load carrying capacity and functionality of the structure.

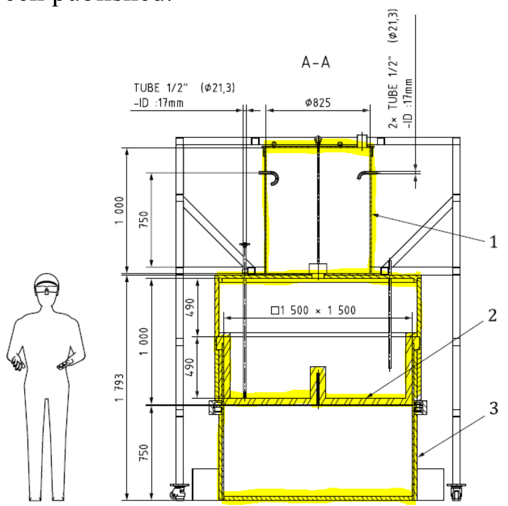
Standardized ISO test methods for cryogenic spill protection

Operators and engineering companies initiated the standardization work of ISO 20088 to solve the challenges associated with cryogenic spills. Together with manufacturers and test laboratories, a standardization working group in the International Organization for Standardization (ISO) was formed to develop test standards for determining the resistance of CSP systems to cryogenic spills. The test standard development was based on industrial incidents recorded by operators. Registered leakages were characterized and evaluated, and different parameters which could affect an incident was identified. The specific data from this work is confidential, but numerical and experimental work has been done during the development of the ISO standards, to ensure that the standardized test methods are relevant and representative. This work identified three important focus areas for cryogenic exposure:

- Part 1, ISO 20088-1: Liquid phase [4]
- Part 2, ISO/CD 20088-2: Vapor phase [5]
- Part 3, ISO 20088-3: Jet release [6]

The cryogenic liquid used in the test method is liquid nitrogen instead of LNG, to avoid fire and explosion hazards.

Part 1 involves immersion of a test specimen in a cryogenic liquid (see Figure 3). Part 2 includes documentation of exposure to cryogenic spills in the vapor phase and has not yet been published.

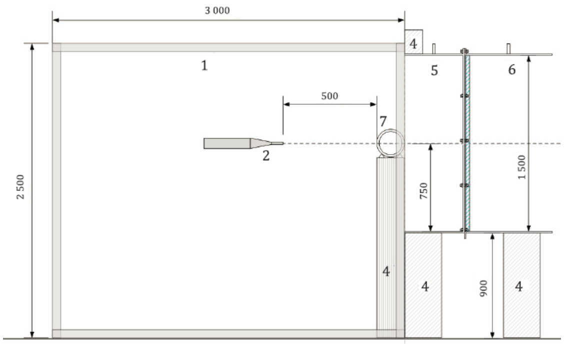


Key
1 release tank
2 specimen holder
3 specimen support

Figure 3: Schematic of test set-up for ISO 2088 part 1, taken from [4]. From top to bottom: Release tank containing 250 liters liquid nitrogen (1), release orifice at the center bottom, specimen holder (2) and specimen support (3). Nitrogen tank and CSP material are indicated by yellow shading, for clarity.

The most recently published, Part 3, includes a localized jet release designed to give an indication of how CSP systems will perform when subjected to sudden cryogenic release. The test simulates a potential accidental release of cryogenic LNG with initial pressures up to 60-80 bar. An overview of this test set-up is shown in Figure 4. A picture from a test according to Part 3 is shown in Figure 5.

The standards do not specify criteria for the lower critical temperature limit for the exposed steel specimen. This is set by the end-user, dependent on area of use, steel quality and other factors, for example in the range of -30 to -40 °C.



Key
1 environmental chamber
2 release nozzle (8 ± 0,8) barg (average pressure ±standard deviation)
3 specimen (beam shown)
4 specimen (and recirculation and protective chambers) supports
5 recirculation chamber (insulated on back surface)
6 protective chamber (support and stability)
7 specimen (tubular shown)

Figure 4: Schematic of test set-up for ISO 20088-3, with pipe configuration, taken from [6]. From left to right: Environmental chamber (1), release nozzle (2), pipe specimen (7) with support (4), re-circulation chamber (5) and protective chamber (6).

Figure 5: Photo of the test set-up during a cryogenic jet release test according to ISO 20088-3, for pipe configuration. The end of the pipe test specimen can be seen on the right. The pipeline leading in to the release nozzle can be seen in front of the environmental chamber. The environmental chamber is covering the release nozzle and most of the test specimen. Notice the fog cloud spreading across a large area.

Temperature data from tests

Typical test data for a cryogenic spill combined with a jet fire is given in Figure 6 (grey curve). The figure also includes flame temperatures from standardized and high temperature jet fire, for comparison. The standardized jet fire test is according to ISO 22899-1 [7] and the high temperature jet fire is according to the method presented by Stølen et.al. [8].

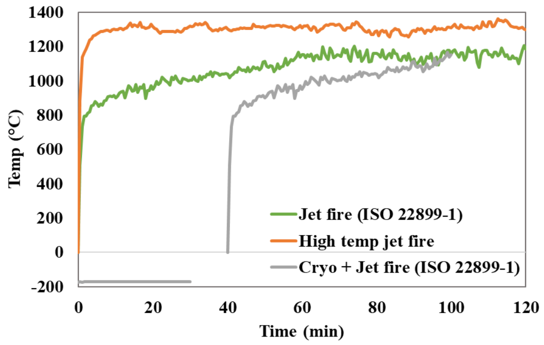


Figure 6: Temperature as a function of time for a standardized jet fire (green), high temperature jet fire (orange) and cryogenic jet release followed by a standardized jet fire (grey).

The presented temperature data in Figure 6 during the cryogenic exposure is measured to approximately -172 °C at the release nozzle (point 2 in Figure 4). In this example, the cryogenic jet release lasted 30 minutes. After a transition period of 10 minutes, the jet fire according to ISO 22899-1 is started at 40 minutes. The temperature during this period is illustrated with the same data as in the green curve.

The temperature measured inside the flame in a jet fire according to ISO 22899-1 (green curve) is typically around 1100 °C. The flame temperature during a high temperature jet fire (orange curve) is higher and typically stabilizes around 1300 °C.

When exposing an uninsulated steel specimen to a cryogenic spill, the steel temperatures at the impact point (point 7 in Figure 4) rapidly drops. In the example shown in Figure 7 (grey, full curve), there was a temperature decrease of 6 °C per second during the first 30 seconds of cryogenic exposure, and the steel temperature stabilized at -176 °C after 50 seconds. In this example with an uninsulated steel test specimen, -30 to -40 °C was reached after 9-10 seconds during the cryogenic exposure. To compare, for *insulated* steel objects, there is a large spread in the time when this temperature level is typically reached during cryogenic exposure, starting from a few minutes, up to longer periods of time (~hour).

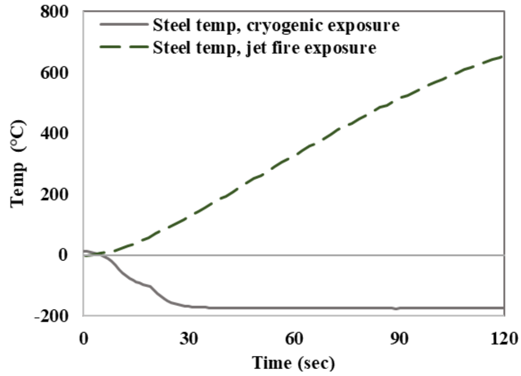


Figure 7: Steel temperature as a function of time during a cryogenic jet release test according to ISO20088-3 (grey, full curve) and steel temperature during a jet fire test according to ISO 22899-1 (green, dotted curve). The specimen is uninsulated, planar steel. During the cryogenic exposure, -30 to -40 °C (a typical lower critical temperature limit) is reached after 9-10 seconds, and the steel stabilizes at -176 °C after 50 seconds.

Figure 7 also includes the steel temperature of an uninsulated steel tubular specimen during a jet fire test according to ISO 22899-1 (with no cryogenic exposure), for comparison. The temperature increase is 5.5 °C per second during the first 120 seconds of the test. A typical upper temperature limit for jet fire exposure of 400-600 °C is reached after 1-2 minutes. To compare, for *insulated* steel objects exposed to a jet fire according to ISO 22899-1, this temperature level is typically reached starting from 15 minutes, up to several hours.

Lessons learned and discussion

Some lessons learned from the development of these test standards, as well as from the first commercial tests according to the new standardized methods, will be presented in this section.

During the development of the test standards, several tests were executed. For ISO 20088-3, a variation of flow rates and pressures of the liquid nitrogen jet release were tested. The results from these tests showed that the cooling rate of exposed carbon steel is not very dependent on the flow characteristics. The steel temperature at the impact point dropped below -40 °C within a few seconds in all tests, similar to that shown in Figure 7. This clearly shows the importance of protecting critical steel structures against cryogenic exposure.

A hazard identified during the experimental work was fog clouds. During the cryogenic tests, large amounts of cryogenic liquid is released, resulting in the formation of large clouds of fog, due to the rapid cooling of the ambient air (see picture in Figure 5). This greatly reduced the visibility in a large area around the test set-up and could potentially represent an evacuation challenge. In a smaller area close to the release, the oxygen in the air will be displaced and reduced to a level where asphyxiation may occur. In addition to these hazards, the extremely low temperatures can cause frost injuries unless proper personal protective equipment is used.

A test is considered successful, if the insulation material is able to keep the steel temperature above the lower critical temperature limit for a given duration of cryogenic exposure, and also below the upper critical temperature limit for a given duration of jet fire exposure. One observation made during the experiments was that once the test specimen was cooled down by the cryogenic liquid, the heat capacity of the steel combined with the insulation of the CSP material, gave an increased duration of the heating time during the jet fire exposure. It took a long time (typically several minutes) to even heat the specimen back up to ambient temperatures. This gives an advantage during the jet fire test as compared to a jet fire test that starts from ambient temperature.

It is known that the size of a fire as well as the level of enclosure influences its properties [9], [10]. This can be seen by comparing the high temperature jet fire (orange) with the standardized jet fire (green) in Figure 6, as the main difference between these tests is the size and enclosure of the flame re-circulation chamber. A possible future development of the cryogenic + standardized jet fire test method, is to have a cryogenic spill combined with a high temperature jet fire. This could potentially give a more realistic heat load to the test specimen.

Still, it is important to notice that the relatively small scales of these test methods never will be a true representation of reality, but rather enable comparison of materials and systems, to identify weak links. Safety margins incorporated into such test methods can in some cases seem excessive, but the true severity of a cryogenic or jet fire incident industrially should not be underestimated; when pushing towards optimized materials and systems, we must ensure that the safety margins are on our side.

Lastly, it has been observed that there is some system inertia in the industry, when it comes to implementing these newly developed standards. This is, unfortunately, common for standardization work. When going forward, these standards urgently need to be implemented and utilized by stakeholders involved in technical safety of LNG and other cryogenic liquids.

Summary

This paper has presented recent developments within the field of cryogenic spill protection and passive fire protection. The first ISO standards for documentation of cryogenic spill resistance of such materials have been presented (ISO 20088 Part 1-3), as well as the option of combining these with jet fire exposure. Based on a combined cryogenic spill and jet fire test, it is possible to determine the optimal use of insulation materials in terms of weight, cost and establish the required level of steel structure protection. Suppliers, end-users and authorities can thereby be sure that an adequate and optimized safety level is reached.

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