A review of the applicability of the jet fire resistance test method to severe release scenarios

Prepared by the Health and Safety Executive
When assessing safety cases for offshore installations, HSE may have to consider if the passive fire protection materials installed are suitable to protect against the events they may encounter. In situations where passive fire protection for structures and components could be subject to an intense jet fire, that suitability is judged by the results of testing to the ISO22899-1 international standard.

Within the offshore industry, it has been suggested that this standard test is not adequate for all fire situations. This has led to some protection products being tested to non-standard methods intended to create a higher heat flux in order to represent a more severe fire.

This report examines a range of jet fire scenarios and concludes that the standard test is representative of most but for certain scenarios may not always be applicable. However, simply increasing the heat flux may not produce a more onerous test.

In order to ensure that hazards from major jet fires are adequately controlled, large scale testing is needed to show how fire protection products respond to the actual fire events. Only with such information can validated, practical scale test procedures be produced, for any situations where the current standard test is not applicable.

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A review of the applicability of the jet fire resistance test method to severe release scenarios

Ian Bradley
Independent Consultant
30 Bondene Avenue West
Gateshead
Tyne and Wear NE10 9NL
**Background of Author**

Ian Bradley was commissioned by HSE to produce a literature review on the applicability of the jet fire resistance test method.

Ian obtained a MEng in Materials Science and Engineering from the University of Sheffield in 2004 and an MSc in Fire and Explosion Engineering from the University of Leeds in 2012.

From 2007-2014 he was employed by a manufacturer of passive fire protection materials across a range of roles. Responsibilities included external fire test design and liaison with assessment and certification bodies.

Ian is a delegate to national and international committees responsible for fire resistance tests standards, including FSH 22/-/14 and ISO TC92 SC2 WG8: Jet fires.

Currently, Ian is undertaking a PhD with the University of Edinburgh investigating the response to hydrocarbon fires of pressure vessels. His research includes test design, fire characterisation and simulation of multiphase flow with boiling.

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KEY MESSAGES

Some high hazard sites, offshore oil and gas platforms for example, need structures and equipment protected from accidental fires. One particularly severe fire scenario is a burning jet of material caused by the ignition of a pressurised leak.

In order to test that protective materials are suitable for this situation, a standard test (ISO22899-1) was developed and this has been in use for nearly 25 years. Some stakeholders have raised concerns that the test, which was developed to represent a large natural gas jet fire, may not be suitable for all other jet fires. Some test organisations have put together modified tests which they consider to be more severe.

HSE commissioned this review to look at whether there is evidence that other types of jet fire are significantly different from a natural gas jet fire and, if so, to assess whether the existing jet fire test could still give applicable results.

The existing standard test was only developed after full scale experiments had been carried out on natural gas jets. The ISO22899-1 test was then developed to replicate the full scale effects on fire protection materials.

Some other scenarios – gas jets up to 60 bar and jet releases of liquids above their boiling points – are also adequately represented by the existing standard test.

Other scenarios may pose a different and possibly more severe challenge to protective materials than is checked by the existing standard test. These scenarios could include liquid jets, mixed gases and liquids such as some unprocessed crude oils and mixtures of natural gas and hydrogen.

There is no existing evidence of the effect of such scenarios on fire protection systems. Because of this, it is not possible to confirm if the existing standard test is applicable, nor what conditions an alternative test needs to reproduce if the existing test is not applicable. There is a lack of experimental data on the response of fire protection materials to these more severe scenarios. Mixed gas/liquid is the most widespread of these scenarios and would be the most appropriate for large scale experimental study.
EXECUTIVE SUMMARY

Objectives

Many structures and control systems in areas of increased fire risk are protected by passive fire protection (PFP) systems. A burning jet of material released under pressure produces a significantly more severe challenge for PFP systems than conventional fires. Full scale benchmark tests of pressurised gas jet fires supported the development, in the early 1990s, of a Jet Fire Resistance Test (JFRT, ISO22899) for PFP systems intended for protection against such fires.

More recently, concerns have been raised by parts of industry that other more severe jet fire scenarios exist and that the JFRT is not representative of those conditions. A number of PFP systems on the market have been tested using ‘high heat flux’ jet fires, implying that they are particularly appropriate for use in such scenarios. However, it is not clear that such tests indicate the potential performance of PFP in such scenarios. These ‘high heat flux’ methods remain unpublished, it is not clear what their test conditions actually are, and there appears to be no validation against the more severe jet fire scenarios. The primary aims of this report are:

1. To assess the applicability of the existing JFRT for a range of alternative scenarios.
2. To show whether there is a need for a supplementary test method, based on analysis of numerous release scenarios, covering a range of fuels, flow rates, release pressures and confinement.

Conclusions

There is a history of test studies that provide data on a range of jet fire scenarios. Some of these provided the evidence to validate the JFRT method. The studies clearly show that a range of factors affect materials within a jet fire, and that an assessment of PFP materials for any specific jet fire scenario needs to be based on more than a single value of total heat flux.

Evidence suggests that sonic gas releases at pressures up to 60 bar and flashing liquid releases are adequately represented by the JFRT. This is less certain for higher pressure gas releases, but it is not clear that simply raising the total heat flux in the test would be representative of higher pressure gas jet fires.

Jet fires from liquids, mixed gases/liquids (such as live crude oils) and natural gas / hydrogen mixtures may pose a more severe test for PFP materials. These are outside the validation testing for the JFRT, which cannot be assumed to be appropriate in such scenarios.

The development of any additional test for PFP performance needs clear identification of the full-scale scenario it is intended to represent and full-scale benchmark tests to show the effects of that scenario on PFP, including any deviation of the PFP response from that in the JFRT. If more severe tests are needed, full-scale data also allows for future validation of any new test that is developed.

It is recommended that data is generated on the response of PFP materials subject to a range of potentially more severe scenarios. The prevalence of situations that could produce mixed gas/liquid jet fires suggests that these should be the priority area for study.
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1. INTRODUCTION

Following the Piper Alpha disaster in 1988 and the conclusions of the Cullen report [1], a joint industry working group was set-up to develop a test procedure for the resistance of passive fire protection systems to the intense thermal and erosive conditions known to be present in jet fires. This began with detailed measurements on full-scale, benchmark jet fire experiments and then investigated how these could be reproduced in a practical test for fire protection systems. The resulting Interim Jet Fire Test procedure (IJFT) was published by HSE [2] and was developed further into the Jet Fire Resistance Test for Passive Fire Protection Materials (JFRT) [3]. This was subsequently adopted as an International Standard by ISO in 2007 [4] with minimal change. This ISO22899-1 standard is now recognised worldwide as the primary means of product qualification for jet fire hazards.

In recent years there has been a growing concern among some parts of the hydrocarbon fire protection industry that the test procedure does not adequately recreate the most severe conditions observed under particular jet fire conditions. Although a specific reason for these concerns is difficult to identify, one of the main driving factors appears to be simplified guidance that characterised jet fires by peak heat flux values (such as Table 1 in the Norsok Technical Safety Standard [5]). Engineering companies and operators have asked protection system manufacturers to confirm the resistance of the systems to such 350 kW/m² heat flux values. A self-sustaining situation seems to have arisen whereby manufacturers feel obliged to undertake ad-hoc “high heat flux” jet fire tests, and then by using the results they inherently promote the necessity of them. Appendix A describes two such tests in more detail.

The lack of a coordinated industry response on the issue has led to a lack of clarity on the applicability of the existing standard jet fire test method, and has fed a situation whereby further tests are being developed and conducted in an ad-hoc manner with little or no consensus in methodology or evidence of similarity in results. There are no published scientific studies examining the necessity of performing such tests. Nor is it clear what hazard scenarios such tests are intended to represent, and whether they are indeed representative of any credible accident scenarios. More fundamentally, the majority of test data which underpins the knowledgebase on jet fires has been obtained during commercial product testing or companies’ internal projects and remains unpublished. This means that an appreciation of the wide range of conditions within a jet fire is limited. This lack of data, and a reliance on simplified guidance, or conversely an excess of data from CFD without guidance on how to apply or interpret results, is leading to frequent difficulties in assessing accurately whether a particular hazard scenario is in fact adequately covered by the existing test procedures.

This lack of coordinated industry response on the issue is producing a situation whereby it is unclear what the benefit and justification to industry of the costs of undertaking further tests are. Furthermore regulators have no technical basis to determine if there are situations when testing beyond ISO22899 may be needed. There has been a break-down in the connection between the design of a test method and the identification of the hazard scenario it intends to reproduce. In some ways, this is reminiscent of the situation immediately prior to publication of the accepted jet
fire method. To quote reports produced at the time, failure to validate a test method will “result in the possibility of suitable candidate systems being overlooked, a reliance on ad-hoc full-scale testing of systems for each configuration and the need to demonstrate that individual fire scenarios have been taken in to consideration on a case by case basis”.

1.1 OBJECTIVES
This report is intended to assess the applicability of the current JFRT to a range of potential jet fire scenarios and, where appropriate, make recommendations on the need for further work to extend the validation of the existing test procedure or develop a supplementary test method. In assessing applicability, it will consider the experimental evidence available with respect to the thermal and physical loads acting on engulfed objects and discuss whether alternative scenarios can be reasonably assumed to be represented by the full-scale benchmark test, and by extension the JFRT.

In the process of developing this report the following steps were undertaken:

1. A review of the experimental evidence of jet fire engulfment conditions available at the time of completion of the IJFT
2. A summary of the development, extension and validation of the interim IJFT and JFRT
3. A further review of large-scale jet fire test evidence generated since publication of the IJFT and JFRT procedures
4. A discussion on the validity of the existing JFRT to a range of further scenarios and whether there is a need for development of a further, supplementary test method
5. A review of existing ad-hoc test methods and comment on practice

Throughout the report the focus is on the response of passive fire protection systems to jet fires as a means of modifying the rate of temperature rise of the substrate. This report does not seek to repeat the analysis and characterisation work of jet fires performed over many years by numerous authors. It references existing guidance and comments on the suitability of such guidance as a means of specifying passive fire protection or developing fire resistance test methods. Such comments, supportive or otherwise, should not be taken as referring to the existence or veracity of such guidance in general.

Although the author considers that simplified characterisation of jet fires in terms of a heat flux value is inappropriate, heat flux values are discussed extensively throughout this report. The issue of heat flux distribution is important to consider in depth for two reasons: firstly, the available data on heat flux distributions is extensive, unlike velocity and dynamic pressure measurements which are less readily available; secondly, the topic of this report is known in industry as ‘high heat flux’ testing and simplified guidance has a tendency to focus on heat flux values.
2. TERMINOLOGY

Throughout the report numerous terms and acronyms are used. Some of these are defined below.

**Full-scale**

The term full-scale refers to any tests designed to directly simulate a potential ‘real-life’ release condition. For the purposes of this report full-scale refers to flow rates approximately 1 kg/s or above, on the basis that this represents the lower end of the flow rates available in the test literature, or to releases into large compartments.

**Medium-scale**

Refers to the current jet fire test methodology scale, which uses a flow rate of 0.3 kg/s.

**IJFT or Interim jet fire test method**

The earliest public version of what would become the current ISO jet fire test.

**JFRT or Jet fire resistance test**

A publically available test procedure developed from the interim jet fire test method.

**ISO 28899-1**

A test procedure adopted as an international standard. Changes made from the JFRT were relatively minor.

**Heat flux**

A measure of the total energy transfer rate per unit area (kW/m²). This is also sometimes referred to as flux density, or simply as flux value.

**Jet fire**

A turbulent diffusion flame resulting from the combustion of a fuel continuously released with some significant momentum in a particular range of directions (taken from [6]).

**PFP - Passive fire protection**

Coatings or systems that are applied to, or installed on, critical items and which act to reduce the rate of heat transfer to the substrate. Such systems are referred to as passive because they do not require physical activation in order to function. Note that recent definitions of passive fire protection have distinguished between reactive types (e.g. intumescents) and truly passive types (e.g. jackets). The term passive fire protection in this report is used to refer to both kinds. Passive fire protection is often shortened to PFP.
3. FULL-SCALE JET FIRE STUDIES BEFORE THE INTERIM JET FIRE TEST

A summary of full-scale test programmes is provided as Appendix B.

At the time of formation of the jet fire working group the body of test evidence on full-scale jet fires, and the thermal exposure of objects impinged by such fires, was limited by the standards of today. A number of studies had been made on intermediate-sized free-flame releases, but these did not measure the heat fluxes imposed on directly impinged objects. The majority of data on the heat loads to large objects impinged by jet flames came from tests performed at the Isle of Grain [7] or from a large CEC funded test programme on unconfined releases of natural gas and propane undertaken by British Gas and Shell [8].

The Isle of Grain tests studied releases of propane (1-10 kg/s) impacting onto copper plate targets at a distance of 7 to 10 m. Water cooled calorimeters recorded heat fluxes of 50-250 kW/m².

The Shell and British Gas tests provided a far more extensive insight into the heat flux distribution across impinged targets. A series of 170 tests were conducted over several years in order to characterise a range of sonic and subsonic releases of natural gas (up to 10 kg/s) and propane (up to 22 kg/s). The impinged target was either a 0.9 m diameter pipe or a 13 tonne vessel. A total of 41 tests with an instrumented target were identified as giving reliable data. The time-averaged maximum total heat flux values reported in these tests are shown in Figure 1. These were recorded by water-cooled calorimeters maintained at 60°C.

The heat flux values given above are time averaged over a period of typically one minute. It was noted in the summary report that increasing the period of time averaging tends to decrease the value. An example calorimeter trace given in the report shows the typical variation in the readings can be in the region of ±25 kW/m². The Shell summary report states: “Instantaneous values of up to
350 kW/m² are possible, but time-averaging reduces this to between 50 kW/m² and 300 kW/m² in areas steadily engulfed by flame. Fluxes are reduced further by wind effects”.

The spatial distribution of heat fluxes is complex, depending on the release conditions and target position and geometry. Figure 2 shows the variation in heat flux distributions on a pipe impinged by an 8 kg/s natural gas release giving a flame length of approximately 25 m to 30 m. At 9 m from the point of release the heat flux on the front of the target is relatively low, despite high velocities, as the partially combusted gas is relatively cool. The areas of highest heat flux are located at the rear. At 15 m the target is near the midpoint of the flame. Convective fluxes remain high at this point, while radiation from the flame is significant on both the front and back of the target. The average heat flux across the engulfed area is typically highest near the middle of the flame. At 21 m the highest maximum heat flux values are expected to be present on the front of the target. The majority of the flame on one side of the target results in a high radiative heat flux in this region, which offsets the reduction in convection due to reduced gas velocities.

![Figure 2: Heat flux distributions in a sonic natural gas flame (8 kg/s)](image)
Reproduced from Bennett, Cowley et al (1991)

The results from early jet fire studies demonstrate the difficulty in characterising a jet fire accurately in simplistic terms. The spatial distribution of heat fluxes is complex, and the upper values recorded by heat flux gauges will vary depending on the period of time averaging. Furthermore, the heat flux distributions vary extensively depending on the position of the target in the flame. Therefore most summary reports of test programmes describe release conditions typically in terms of time-averaged heat flux values at each measuring point, after determining a suitable time period for averaging. Maximum heat flux values and global average heat fluxes are often listed in the zone of engulfment, which itself often requires defining in terms of an arbitrary minimum heat flux, such that heat from flame impingement is distinct from that caused by external radiation. The complexity in characterising the heat flux densities coupled with the high erosive forces imparted by gas velocities of typically 20 m/s to 100 m/s for natural gas flames in the turbulent combustion region, makes it impossible to extrapolate the jet fire performance of a PFP material from furnace based tests alone.

To assess the ability of passive fire protection materials to withstand the combination of high erosive forces and highly localised heat flux values, Shell conducted a programme known as “SOFIPP” [9] [10] [11] to study the thermal response of steel under two types of protection system that were commercially available at the time. A 3 kg/s sonic natural gas release was chosen for the tests with
the targets set at a distance of 9 m. This release had been well characterised in the CEC funded work described above and was chosen to give a severe, yet representative, combination of erosion and heat fluxes in a long duration test. The targets were I-sections, instrumented with thermocouples and coated with the protection systems.

In summary, information available at the time of the international jet fire working group’s formation had shown the extensive variation in flux distributions to impinged objects, and highlighted the difficulty in characterising them in simple terms. Time-averaged peak and global average heat fluxes were given in the summary report as 300 kW/m² & 200 kW/m², respectively, for natural gas and 250 kW/m² and 150 kW/m² for propane (see Figure 3). It should be noted that these values need to be used with caution as they necessarily include a degree of time and spatial averaging. Instantaneous peaks of 350 kW/m² were recorded, but these must be considered unrepresentative of the overall severity of the test.

Figure 3: Average heat fluxes in flame impinged areas
Reproduced from Bennett, Cowley et al 1991
4. DEVELOPMENT, EXTENSION AND VALIDATION OF THE IJFT METHOD

4.1 DEVELOPMENT OF THE SINTEF JET FIRE TEST PROCEDURE

SINTEF started work on simulating jet fire testing in 1986, to meet project specific requirements for SAGA petroleum. The method progressed from flat plates of various sizes through to testing on a short length of 1.5 m deep I-girder. To reduce flame escape down the webs of the specimen the I-girder was blocked off at the sides. The resulting shape formed the basis of the 1.5 m x 1.5 m x 0.5 m box that is still in use today for jet fire testing [12].

SINTEF performed numerous studies investigating the heat fluxes, temperatures and gas velocities of the test under a range of configurations. Parameters varied included the specimen to nozzle distance, nozzle position and, to an extent, the flow rate [13].

The instrumentation used to characterise heat flux was a combination of water cooled total heat flux gauges, radiometers, thermocouples and uncooled steel calorimeters (similar to directional flame thermometers that use multiple thermocouples along a length of material to back-calculate the heat flux from the 1D temperature profile). Early development work showed a range of heat flux measurements, depending on the instrumentation used (see Figure 4).

![Figure 4: Variation in measured peak heat flux by test and instrumentation during SINTEF development test characterisation, showing the sensitivity to measurement technique](image)

4.2 INTERIM JET FIRE TEST METHOD (IJFT)

An international jet fire working group was formed in 1992. It started work with a review of available literature, benefiting from access to a range of unpublished information. The development work done by SINTEF in previous years [14] was taken as the basis on which to proceed, however it was found that no PFP materials had been tested to both large-scale and medium-scale tests in a similar configuration. A joint industry project (JIP) was proposed and PFP manufacturers were invited to join, although reference was made at the time about the reluctance of PFP manufacturers to finance
the JIP. The working group stated that failure to validate a test procedure would “result in the possibility of suitable candidate systems being overlooked, a reliance on ad-hoc full-scale testing of systems for each configuration and the need to demonstrate that individual fire scenarios have been taken in to consideration on a case by case basis”. These words could be considered equally applicable to the situation PFP manufacturers find themselves in today regarding “high heat flux” jet fire testing.

Changes from the SINTEF procedure were relatively minor. The flow rate of propane was fixed at 0.3 kg/s and the height of the jet set at ¼ height of the vertical face of the sample, having reviewed ¼ and ½ height configurations tested by SINTEF. The working group expanded the test configuration beyond coatings intended for flat panels to include steelwork edge features by using a central vertical web, and to stand-alone panel materials or systems with joints in the rear-plate location. The resulting document was published as the Interim Jet Fire Test Method [2].

More detailed characterisation of the heat flux distribution in the box configuration was performed using water cooled total heat flux gauges. The results from heat flux gauges positioned as shown in Figure 5 were used with temperature data to produce an estimate of the heat flux distribution, as shown in Figure 6. The maximum flames velocities 20 mm from the back plate were measured using bi-directional probes and reported as approximately 45 m/s across the surface of the test specimen. Higher velocities of 55 m/s were measured prior to impact in the jet direction.

![Figure 5: Calorimeter positions during characterisation of the box configuration medium-scale test](Reproduced from [15])

The maximum heat flux recorded using water-cooled calorimeters was approximately 300 kW/m² during development of the jet fire test. Anecdotal evidence exists of stainless steel melting during medium-scale jet fire resistance testing, which if confirmed demonstrates the potential for highly localised, transient peaks in excess of this value.
4.3 ASSESSMENT OF THE UNIFORMITY OF THE JET FIRE TEST

The jet fire working group had concluded that conditions in the IJFT were sufficiently representative of full-scale sonic releases of natural gas at 3 kg/s. As part of validation of the IJFT prior to industry acceptance, a round-robin study of the uniformity of the test procedure was undertaken [16]. Three test laboratories took part: SINTEF NBL in Norway, HSL Buxton in the UK and Southwest Research Institute (SwRI) in Texas, USA.

Six test specimens were produced using the box with central web configuration. Each box was coated with an epoxy intumescent from one of two manufacturers that participated in the project. The project provided a number of recommendations for minor improvements to the IJFT, and concluded the IJFT does provide a uniform test for the rear wall of the test specimen. It did not conclude that it provides a uniform test for the central web of the test specimen, due to variations seen in the performance in the top half of the flange. However, it qualified this statement by adding this could be due to the vulnerability of the flange magnifying small variations in the test procedure, or it could reflect variability in the performance of the PFP materials or their application conditions.

Two of the three tests were performed inside dedicated buildings, the remaining test was performed outdoors in a 4 m high by 3 m wide by 8 m long brick enclosure. It was noted in the report that the protection material in the outdoor test performed worse, and it was suggested that the proximity of the walls (and the incident radiation from the heated walls) caused an increase in severity in the test. Current ad-hoc “High heat flux” jet fire tests being done by SP research also use re-radiation from an enclosure to increase the severity of the test [17].

Further review of the data [18] focussed on the maximum and minimum temperatures observed, the former being the key criteria for performance evaluation in the jet fire test. It concluded there was “generally good uniformity between the different test specimens for both the back plate and the central web.” It noted the observations made at the time of the initial study regarding an apparent increase in severity of the central web in the HSL tests, and stated the possibility this was due to small fluctuations in the test protection material thickness or application conditions.
4.4 EXTENSION OF THE JET FIRE RESISTANCE TEST TO TUBULAR SPECIMENS

The original IJFT procedure did not include a configuration for tubular specimens, despite SINTEF having performed initial studies in this area [13]. SwRI undertook a research programme [19] which led to a series of 8 tests in late 1995 and early 1996 on tubular sections at the IJFT-scale [20]. Six were unprotected to characterise the flame, and two further tests were performed with an intumescent coating to allow for direct comparison with large-scale tests (see section 4.5).

Readings of heat flux were initially lower than expected (lower than those seen in the preliminary work performed by SwRI). Soot depositing on the gauges was identified as the cause and a temporary cover shield was used in later tests to allow 10 minutes of stabilisation prior to measurement. With this method, peak heat fluxes of 293 kW/m² and 287 kW/m² were recorded.

It was concluded that for external diameters of up to 500 mm the test procedure could be extended to tubular geometries. This outer diameter was reduced to 300 mm by the jet fire working group on the basis that the heat flux at 500mm was approximately 20% lower than at 300mm.

Despite these conclusions, it should be noted that the heat flux values quoted represent instantaneous values, not time averaged values. A thirty-second time-average over the values would give heat flux readings of 280 kW/m² and 270 kW/m² respectively. The cover shield approach, while useful in this situation, represented a departure from the measurement conditions in the large-scale tests. However, it is worth noting the average of the three total heat flux readings was consistently similar to the quoted value for the box configuration of 240 kW/m², with no total heat flux gauge giving a time averaged value below 200 kW/m² once faulty readings are excluded.

4.5 VALIDATION AGAINST LARGE-SCALE TESTS

Full-scale tests were performed by British Gas at Spadeadam on two I-sections [21] and two tubular sections [22], all protected by PFP. All specimens were engulfed in a 3 kg/s natural gas jet fire, at a distance of 9m from the point of release. The tests were conducted shortly before the IJFT test procedure was revised and published by HSE as OTI 95 634, entitled “Jet-Fire Resistance Test of Passive Fire Protection Materials” [3].

Subsequent to publication of the test procedure, the performance of two types of intumescent materials was compared for differences between large-scale and medium-scale tests. A report on analysis of the available data [18] drew conclusions for the I-section and the tubular tests. For I-sections it was broadly positive, stating “an analogy may be made between the I-sections tested at large-scale and the central web of the box of the medium-scale tests”, and highlighting the requirement to consider a point of failure, rather than an average of results, to ensure correlation between the large-scale and medium-scale tests. Regarding tubular sections, the report stated the results were not conclusive, attributing this to a reduction in the dynamic forces associated with the medium-scale test.

A paper on the subject published by Al-Hassan, Wenzel and Mather [23] went further, concluding: “Measurements of the heat fluxes indicated that the Interim Jet Fire Test Procedure can be modified..."
to test tubular specimens. However, validation tests with PFP have shown that despite the measured heat fluxes [being] comparable, the erosion effects are not the same as produced at the large scale.”

Further insight was provided by a comparative CFD study of the jet fire test procedure in the planar and tubular configurations and the benchmark 3 kg/s sonic natural gas release [15]. In the benchmark release study, the maximum radiative flux predicted was 210 kW/m² and the axial velocity 90 m/s at a distance from the release point of 9 m. The study of the planar test configuration predicted velocities in excess of 50 m/s and peak heat fluxes of 230 kW/m² (140 kW/m² radiative) near the point of impingement. The report concluded that the radiative and convective fluxes that occur in the planar configuration jet fire test do replicate those found in the reference large-scale release, although no further details are given for how this conclusion was arrived at.

The tubular section analysis reached similar conclusions relating to the radiative and convective components, although it added a note of caution on the dynamic pressures. It predicted peak dynamic pressures in excess of the large-scale test, however these were confined to small areas that coincided with the impingement of only partially-combusted (and hence cooler) gases. If correct, this is a potential explanation of the lower erosion rates exhibited by intumescent materials in the medium-scale tests during the validation programme. Since publication of the above reports, anecdotal evidence has emerged to suggest there is a correlation between peak temperatures and erosion rates for intumescent materials. This would support the previous statement.

4.6 SUMMARY

As a result of extensive large-scale jet fire tests performed at Spadeadam, an unconfined 3 kg/s sonic natural gas release impinging on a target at a distance of 9 m was identified as being suitable for use as a benchmark for future medium-scale developments. It was noted in numerous documents that this should not be considered a ‘standard’ release as no single release can seek to replicate the wide range of conditions found within jet fires.

An international working group was formed to develop a jet fire test and in 1993 published the interim jet fire test procedure. It was based on a jet fire simulation testing concept that had been developed shortly before by SINTEF NBL. With the exception of a number of expansions in scope, and a few changes, the current jet fire standard strongly adheres to the principles of the interim procedure.

The heat flux distribution across the box configuration was characterised during development work, and was considered by the jet fire working group to be acceptably representative of the distribution within the benchmark 3 kg/s sonic natural gas release.

The heat flux distribution of the tubular configuration was also considered by the jet fire working group to be acceptably representative of the distribution within a 3 kg/s sonic natural gas release. It would appear that the time-averaged maximum heat flux values are somewhat lower than the values observed in the box configuration, however this small difference was not considered significant in terms of assessing the validity of the procedure, as a focus on peak heat flux values can highly misleading as explained elsewhere within this report.
The ratio of radiative to convective fluxes varies significantly across both full-scale test specimens and the medium-scale test configurations. Full-scale unconfined test results show a strong dependence on release conditions, target geometry and target position, but radiative components between 50% and 100% are typical. Experimental and numerical studies of the medium-scale test estimate the radiative component to account for approximately 50%-70% of the total heat flux. Note that care should be taken with these figures as there are extensive variations.

Radiative heat fluxes recorded in the medium-scale development tests and the full-scale benchmark tests showed reasonable agreement. Heat flux values showed a greater variation in the full-scale test (as is to be expected), however time-averaged maximum values were in the region of 180 kW/m² for both tests. Note that the limits in radiative heat flux data available make a detailed comparison difficult.

Although the gas velocities recorded in the benchmark full-scale test at the target location were higher than in the medium-scale development work, and the spread of heat flux values measured greater, it must be recognised that the areas of maximum heat flux in the benchmark full-scale tests are small and the regions of maximum convective heat transfer do not necessarily overlap with the regions of maximum radiative heat transfer. Characterisation of the severity of any test on the basis of a peak heat flux value alone is misleading.

The medium-scale JFRT exhibits lower gas velocities and a narrower distribution of heat fluxes than the full-scale test. However, the design of the JFRT results in the areas of maximum erosion and maximum heat flux being in close proximity, which is not expected in full-scale releases.

It is impossible to recreate the exact conditions of a full-scale release in a laboratory, due to well-established scaling effects relating to the properties of the flame. Therefore, validation of any medium-scale test must be performed not only through quantification of the contribution of key phenomena that result in failure, but through demonstration of an equivalent overall level of severity.

Comparison of products tested at large-scale and medium-scale showed a good correlation on I-sections. The evidence allowed the jet fire working group to conclude that the overall severity of the tests in relation to the response of PFP is similar for the box configuration.

When the same comparison was performed with tubular sections, a notable difference in performance was shown. It was concluded by some at the time that erosion effects are less severe in the medium-scale tubular configuration.

In conclusion, validation work performed supports the assumption that the JFRT box configuration is representative of the benchmark full-scale release. By extension, the JFRT can also be reasonably assumed to be applicable for other jet fire scenarios that produce conditions and an overall severity level commensurate to the benchmark scenario.
5. FULL-SCALE JET FIRE STUDIES SINCE PUBLICATION OF THE IJFT

5.1 SCENARIOS CONSIDERED
In studies of the characteristics, behaviour and impact of oil and gas fires, Cowley and Johnson [6], [24] list typical types of offshore accident scenarios that could result in a jet fire. These include jet fires within a module, jet fires beneath the topsides, and well-head blowout fires. The range of fuels and release rates described are notably wider than the scope of jet fires tests that had been conducted at the time of their study.

Extensive work was conducted in the decade following publication of the IJFT procedure to address gaps in the knowledge base relating to alternative release scenarios. This section summarises pertinent data and conclusions from the relevant test programmes.

Cowley and Johnson made reference to the potential transient nature of jet fire. Loss of inventory and blowdown can act to reduce the pressure and hence the flow rate and the flame length. An object that is impinged by a jet fire may experience a greater or lesser severity of heating as the fire progresses, due to the variation in position within the flame structure. The studies referenced here generally used a constant flow rate with the aim of achieving steady-state conditions (to the extent permitted by environmental conditions).

5.2 CONFINED RELEASES OF PROPANE AND CONDENSATE
In 1993 a series of tests were conducted by Shell research at SINTEF NBL to investigate the behaviour of propane releases into a 135 m³ compartment [25]. Both vertical and horizontal releases were studied, at flow rates of approximately 0.3 kg/s. The flame temperatures, total heat fluxes and radiative heat fluxes generated were highly dependent on the flame stoichiometry, the release conditions, the vent configuration and the compartment boundary materials. Jet fires combusting in slightly fuel-rich environments generally gave rise to the most severe conditions. Vertical releases resulted in the highest temperatures and heat fluxes at the top of the compartment, whereas horizontal releases gave rise to the most severe conditions towards to bottom part of the hot upper layer. Enhanced air entrainment due to the jet motion was proposed as a reason for the severe conditions observed at this location.

Subsequent to this work, a more comprehensive investigation was undertaken as part of the joint industry project “Blast and Fire Engineering for Topside Structures Phase 2, Test Programme F3” [26] [27] [28]. The fuel used was predominantly condensate (although a propane test was included) and flow rates were between 0.3 kg/s and 1.0 kg/s. Figure 7 shows the reported heat flux values for various locations once steady-state conditions were reached.
A number of the tests included two cylindrical targets instrumented with total heat flux gauges and radiometers. The maximum time-averaged heat flux values reported are shown in Figure 8.

Figure 7 and Figure 8 above should be treated with caution, as the numbers presented do not capture all the differences between tests. For example, some of the tests did not reach steady state due to the activation of deluge.

From the results reported by Chamberlain for both the 135 m$^3$ and 415 m$^3$ compartment studies it is evident that a wide range in heat fluxes to targets and walls within a compartment is possible. The initial heat fluxes in impinged regions are typically in the range of 200 kW/m$^2$ to 250 kW/m$^2$. As the
test progresses the walls and roof heat up until a quasi-steady-state is reached, typically within 10 minutes, after which re-radiation from walls can increase the heat fluxes up to 300 kW/m² to 350 kW/m².

The distribution of heat flux values is strongly dependent on the factors that affect flame temperature, described above. It is worthy of note that the majority of maximum heat fluxes recorded by the targets (which were offset from the walls) were substantially lower than the wall values, with the exception of one test: JF9.

During the test series two unsuccessful attempts were made to recreate the especially severe conditions observed in JF9. It was proposed that the particular combinations of vent configuration, compartment geometry and release conditions combined to give an optimal residency time and flow conditions for the combustion of soot products. This requires temperatures in excess of 1200 °C.

In summary, there is a large variation in the range of temperatures and heat fluxes observed in jet fires within compartments. The majority of heat fluxes recorded in compartment jet fires lie within the range of those measured during studies of unconfined releases in 1988-1992. The spatial distribution of heat flux values will differ significantly, and the confinement will improve stability of the heat flux distributions. Like unconfined fires, peak measurements can reach (and in some cases exceed) 350 kW/m², however the majority of heat fluxes recorded were in the range of 100 kW/m² to 150 kW/m².

The sensitivity of the test conditions to the properties of the compartment, vent and release makes it possible to design test scenarios which are severe by nature, producing substantial areas where heat fluxes are towards the top of the range stated above. In one particular test, especially high (yet reliable) heat flux values were recorded to the targets throughout a large cross-section of the compartment. These conditions were not recreated despite two attempts.

The erosive forces experienced by the PFP are expected to be no more severe than those in the full-scale releases tested as part of the SOFIPP [9], JIVE [29] or JFRT validation [18] programmes. The potential proximity of the compartment edge to the point of release increases the potential for higher velocities at the point of impact, but this will be offset by contact with partially-combusted gas at relatively low temperatures. Lower temperatures have previously been proposed as the reason for reduced erosion in regions of high dynamic pressures.

One note of caution must be added to the above statement. Anecdotal evidence has emerged in recent years that the rate of erosion of intumescent materials cannot be completely separated from the temperatures reached by the material. Compartment fires have the capability to induce higher temperatures in protection systems, and the performance of intumescent systems may be affected as a result.

5.3 NATURAL GAS – BUTANE MIXTURES
A study of jet fires consisting of mixtures of natural gas and butane was undertaken by Shell and British Gas in 1992-1993 as part of the European Community part-funded JIVE project (Hazard consequences of jet fire interactions with pressure vessels) [30] [31].
A series of tests were performed with horizontal releases of natural gas and butane in various ratios. The total flow rate was kept constant at 2.5 kg/s. A cylindrical target was used by Shell to characterise the interaction of flames with objects, and of the tests performed 27 were judged to give good data for analysis.

Details of these tests are not reported here, however Figure 9 shows a summary of the influence of the fuel composition on the heat flux distribution. The y-axis shows the total area (in m²) which exceeds a given heat flux value, as a function of the butane content. This figure should be taken as informative only, as the exact nature of the heat flux distribution will depend on several factors, not least the position of the target in the flame.

It can be concluded from the project results that, despite the difference in flame properties resulting from the different fuel mixtures, the overall severity is no greater than that of the benchmark gaseous test. The distribution of total heat flux values on impinged objects is within the range of values measured in the series of large scale releases performed by Shell and British Gas in 1988-1992, while the increased radiative fraction is offset by the reduction in erosive forces due to lower exit velocities.

### 5.4 CRUDE OIL AND CRUDE OIL-NATURAL GAS MIXTURES.

As part of the “BFETS phase 2” joint industry project, British Gas Research & Technology was commissioned to study jet fires of crude oil and crude oil-natural gas mixtures [32]. A series of 12 horizontal releases were performed, with 6 impinging on an instrumented target. Three ratios of crude oil to natural gas were used, with the total flow rate kept constant at approximately 5 kg/s. The time averaged heat flux values listed in the summary report are plotted in Figure 10.

The results show the presence of time averaged heat flux values that exceeded 350 kW/m², and time averaged radiant heat fluxes up to 250 kW/m². The maximum time-averaged peak heat flux values are notably higher than the values reported during the studies of natural gas and propane releases (or the natural gas and butane mixes) in the early 1990s. Simplified guidance produced since these tests have characterised two-phase releases in more severe terms (e.g. the FABIG design guide [33]).
For the purpose of this report a selection of these tests has been re-analysed to allow comparison of the overall severity of heat flux distribution. The 4:1 ratio oil-gas test impacting on a target at a distance of 15 m has been compared with four 8 kg/s natural gas releases impinging on a target at four varying distances. In all cases the target was a 0.9 m diameter cylinder. The heat fluxes were measured using water-cooled total heat flux gauges.

A simplified analysis of the heat flux distribution was performed by dividing the ‘rolled-out’ pipe surface into a number of rectangular elements, with a heat flux gauge at the centre of each element. The heat flux recorded by the gauge was attributed to the area of the element, allowing a heat flux exceedance curve to be determined. The rolled-out pipe with dimensions and values is shown in Figure 11. The results of this approach are presented in Figure 12. It should be evident that such an analysis gives only an approximation of the heat flux distribution. The number of measurement points is limited and the heat flux will not vary linearly between measurement points. The effects of time variations or skew of the distribution due to instrument failure have not been considered.

Despite the approximations involved, Figure 12 highlights differences in conditions. The area subject to the highest heat flux values (>270 kW/m²) is notably larger for crude-gas mixtures than for the natural gas jet fires reported by Bennett, Cowley et al in 1991. The maximum heat flux values recorded are also higher, with time averaged values in excess of 400 kW/m² present in the crude-natural gas mixtures.
Figure 11: Oil:Gas (4:1) average heat flux values at 15m
Reproduced from [31]
On the basis of the two-phase study results, it is reasonable to conclude that heat flux distributions from two-phase jet fires are significantly more severe than those caused by single-phase fuels (such as natural gas or crude oil) alone. The radiative heat transfer rate also exceeds that of gaseous releases. It is therefore reasonable to conclude that the severity of two-phase tests is likely to exceed that of the full-scale natural gas release used as a benchmark for testing of fire protection systems during the SOFIFF and IJFT validation test programmes.

At the time, it would also have been reasonable to conclude that maximum heat flux values from two-phase jet fires are significantly higher than natural gas jet fires. However, data subsequently generated for gaseous jet fires shows that the difference in time-averaged maximum flux values is less significant than could be concluded from comparison of this project with the values reported by Bennett, Cowley et al (1991) alone. This is discussed further in section 5.8.

![Figure 12: Heat flux exceedance curves for Crude oil-natural gas mixture and selected natural gas tests](image)

### 5.5 JIVE - PROPANE IMPINGEMENT ON PRESSURE VESSELS

In 1995, HSE performed a study at Buxton to characterise and conduct 1.5 kg/s propane jet fire tests of LPG vessels. The work was conducted under project R04.029 [29], as part of the CEC-funded JIVE project [31]. Calorimeters installed in a cylindrical target gave a heat flux of 190 kW/m² to
200 kW/m² on the top, front and back; the heat flux measured on the bottom was 120 kW/m² to 130 kW/m². These values are similar to the values reported by Cowling [8], and do not change our understanding of conditions in propane jet fire engulfment. The tests are worthy of note, however, because direct comparison was made between an intumescent and a cementitious system in full-scale and medium-scale tests. The full-scale tests used instrumented 2-tonne LPG vessels whereas the medium-scale tests used the JFRT box configuration test. The project concluded that the two set ups showed comparable performance and that the jet fire test is therefore applicable for LPG scenarios.

5.6 NATURAL GAS RELEASES ONTO FLAT PLATE

British Gas Research and Technology undertook a testing programme in 1996 to investigate the effect of numerous parameters on the characteristics of natural gas flames. As reported by Gosse and Pritchard [34], the parameters included: confinement, stand-off distance, mass flow rate, exit pressure, orifice diameter and wind speed. The test configuration differed from the majority of other large-scale jet fire tests, in that the vertical jet impacted on a large flat surface. The sonic natural gas releases studied covered a range of pressures up to 116 bar and mass flow rates up to 3.13 kg/s.

In their conclusions, Gosse and Pritchard state that varying the release pressure whilst maintaining the same mass flow rate has no significant effect on the results. A selection of results presented in the summary report show a relatively small change to the dynamic pressures measured by pitot tubes at varying distance from the release point. It should be noted the report states this conclusion was based on investigation of a limited number of tests at pressures up to 40 bar and at a short stand-off distance (2m) which gives flame stabilisation on the target. It is unclear whether the 116 bar releases at greater stand-off distances also support this conclusion.

Increasing the mass flow rate was found to increase the maximum heat flux and delay the radial decay in heat fluxes from the point of jet impact.

In this study, the jet impacted onto a large flat target. This produced flames which were optically thin compared to those in most other studies, where a free-flame release typically engulfed an object. Although there was a relatively small range of mass flow rates in this study (relative to free-flame studies) it is clear that the mass flow rate was of greater significance in this particular test configuration than for relatively small objects fully engulfed in free-flame releases. Increasing mass flow rate increased both the optical thickness of the flame and the dynamic pressures.

Partial confinement was achieved by varying the height between the impacted surface and the floor. The overall heat flux distribution was found to vary little, although it was noted that the radiation-convection balance could alter, as increased partial confinement leads to higher gas temperatures and lower velocities.

The stand-off distance was found to have a significant effect on the heat loading to the target. At the highest stand-off distance tested the flame was observed to have stabilised in the jet prior to impact. This resulted in the highest heat fluxes being recorded close to the point of impact. Shorter stand-off distances resulted in flame stabilisation on the target and produced lower maximum heat flux values, and pushed the location of maximum heat flux radially away from the point of impact.
5.7 ‘LIVE CRUDE RELEASES’ AND CRUDE RELEASES WITH SIGNIFICANT WATER CONTENT

In 2000 British Gas R&T published a report on large scale experiments to study jet fires of crude oil / gas / water mixtures [35]. The work was undertaken jointly by Shell Global Solutions and British Gas Technology at the Spadeadam test facility.

The project was divided into two phases. Phase one investigated the characteristics of releases designed to simulate ‘live’ crude oil, either by pre-mixing natural gas, propane and crude oil or by simultaneous separate release. Flow rates of 3.5 kg/s to 7.5 kg/s were achieved at discharge pressures ranging from 20 bar to 90 bar. Oil to gas ratios were approximately 13:1 or 4:1 by mass. The thermal response of impinged objects was measured through the use of a 0.9 m diameter pipe placed 15 m from the point of the release. The pipe was instrumented with a total of forty heat flux calorimeters, two radiometers and thermocouples.

Of the eight tests performed in phase 1, six gave usable data on the heat flux to impinged objects. Figure 13 shows the reported maximum time-averaged heat flux values.

![Figure 13: 'Live' crude releases, selected results at 15 m](image)

It is important to appreciate that results in Figure 13 are a simplification of the conditions experienced by the target. More detailed analysis of the heat flux distribution across the target in two of the above tests (I-02 and I-05), shown in Figure 14, indicates the heat flux distributions recorded were broadly similar to those reported by Cowley for natural gas fires, however the maximum time-averaged values were generally higher for live crude than for natural gas tests.
Figure 14 is a simplified analysis, and does not take into account fluctuations in time due to wind. Closer analysis of individual calorimeter traces reveals a large spread in values recorded. As per previous studies, instantaneous values significantly higher than the time-averaged values are seen. Figure 15 shows selected calorimeter traces at the centre of the pipe for test I05. Instantaneous values in excess of 400 kW/m² were recorded, however time averaging reduced these to 210 kW/m² to 310 kW/m².
In summary, the results from ‘Live’ Crude oil jet fires without water complement those from previous studies of crude oil-natural gas tests, confirming the increased potential for severity levels associated with a combination of significant momentum, and a sooty, highly radiative flame.

Numerous instantaneous peak heat fluxes in excess of 400 kW/m² were recorded, but time averaged values were much lower, as previously reported. This behaviour is typical of flames that produce large quantities of smoke. The noise seen in calorimeter readings is similar in nature (although the readings themselves are dissimilar in magnitude) to that observed in other heavy hydrocarbon fire studies.

Phase two of this test series studied releases of live crude with water cuts of up to 120 % by mass of crude. Small water cuts (20 % - 40 %) can suppress smoke formation and increase the radiative fraction of the total heat flux to engulfed objects, however as concluded by Hankinson et al. in [37]: “Overall, the heat loading to the pipe target was reduced by the presence of water”. For this reason, it is reasonable to assume that liquid and two-phase jet fires with water cuts do not represent a more significant hazard than equivalent jets without water, and they are not considered further.

5.8 NATURAL GAS (FURTHER STUDIES)
The EC funded NATURALHY project (WP2) investigated the jet fire characteristics of mixed natural gas and hydrogen. As reported by Lowesmith, [38] [39], six tests were conducted. The first three involved the release of natural gas only, the second three were a mixture of natural gas and hydrogen, the latter approximately 24% by mass.

The natural gas releases were performed at pressures of 60 bar through hole diameters of 20 mm, 35 mm and 50 mm. The heat flux to impinged objects was measured using a 0.9 m diameter pipe instrumented with forty water-cooled heat flux gauges (as per the crude tests discussed above).
Mass flow rates for the three tests were reported as 2.9 kg/s, 9.6 kg/s and 19.5 kg/s respectively. The instrumented pipe was positioned at a point anticipated to be in the middle of the flame, at a distance from the release point of 9 m, 15 m and 21 m for the three hole diameters stated above.

The first test performed is of particular interest because it is functionally identical to the 3 kg/s sonic natural gas release reported by Bennett, Cowley et al (1991) that was used as the basis for validation of the jet fire test through full-scale testing of PFP material response.

Figure 16 below shows the spatial distribution of heat fluxes recorded for the 3 kg/s natural gas test at distance of approximately 9 m as reported by Lowesmith [38]. The majority of time-averaged heat flux values in the engulfed region lie within the range 150 kW/m² to 250 kW/m². However, there is a significant difference between the Lowesmith and Cowley results regarding the maximum time-averaged heat flux values.

![Figure 16: NATURAL HY Gas test 1 heat flux distribution: 60 bar, 3 kg/s, target at 9 m](Reproduced from [38])

Values of up to 380 kW/m² were reported in the 2008 tests, compared with a maximum of 280 kW/m² reported by Cowley. The release conditions were almost identical, and the instrumentation also similar. Therefore the difference between readings must be attributable to the inherent variability of large open flames and their sensitivity to atmospheric conditions, the natural variation in results obtained when measuring a complex phenomenon at only a small number of positions across a large surface, and differences in interpretation of results and reporting.

The potential for the highest time-average heat fluxes recorded in 2008 to have also been present in the 1991 tests is indicated by Cowley in comment that instantaneous readings in excess of 350 kW/m² were observed. However, it is likely that the highest values were not sustained in regions that coincided with calorimeter positions.

Time-averaging can be excluded as the primary cause of the difference in maximum heat fluxes reported in 1991 and 2008. The period of time averaging used for the 2008 test was from 50 s to
90 s (a period of 40 s) [40]. The time period for averaging in the pre-1991 tests was reported as being typically one minute. It is recognised that increasing the period of time-averaging typically reduces the values obtained, however a trace of selected calorimeters from the 2008 test is shown in Figure 17 and shows that the difference made by selection of the time averaging period for the recent test is relatively minor.

The second and third natural gas releases in the NATURALHY project did not replicate scenarios tested in the early 1990s. Test 2 had a flow rate similar to that obtained in previous tests, however these previous flow rates had been achieved through lower pressures (approximately 10 bar) and larger discharge diameters (75 mm). Test 3 had a flow rate double the previously reported maximum for a test that included a well-instrumented target. The heat flux distributions for tests 2 and 3 are shown in Figure 18 and Figure 19.

Test 2 produced a similar heat flux distribution to that reported by Cowley for an 8 kg/s natural gas release. Maximum time-averaged heat flux values in the more recent tests are somewhat higher, attributable to the increased higher flow rate and the higher release pressure, increasing convective heat transfer due to higher velocities at a distance of 15 m.

Test 3 produced a significantly more severe heat flux distribution than had been reported previously by Cowley for a target at a similar distance in tests conducted at lower flow rates. Sustained adjacent areas of heat flux measurements above 335 kW/m² were present along the top of the pipe.
The radiative heat flux measurements on the target for the 3 tests are given in Table 1.

**Table 1: NATURALHY Gas tests radiative flux values**

<table>
<thead>
<tr>
<th>Test</th>
<th>Average heat flux (kW/m²)</th>
<th>Front</th>
<th>Top</th>
<th>Back</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>121</td>
<td>58</td>
<td>54</td>
<td>185</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>145</td>
<td>99</td>
<td>145</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>122</td>
<td>161</td>
<td>148</td>
<td>109</td>
<td></td>
</tr>
</tbody>
</table>
Direct measurements of the radiative heat flux do not show a significant difference between the maximum radiant heat input between tests. These results should be used with caution, as only four radiometers were used and they were positioned close to the centre line.

Analysing the data reported by Lowesmith by the same methodology applied to the crude and Cowley tests in section 5.4 gives a heat flux exceedance curve by cumulative area as shown in Figure 20. The heat flux distributions differ in severity. Part of this difference can be attributed to instrumentation spread over a greater area in the early tests reported by Cowley, thus concentrating the measurements in areas of higher heat flux. However, even when this difference is accounted for it remains evident that the 3 kg/s release reported by Lowesmith shows a more severe heat flux distribution than reported in earlier tests at similar (or somewhat higher) flow rates. The 20 kg/s release studied by Lowesmith shows a heat flux distribution to a target more severe than any previously reported unconfined jet fire test, with areas of high heat fluxes notably larger than those observed in the two-phase releases studied a decade before.

![Figure 20: Heat flux exceedance curve for selected tests, including NATURALHY tests (2008)](image-url)
In summary, during 2008 a repeat was performed of the important 3 kg/s natural gas release used as a benchmark scenario to validate the jet fire test procedure. Significantly higher maximum heat flux values were reported in the repeat test than were reported by Cowley in the early 1990s.

The natural gas releases performed as part of the study have confirmed the presence of high time-averaged maximum heat flux values across a wide range of flow rates. Higher flow rates have been shown to be capable of producing a substantial increase in the severity of the heat flux distribution, however the magnitude of the time-averaged maximum values varies less substantially.

5.9 NATURAL GAS – HYDROGEN MIXTURES

It is not considered necessary to go into detail on mixtures of natural gas and hydrogen in this report. Instead the reader is referred to the publication by Lowesmith [39]. Significantly higher heat fluxes were recorded, and the heat flux distribution appears to sustain the view that the test severity exceeds that of natural gas releases alone. The increase in heat flux was primarily attributed to convection, related to increased exit velocities due to the increased speed of sound in the mixture. It is reasonable to assume that the erosive forces on PFP materials would exceed those in the natural gas benchmark case. The JFRT method should not be considered validated for natural gas and hydrogen mixture jet fires.

5.10 RELEASES CONTAINING PARTICULATES (E.G. SAND)

Releases of any fuel type containing solid particulates remain completely untested. These would act to provide additional physical erosion of a PFP material and the JFRT cannot be considered validated for such scenarios. Further study of the issue is recommended.
6. CHARACTERISTATION OF JET FIRES

The large variation in heat flux distributions and erosive forces described in the previous sections make it exceedingly hard to characterise a jet fire in simple terms. Despite this, the desire for simplified guidance within industry has led to publication of categorisation of fires in terms of heat fluxes. One example of this is given in Figure 21. Another example is the use of heat flux in tables 4.2-4.9 in FABIG TN13 [33].

![Figure 21: Simplified characterisation of jet fires, reproduced from Norsok S-001 [5]](image)

It is outside of the scope of this report to comment on the specific content of such tables, and the author of this report acknowledges the tremendous effort and difficulty involved in producing guidance such as the tables in FABIG TN13. This report is concerned with the appropriateness of using such tables when specifying PFP systems and, in particular, whether they are appropriate for deciding the applicability of any particular test method.

The purpose of simplified guidance in documents such as Norsok S-001, FABIG TN13 or other sources must be understood. Guidance is provided as a means of allowing industry to assess the fire hazards that may be present in a particular facility. Such guidance usually includes information on flame characteristics such as shape, size, temperature and the surface emissive power, as well as values for heat transfer to engulfed objects [41]. The guidance is not intended to be taken as definitive of the wide range of conditions that can occur in jet fires. Any values given are intended to simplify the wide range of conditions that occur across numerous release conditions and within a single test. They take no account of the target geometry or position, nor the spatial and time variance of results. The simplification is demonstrated in Figure 22 and Figure 23, provided by B. Lowesmith [40]. The spread in maximum peak heat fluxes that are recorded across similar fuels and flow rates is extensive. Both figures show that the maximum values recorded exceed the guidance in a large proportion of cases.

As stated above, simplified guidance is a useful tool for industry to assess hazards in general terms. The problem lies not with the existence of such guidance, nor with particular values stated (as there is no single value that could be considered solely correct, and even stating a range cannot capture the complexity of flux distributions). Instead, the problem lies with application of such guidance.

From the examination of data available from jet fires, it should be concluded that it is misleading to focus solely on maximum heat flux values when considering PFP response and the specification of PFP materials for jet fire. The characterisation of severity of a jet fire, in terms of PFP response, simply on the basis of a single heat flux value must be rejected.
There is no adequate substitute for a detailed characterisation of the severity of a jet fire from the point of view of PFP response, and hence for determining test method applicability, including a full description of the fuel type, release pressure, hole diameter, distance to target and degree of confinement.

**Figure 22:** Maximum heat fluxes reported for a range of tests, taken from [40]

**Figure 23:** Comparison of simplified guidance and the maximum heat fluxes reported in the NATURALHY project taken from [40]
7. DISCUSSION ON THE APPLICABILITY OF THE JFRT / ISO22899 TEST

7.1 GENERAL CONSIDERATIONS
The JFRT box configuration has been shown to reproduce both the PFP response and steel temperature rises observed in equivalent I-sections located 9 m from a benchmark ‘full-scale’ 3 kg/s sonic natural gas release.

The release was chosen as a benchmark due to the combination of high erosive characteristics and severe heat flux distributions. Velocity and dynamic pressure measurements are not extensive, but 90 m/s and dynamic pressures of potentially 500 Pa to 900 Pa are considered representative of 9 m from the point of release.

The original work reported by Cowley indicated time averaged maximum values for this test of approximately 280 kW/m², with instantaneous heat flux in excess of 350 kW/m². Subsequent work by Lowesmith et al. has reported highly localised maxima of 380 kW/m², for the same release conditions.

It is impossible to recreate the exact range of conditions found in any single full-scale release on a smaller test scale. The validation of the JFRT by the original jet-fire working group was not based on the criteria of replicating a particular heat flux value, or any other single value relating to a specific aspect of the test. It was based on recreating representative conditions to achieve a level of severity commensurate with that of the full-scale benchmark release.

The JFRT was designed to give a combination of erosive forces and heat fluxes that together test a PFP material level of severity representative of the benchmark release. It was demonstrated adequately that this is the case for the box configuration. Therefore, when considering the validity of the jet fire test for alternative scenarios, the question is not whether the test can be shown to be directly representative of alternative full-scale releases, but whether alternative full-scales releases are of such differing severity to the benchmark case that PFP materials will be expected to perform less effectively.

In determining the severity of jet fire scenarios to an object protected with PFP the following criteria are important:

- The heat flux distribution
- The radiative-convective balance and the flame temperatures
- The erosive forces imparted by local gas velocities
- The erosive forces imparted by droplets or particulates in the flow
- The duration of the test
- The stability and reproducibility of the fire

The applicability of the benchmark test, and by extension the JFRT, to represent conditions in alternative jet fire scenarios is considered below.
7.2 UNCONFINED GASEOUS RELEASES AT FLOW RATES UP TO 3 KG/S, AT RELEASE PRESSURES NOT EXCEEDING 60 BAR

The jet fire test and jet fire test procedure can be considered as validated for any natural gas release at lower flow rates or lower pressures, for either horizontal or vertical releases, in the absence of confinement.

7.3 UNCONFINED NATURAL GAS RELEASES EXCEEDING FLOW RATE OF 3 KG/S, AT RELEASE PRESSURES NOT EXCEEDING 60 BAR

Higher flow rates will lead to larger flames, and hence an increase in the overall radiative heat transfer to an engulfed object. However, the instantaneous peak heat flux values vary little. Even releases considered small by current guidance (up to 3 kg/s) create flames long enough for an area on an engulfed target to ‘see’ a volume of flame with an optical path length corresponding to an effective flame emissivity of 1. Test evidence generated in the NATURALHY project showed the potential for time-averaged peak heat fluxes in the region of 350 kW/m² to 400 kW/m² for releases no bigger than the benchmark test.

The primary effect of increasing flow rate is to increase flame size and therefore to increase the probability that a given area on the target receives high levels of incident radiation. The effect on the magnitude of the peak incident radiative heat flux is less significant, as this is related to the fundamental combustion properties of the fuel. Quantifying this effect is difficult due to the inherent limitations in instrumentation density, and the high sensitivity of the flame to atmospheric effects.

Despite the peak heat flux values changing relatively little, the experimental data shows that increasing flow rate does increase the severity of the heat flux distribution, which will inevitably lead to an increase in the rate of average temperature rise of the substrate. The increase in area exposed to higher heat flux levels will also reduce the capacity for internal heat dissipation within the substrate and cause the maximum rate of temperature rise to increase, although this will be to a lesser extent.

The effect of increasing the severity of the heat flux distribution on the response of PFP materials, or substrate temperature rise when protected by PFP materials, cannot be quantified at present due to the inherent variation in jet fires and the limitations in test evidence. However, there is evidence to suggest that a change in the magnitude of heat flux alone would not lead to a significant difference on PFP response. Furnace-based tests developed for simulating fires in tunnels expose PFP materials to temperatures in excess of 1300 °C. A large number of systems, including many used in the oil & gas environment, have been shown to be capable of surviving in a relatively homogenous 350 kW/m² environment in the absence of erosive forces. Clearly, such tests are not directly applicable to jet fire scenarios for numerous reasons, however they act to demonstrate that erosive forces are of primary importance in the jet fire test and an increase in average heat flux levels alone does not automatically mean the PFP will catastrophically fail.

The radiation-convection balance must also be considered, as it will have a significant influence on the rate of temperature rise for substrates protected by PFP. As the surface of the PFP material heats up, the rate of convective heat transfer decreases in proportion to difference between the fire and PFP surface temperature. The rate of radiant heat transfer decreases more slowly, in a non-
linear manner. After just a few minutes of exposure the insulation surface temperature is likely to be in a quasi-equilibrium state and radiation will become the dominant method of heat transfer to the target. Hence the rate of temperature rise will be driven by the flame temperature, flame emissivity and the degree of smoke obscuration, regardless of the initial total heat flux values.

Both the erosive forces and radiative fraction of the total heat transfer can be considered to be no more severe than the benchmark test for gaseous releases of higher flow rates at release pressures of up to 60 bar. It is recognised that more severe total heat flux distributions will give rise to increased rate of temperature rise, however the jet fire test is not a test of the average rate of temperature rise, nor is it designed to give an exact indication of the rate of temperature rise in any real-life scenario. It has been validated on the basis of a single-point of failure corresponding with an equivalent single point of failure in a full-scale test. Therefore, the test method is inherently conservative when considering average substrate temperatures, and should only be considered inappropriate if it is being used in a situation where PFP exhibits a significant difference in performance, such as catastrophic failure, or a significant difference in the rate of peak temperature rise.

This report concludes that it is therefore reasonable to assume that tests of natural gas at pressures up to 60 bar are unlikely to result in a significant difference in PFP material response regardless of flow rate. Therefore, it can be reasonably assumed that the benchmark test, and by extension the JFRT, is applicable to such scenarios. This conclusion is reached in recognition of the fact that the rate of temperature rise for such scenarios will inevitably be higher. However, such increases may or may not be relevant depending on the transient nature of the flow rate and the type of substrate. If identified as a concern, such rises could be accommodated through substrate redesign or PFP system redundancy.

The above conclusion must be qualified, as it is based on the assumption of no relationship between the heat flux distribution (and hence maximum PFP surface temperature) and erosion rate of the PFP. For certain types of materials, such as epoxy intumescents that undergo complex chemical and physical changes during fire exposure, this assumption may not be correct. Further work is recommended to quantify the significance of the change in rate of temperature rise associated with larger releases, and to investigate whether there is a relationship between erosion and thermal conditions for epoxy intumescents.

7.4 UNCONFINED SONIC GASEOUS RELEASES AT PressURES EXCEEDING 60 BAR

The exact position within a natural gas jet flame that presents the most severe test for PFP is difficult to predict, and may vary for different types of protection systems. It will always be possible to identify a range of positions that could increase the severity of one aspect of the test. For example, a position near the start of the turbulent combustion zone could give the greatest erosive forces, near the middle could give the greatest average flux density and near the end of the flame could give maximum local radiative flux. One single test cannot be expected to represent the worst case for all aspects of a test (indeed this would be unrepresentative, as well as overly conservative). It must instead seek to represent a reasonable balance of the factors that cause failure, with focus on the most critical. For the jet fires this is clearly erosion.
Sonic flow of gases is choked, limiting the exit velocity to the speed of sound for the medium. Therefore, erosive forces caused by dynamic pressures can be related to the distance from the point of release. The benchmark test used a distance of 9 m, giving predicted gas velocities in the region of 90 m/s. Shorter distances would give higher velocities, however the luminous yellow part of the benchmark flame appears at approximately 8 m and the erosion rate is expected to drop once partially un-combusted gas impinging on the target reduces the PFP temperature. The benchmark set-up was considered to approximate the worst case scenario with respect to erosion. As summarised by Acton, White and Shirvill in 1998 [42]: “The release was at the highest pressure studied, and consequently maintains higher velocities over a greater distance.”, and “Similar considerations led to the distance from the release hole to the target being the closest characterised in the previous work (9 m), where the gas velocities and hence the erosive effect, would be greater than for positions further away”.

A lack of published test evidence at pressures exceeding 60 bar makes it difficult to reach conclusions regarding the applicability of the jet fire test to higher pressure release scenarios. Higher pressures will sustain higher velocities for greater distances along the flame length, potentially increasing the convective heat transfer. The concern is not an increase in peak erosive forces, but the possibility for high erosive forces to be maintained at an increased distance along the turbulent combustion zone towards locations of increased severity of heat flux distribution.

This report asserts that no firm conclusion can be drawn regarding the applicability of the test to gaseous releases that exceed 60 bar. The previous section concluded that more severe heat flux distributions alone are not sufficient to conclude significant departure from the benchmark test conditions, however the possibility of high erosive forces occurring in areas with a more severe heat flux distribution is likely to be more critical.

It should be stressed that the erosive forces will not exceed levels similar to the benchmark test, and there is no current evidence that the JFRT is not applicable. However, in the absence of supporting data the recommendation from the previous section for further work to assess the relationship between material erosion resistance and heat flux distribution is equally relevant to gaseous releases exceeding 60 bar.

It should be noted that high pressure releases are likely to be transient in many cases. It is recognised that the potential exists for higher erosion rates, however the relevance of this should be considered in engineering terms. Inorganic PFP materials such as blankets or cements generally show good resistance to erosion and may withstand higher rates of erosion successfully for short periods. Intumescent materials can be more susceptible to erosion, but this effect is largely seen at higher temperatures.

7.5 UNCONFINED SONIC FLASHING LIQUID (PROPANE, BUTANE, CONDENSATE) RELEASES – HIGHER FLOW RATES
Flashing liquid releases have been studied extensively up to flow rates in excess of 20 kg/s. The lower exit velocities compared to the benchmark test generally result in lower convective heat fluxes to engulfed objects and lower erosive forces. Comparative full and medium-scale validation testing has been performed. Flow rates higher than ones tested may increase the areas exposed to the
upper range of heat fluxes observed, however the erosive forces will remain lower than the benchmark test. It is reasonable to conclude the JFRT is applicable to flashing liquid scenarios regardless of flow rate, on the basis of lower erosive forces.

7.6 CRUDE OIL RELEASES
In 1998 it was stated by Acton, White and Shirvill in their summary of the applicability of the jet fire test [42] that: “The thermal properties of jet fires of higher liquid hydrocarbon fuels such as crude oil, or jet fires fuelled by a mixture of natural gas and liquid higher hydrocarbon fuels, may be significantly different from those of the gaseous fuels studied, and may be more severe.”

A body of test evidence relating to crude oil releases or crude oil mixtures has now been accumulated. In general, crude oil only releases do not display more severe heat flux distributions than the gaseous releases studied beforehand (and since). The nature of the fuel increases the effective flame emissivity; however, this is offset by lower convective heat fluxes associated with lower exit velocities and by smoke acting to shield of the target from radiation coming from further away in the flame.

The erosive forces associated with liquid releases cannot be directly related to the local gas velocity in the way gaseous releases or flashing liquids can, due to the potential effects associated with liquid impact. The momentum associated with liquid droplets could give rise to greater erosion, despite the reduced velocities. Penetration of the surface of the PFP material could potentially change the structure of the material, or cause internal pressures on vaporization that would promote fissures and cracking.

This report concludes that the thermal properties of crude-oil jet fires have been shown to be comparable to gaseous releases with respect to PFP testing. However, it cannot be stated that the test is validated against the effects of liquid impingement, and it is therefore recommended that the industry acts to generate data for such scenarios. It is reasonable to use the current jet fire test method for crude-oil releases in the interim, in the absence of test data relating to liquid impingement, based on the thermal properties of such fires.

7.7 TWO-PHASE RELEASES (LIVE CRUDE, CRUDE-NATURAL GAS MIX)
Experimental studies have shown that two-phase releases combine the high convective fluxes associated with momentum-driven gaseous releases with the high radiant heat fluxes associated with higher molecular weight hydrocarbon fuels. The heat flux distributions appear to be more severe than gaseous releases of equivalent flow rate, in that the proportion of the target subject to areas of high flux is greater than corresponding gaseous tests, despite local maximum heat flux values being reasonably similar to those in gaseous tests. Of further concern is the increased radiative fraction of heat transfer. This is likely to lead to a higher quasi-equilibrium surface temperature of PFP, which may in turn lead to material specific changes in behaviour (as discussed previously).

Looking at heat flux measurements alone, it can be concluded that two-phase scenarios would result in a higher average rate of substrate temperature rise than gaseous releases of equal flow rate.
However, the jet fire test is not a test of average material temperature rise, but of peak temperature rise. It is unknown whether the maximum rate of temperature rise recorded by a protected substrate in a two-phase release would differ significantly from the maximum rate of rise recorded by PFP protected substrates in the benchmark gaseous test. As discussed previously, it cannot be concluded that the current jet fire test is either representative or unrepresentative of two-phase releases on the basis of the heat flux measurements alone.

Studies of two-phase 5 kg/s releases typically recorded the most severe heat flux distributions at a distance of 9 m. The natural gas benchmark test is expected to produce a more severe heat flux distribution closer to 15 m, but was performed at 9 m because sacrificing the potential for maximum peak heat fluxes for increased erosion was judged to be a worst-case scenario. The data from the two-phase tests studied since then indicates that targets engulfed in two-phase releases would experience both highest erosion and the most severe heat flux distribution at a distance approximately 9 m from the flame.

Further concerns raised by Acton, White and Shirvill in 1998 regarding the erosive effects of droplet impingement or droplet penetration remain equally valid today.

For the reasons above, this report concludes that benchmark gaseous test, and by extension the JFRT, cannot be reasonably assumed to be representative of two-phase releases. This report recommends that experimental data regarding the response of PFP in such scenarios is generated.

7.8 CONFINED RELEASES OF GASEOUS OR FLASHING LIQUID FUELS

In their 1998 paper on the applicability of the jet fire test Acton, White and Shirvill concluded: “Confined fire may produce higher total heat fluxes, but in practical situations of partial confinement, conditions are unlikely to be produced which are a significantly more severe test of PFP than the unconfined large scale test (and hence the jet fire resistance test)”.

No further experimental data has been published for confined jet fires since this statement was written, and the conclusion remains equally valid today. The body of test evidence for confined jet fires is based on natural gas, condensate and butane fuelled releases. The majority of tests recorded heat fluxes similar to the unconfined releases reported in the preceding years. There was one test (JF9), in which particularly high flame temperatures and heat fluxes were recorded. Reasons for this were proposed relating to residence times of soot being sufficient for oxidation to occur at temperatures in excess of 1200 °C, however the exact conditions were not recreated. It was observed that a couple of further tests reached conditions close to the onset threshold of soot oxidation, which raises the question of whether longer duration tests may have resulted in consistently more severe conditions for a number of release and compartment configurations.

The existence of JF9 presents a dilemma for anybody seeking to agree on a standard test methodology, which is: if a distinctly more severe set of conditions is capable of arising, but these are unlikely to occur and cannot be recreated with any degree of certainty in practical testing, should a test standard then seek to represent these conditions?

It is the opinion of the author of this report that test standards should not be designed for worst-case scenarios, as the cost to industry would be disproportionate in the majority of situations. Such
conditions are best handled through engineering judgement, based on the critical application of such test results and the adoption of other measures as deemed appropriate.

Putting aside philosophical questions about whether extreme events should form the basis of specification and test design, this report agrees with the conclusions of Acton, White and Shirvill stated above. It cannot be concluded that the JFRT is representative of all possible confined jet fires, however the majority of practical scenarios that involve the fuels listed should not present a level of severity that is significantly different from the range of unconfined releases tested, from the point of view of PFP material response.

Should a particular scenario arise in which engineers predict that conditions similar to those experienced in JF9 may occur, then it is reasonable to ask whether a protection system is capable of resisting such conditions. However, given the difficulty shown in replicating the conditions experimentally there is a large degree of uncertainty as to whether those conditions can be defined, predicted or tested with precision. Detailed quantification of protection systems under such conditions is therefore likely to be of little value. A pass/fail test that fundamentally shows the ability of the material to survive the increased temperatures associated with soot oxidation in compartments would be of more use. A test method currently being developed by SP research (formerly SINTEF) shows promise for recreating such conditions.

It should be noted that prediction of conditions within compartments is not trivial. Advances in CFD modelling of compartment fires in the last 20 years may have improved our ability to predict the conditions arising in jet fires (in confined and unconfined scenarios). However, the results of CFD studies are too often accepted without challenge and without appreciation of the limitations in the validation of the underlying sub-models. Regardless of accuracy, the output of any CFD simulation is extensive, yet there is very little guidance available on how to interpret and apply the results. It is cautioned that heat flux values to engulfed objects provided by CFD programmes suffer the same problem as heat flux values produced by simplified guidance, or by analysis of just a single test, in that heat flux distributions are complex and do not reflect the overall severity of the test when used in isolation. While recognising heat flux outputs by CFD may be of use in characterising a fire hazard, the present use of such values as a means of specifying PFP, or in determining the applicability of a PFP test method, is rejected by this report.

7.9 NATURAL GAS – HYDROGEN MIXTURES
Relatively recent work has shown mixtures of natural gas and hydrogen to be significantly more severe than equivalent natural gas releases. The higher exit velocities will increase both the convective heat transfer and the erosive forces. This report concludes the JFRT should not be considered applicable for such scenarios unless specific evidence is generated to show its applicability.
7.10 CRYOGENIC JETS OF LIQUEFIED NATURAL GAS
A topic of current importance to industry is the response of substrates and protection systems to spills of liquefied natural gas (LNG). LNG releases can be in the form of high pressure releases, giving rise to flashing liquid jet fires.

Flashing liquid releases are shaped by buoyancy to a greater extent than gaseous releases, and velocities at the point of impingement will typically be lower than for momentum driven gaseous releases. The heat flux distribution over an engulfed object can be expected to be reasonably similar to the range of conditions seen within gaseous releases.

However, the effect of the presence of liquid droplets is not a simple consideration. The increased momentum associated with liquid droplets could give rise to increased erosive effects. Conversely, the presence of a cool liquid core impinging on a target may act to reduce erosion effects due to the PFP material being cooler in this zone. A cool zone may also give rise to increased temperature gradients and affect the performance of the system at the edges where the gradient is highest.

It is recommended that the industry acts to generate data to assess the severity of impinging jet fires fuelled by cryogenically stored gases.
8. DISCUSSION ON THE NEED FOR A SUPPLEMENTARY (“HIGHER HEAT FLUX”) TEST

In this report, numerous scenarios have been identified to which the JFRT can be considered applicable. Some scenarios have been identified where there is a reasonable assumption of applicability but further confirmation work is recommended, and some scenarios have been identified to which the existing test cannot be reasonably assumed to be applicable.

A question of importance to industry at the time of writing is whether work needs to be done to standardise a more severe jet fire test. This report concludes that at present the answer is no, and that such work is currently premature.

Predictable increases in the rate of average substrate temperature rise under more severe heat flux distributions do not justify the development of a new test method if the material behaviour is similar and the change in rate of maximum temperature rise is not significant. Such differences can be handled through engineering approaches or redundancy built-in to the PFP specification.

This statement should not be taken to imply that the current test methodology is completely adequate. On the contrary, test evidence since the finalisation of the IJFT supports concerns relating to two-phase releases, and questions remain over the relationship between more severe heat flux distributions and erosion for certain types of PFP materials.

The reason for concluding that it is premature to implement a further standard test method is because there is no test evidence to suggest that PFP materials would perform significantly differently in the alternative scenarios described, nor is there clarity over what factors would cause any differences in performance.

A first step must be to generate test evidence to understand the types of scenarios that give rise to a difference in performance, and the modes of failure that occur.

Only if a more severe benchmark scenario can be identified, a difference in material response established, the mode of failure characterised, and the test conditions characterised in detail (including erosive forces), should consideration then be given to development of a new test method.

This report rejects the notion that alternative medium-scale test methods are automatically representative of more severe real-world scenarios simply because PFP systems demonstrate inferior performance in the test. Characterising the hazard scenarios concerned is challenging, and severity of test is a complex issue. It is not necessarily correct to assume that the current JFRT is not applicable to a range of jet fire scenarios on the basis that a different, unvalidated medium-scale testing regime produces different results. At present no test other than the standard JFRT has been validated as being representative of a particular jet fire hazard scenario.

This report rejects moves to develop a medium-scale test without a clear understanding of the real-life scenario it seeks to replicate. Without such a link validation of the test is clearly impossible.
Further, this report rejects moves to develop a test based solely on a single peak heat flux value, for the same reasons that it rejects characterisation of jet fires in terms of a peak heat flux value alone. Actual flux distributions are complex, and instantaneous maxima are present in tests that do not represent time and spatially averaged values. Maximum flux values are an important part of defining a medium-scale test severity, but achieving an equivalent severity level cannot be based on a peak heat flux alone. The heat flux distribution, the radiative component and the erosive forces are all highly important. Achieving an appropriate degree of severity on a reduced scale requires a confluence of erosion, convection and radiation loads.
9. CONCLUSIONS

A supplementary standardised jet fire test method should not be developed until there is a fully characterised full-scale benchmark test that can be used for validation purposes. There is currently no evidence that PFP materials will respond differently in the potentially more severe scenarios identified. Only if a clear difference in PFP response is identified in a well-characterised benchmark case should development of a test method be considered.

Simplified guidance that characterises jet fires in terms of a maximum or average heat flux has a useful role to play in the industry, however jet fires should not be characterised in terms of a heat flux as a means of specifying PFP or as a test methodology for jet fires.

Alternative fuel types, or larger flow rates, will increase the severity of the overall heat flux distribution, however the peak values are shown to increase relatively little. Time averaged values at positions of local maxima increase somewhat, but the main effect is an increase in the area of the target subjected to the higher heat flux values.

The JFRT is based on the peak rate of temperature rise, and is not concerned with average heat flux or solely peak heat flux. Instead, it is the confluence of erosive forces and heat fluxes together that produce failure. In many cases the failure seen can be described as sudden, with the protection system being catastrophically damaged or stripped away by the combination of high erosive forces and temperature-induced material property changes.

The JFRT was not validated up to a certain heat flux threshold or a particular gas velocity. The validation procedure compared it to a benchmark release with a much wider distribution of heat fluxes and higher gas velocities. It must therefore be considered validated against a scenario.

The validation was through comparative testing of protected sections in the full-scale and medium-scale set-ups. The validation performed has limitations, and some test results were inconclusive, however the consensus at the end of the programme was that the test configuration had been demonstrated to be representative of the full-scale benchmark test.

It was not practical to validate the jet fire test for a wide range of jet fire scenarios. Instead assessing the applicability of the procedure to alternative scenarios requires comparison of the conditions in the scenario with those in the benchmark test.

Scenarios for which the jet fire resistance test is applicable:

- The current jet fire test method can be reasonably assumed to be representative of the conditions associated with natural gas releases at pressures up to 60 bar irrespective of flow rate. Gaseous releases at such pressure will produce erosive forces similar to the benchmark scenario and no significant difference is expected in PFP response. It is recognised that a significantly larger release will inevitably result in an increased rate of temperature rise, however such effects are typically transient and can be handled through an engineering approach if deemed necessary. Variation in rates of temperature rise are to be expected, and do not invalidate the applicability of the benchmark conditions alone.
• Flashing liquid releases of any flow rate are adequately represented by the jet fire resistance test method. The lower exit velocities and buoyancy-dominant flames have convective heat fluxes and erosive forces that do not exceed the benchmark test case.

• The test is applicable for the majority of gaseous and flashing liquid releases into confined environments. There is the potential for exceptionally severe conditions to occur if the release conditions, compartment design and vent configuration create a soot residence time and temperatures that facilitate oxidation of the soot at the bottom of the hot layer, close to the region of air entrainment. However, such conditions are difficult to observe experimentally and represent an exception to the majority of available test evidence.

Scenarios in which there can be a reasonable assumption of applicability:

• Evidence for the applicability of the JFRT to gaseous releases at pressures above 60 bar is inconclusive. Peak erosive forces will be no greater than the benchmark test, however the continuation of higher velocities further along the flame length will increase the erosive forces on PFP systems at distances that coincide with more severe heat flux distributions. It is stressed that inconclusive should not be taken to mean that the JFRT is automatically unrepresentative. Use of the test is recommended at present, combined with an engineering approach. In the majority of practical cases it is expected that pressure will decrease with time. The conditions (either reservoir pressure, gas velocities or dynamic pressures) can be modelled and engineering judgement should be used to determine whether the overall severity of the scenario exceeds that of the benchmark case. In the event that concerns remain then mechanical retention, system redundancy or shielding could be specified to offset increased erosive effects.

Scenarios where the JFRT cannot be reasonably assumed to be applicable:

• Liquid and two-phase releases. These potentially represent a more severe test of PFP materials, and the JFRT validation cannot be considered applicable to these scenarios. It is stressed that the test may be proved to be representative, however in the absence of supporting data there are numerous reasons for concern. The presence of liquid droplets may change the erosive forces due to the increased momentum on impact with the target and penetration of the PFP material by the liquid could also give rise to further damage.

• Live crude oil. The total heat flux distributions for crude oil do not represent a significant departure from those in natural gas tests. However, two-phase releases do generate more severe heat flux distributions than natural gas releases of an equivalent size. Of more concern to the response of PFP is the increased radiative heat flux component present with heavy-hydrocarbon fuelled releases, giving rise to some of the largest radiative heat fluxes (250 kW/m²) directly measured in jet fire tests. Assuming the PFP surface reaches a quasi-equilibrium shortly after the onset of flame engulfment, this will result in higher rate of heat transfer to the PFP. Furthermore, the coincidence of highest erosive forces and highest radiative heat flux potentially represents a further increase in severity beyond the JFRT benchmark case.

• Natural gas/hydrogen mixes. Natural gas and hydrogen mixtures can be considered a more severe scenario than the benchmark test case, and the jet fire resistance test should not be considered applicable for such scenarios.
• Mixtures containing solids. Releases of any type containing significant quantities of solid particulates are outside the scope of current test evidence and the JFRT should not be considered applicable for such scenarios.
10. RECOMMENDATIONS AND PRIORITIES FOR ANY FURTHER WORK

10.1 GENERAL RECOMMENDATIONS

1. Data should be generated on the response of PFP materials when subject to two-phase releases. Detailed recommendations are given below.

2. Further test evidence should be generated on PFP material response in tests that experience more severe heat flux distributions, and should assess whether types of products (particularly intumescents) are susceptible to increased erosion in such conditions.

3. Cryogenic releases of LNG impacting on objects with a sub-cooled core are a topic of current interest that suffers from a lack of available data. The presence of liquid droplets and increased temperature gradients have the potential to affect PFP response. Further study is recommended.

4. It should be investigated whether PFP materials (particularly intumescents) respond differently when exposed to the extreme conditions that can be generated in confined jet fires.

10.2 FULL-SCALE TWO-PHASE JET FIRE TEST PLAN

The recommendations given here are based around previous studies as this provides a tried and tested experimental set-up and pre-existing information on flame characteristics.

The test programme given below is a means of investigating a number of the concerns stated within this report simultaneously. The conditions produced will extend validation (or highlight limitations) of the JFRT through a combination of liquid droplet impingement, a more severe heat flux distribution and a higher radiative fraction of the total heat transfer.

In addition to providing direct evidence on the suitability (or unsuitability) of the PFP material type used in the tests for the release scenario described, the below test programme will allow for direct comparison with the large scale gaseous release validation work performed for the JFRT procedure.

It is recommended that the investigation uses epoxy intumescents as the PFP material, partly because of the extensive use of such materials, but primarily because of the concern that the erosion experienced by such materials may not be independent of the severity of heat flux distribution.

Reference should be made to British Gas R&T report GRC R 1019 for more details on the proposed test set-up, and OTO 96 054 and OTO 96 055 for test specimen design.
Test programme:

4 tests: An I-section and pipe protected with two different PFP materials

Fuel:

Crude oil – natural gas mix (4:1 by mass preference, 3:2 also acceptable)

Release conditions:

5 kg/s total mass release rate, 20 bar exit pressure, horizontal release 3m above ground.

Test duration:

Up to 60 minutes (although terminated if catastrophic failure of PFP material occurs)

Targets:

Universal Beam (UB) 356x368x153 and Circular Hollow Section (CHS) Ø508 x 10mm instrumented with a minimum of 20 type K thermocouples. Located at a distance of 9m from the release point.

PFP system:

A randomly selected epoxy intumescent system installed by a 3rd party contractor at a thickness to limit the temperature rise to 400°C for a duration of 40 minutes.
REFERENCES


http://www.hse.gov.uk/research/othhtm/400-499/oth477.htm (accessed 05/12/2017)


[29] Roberts "Hazard consequences of jet-fire interactions with vessels containing pressurised liquids: Final report" HSL report PS/96/03, HSE, 1996  Available from HSE, Buxton


[34] British Gas R&T, “GRC R0659, Large scale natural gas jet fires impacting on flat surfaces,” 1996.


[40] Lowesmith, Correspondance, 2017 (appendix C).


APPENDIX A – NOTES ON MEDIUM-SCALE “HHF” TEST METHODS

A.1 SP RESEARCH (SINTEF), NORWAY

The following information has been kindly provided by Reidar Stølen of SP research

The fire research laboratory of SP research (formerly SINTEF) is currently taking a lead in offering extended (or high heat flux) jet fire tests. They predominantly use compartmentation to increase the heat load, partially through an increase in optical thickness of the fireball created in front of the test specimen, and partly through re-radiation from the compartment walls. The compartment is approximately 3m x 3m with a roof and fully open front.

Variations of the test have achieved higher temperatures by blowing air into the compartment side-walls.

The heat flux is typically back-calculated using the Stefan-Boltzmann relationship from equilibrium temperatures reached by (uncooled) calorimeters in the fire.

Other aspects of the test remain similar to the ISO jet fire test, including the nozzle, fuel, flow rate, target and dynamic pressures produced.

At the time of writing, no studies are available comparing the conditions produced in the above test with a specific full-scale release method.

Points of commendation:

- Likely to be a good representation of extreme conditions that can be obtained in compartment fires
- Practical and economic set-up

Points of concern:

- Relatively similar in severity to the ISO JF test for the first 5 minutes, highlighting the flame is not optically thick and re-radiation from compartment walls is important. Transient releases with short durations of high flow rate may not reflect this
- Currently unvalidated against a full-scale release
A.2 DNV GL, U.K.
The following information has kindly been provided by Rob Crewe.

DNV GL have performed studies of the severity of an extended test that uses air entrainment to produce more severe conditions. A second air nozzle directly above the propane nozzle releases air at a similar flow rate to the propane, giving rise to more efficient combustion and greater gas velocities over the target specimen.

Other aspects of the test remain similar to the ISO jet fire test, including the propane nozzle and flow rate and the target.

DNV GL have also been developing a method of characterisation of the heat flux distribution within the ISO jet fire test box configuration in conjunction with the University of Leeds. It is based on a back-calculation from a combination of the rate of temperature rise and the equilibrium temperature, and supported by total heat flux calorimeter readings.

The methodology has been used to characterise both the ISO test (giving similar results to those published by Shell/SINTEF in 1993) and the development test above.

Like the test in the previous section, at the time of writing, no studies are available comparing the conditions produced in the above test with a specific full-scale release method.

Points of commendation:

- Characterisation methodology shows promise as a detailed, cost-effective means of characterising test development
- Practical and economic set-up

Points of concern:

- Anecdotal evidence suggests the methodology used produces a significantly more erosive and severe test. It is unknown whether this is representative of full-scale releases
- Currently unvalidated against a full-scale release
## APPENDIX B – FULL-SCALE TEST PROGRAMMES

<table>
<thead>
<tr>
<th>Year</th>
<th>Programme</th>
<th>Conducted by</th>
<th>Reported in</th>
<th>Tests</th>
<th>Fuel (flow rate)</th>
<th>Target (distance)</th>
<th>Target instrumentation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>Isle of Grain</td>
<td>Shell/BP</td>
<td>Gastech 88</td>
<td>10</td>
<td>Propane (1-10 kg/s)</td>
<td>Copper plate (7m-10m)</td>
<td>Cooled calorimeters</td>
<td>50-250 kW/m² recorded</td>
</tr>
<tr>
<td>1989</td>
<td>SOFIPP</td>
<td>Shell/BG</td>
<td>OTO 90 012</td>
<td>&gt;5</td>
<td>Natural gas (3 kg/s – 60 bar)</td>
<td>Ø 457x12.7 CHS and 356x358x129 (9m)</td>
<td>TCs only</td>
<td>Cement-based and intumescent PFP materials tested</td>
</tr>
<tr>
<td>1989-1991</td>
<td>EV4T-0016-UK</td>
<td>Shell/BG</td>
<td>MRS E612 / Shell 91.022</td>
<td>170</td>
<td>Propane (1.5-22 kg/s) Natural gas (3-10 kg/s)</td>
<td>Ø0.9m pipe or 13 tonne LPG tank (9-40m)</td>
<td>TCs, calorimeters, radiometers</td>
<td>Extensive additional measurement of flame characteristics</td>
</tr>
<tr>
<td>1993</td>
<td>BFETS Phase 1</td>
<td>Shell / SINTEF</td>
<td>IchemE, Chamberlain, 1994</td>
<td>&gt;9</td>
<td>Propane (0.21-0.3 kg/s)</td>
<td>135m³ compartment (~3m), cylindrical target (in 4 tests)</td>
<td>TCs, calorimeters, radiometers</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>BFETS Phase 2 FP3</td>
<td>Shell / SINTEF</td>
<td>SCI FP3 Final Report</td>
<td>15 (Jet fires)</td>
<td>Condensate (0.3-1.0 kg/s) and one propane (1.08 kg/s)</td>
<td>415m³ compartment (+some 135m³), 11 tests had targets</td>
<td>TCs, calorimeters, radiometers</td>
<td>Cylindrical targets were both vertical and horizontal</td>
</tr>
<tr>
<td>Year</td>
<td>Programme</td>
<td>Conducted by</td>
<td>Reported in</td>
<td>Tests</td>
<td>Fuel (flow rate)</td>
<td>Target (distance)</td>
<td>Target instrumentation</td>
<td>Notes</td>
</tr>
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<td>--------------------------------------------</td>
</tr>
<tr>
<td>1995</td>
<td>JIVE</td>
<td>Shell / BG</td>
<td>JIVE report (TNO)</td>
<td>&gt;27</td>
<td>Natural-butane mix kg/s</td>
<td>Pipe</td>
<td>TCs, calorimeters, radiometers</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>gas (2.5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>JIVE</td>
<td>HSL</td>
<td>R04.029</td>
<td></td>
<td>Propane kg/s</td>
<td>(1.5)</td>
<td>Vessel (4m) and Ø1.2m pipe</td>
<td>JSRT tests made for comparison</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TCs and calorimeters</td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>HSE project (R04.029)</td>
<td>HSL</td>
<td>PS/96/03</td>
<td>4</td>
<td>Propane kg/s</td>
<td>(1.5)</td>
<td>2 tonne vessel (Ø1.2m x 4m)</td>
<td>calorimeters</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4 varying fill levels tested</td>
</tr>
<tr>
<td>1995</td>
<td>BFETS Phase 2</td>
<td>British Gas</td>
<td>R1019</td>
<td>12 impinging</td>
<td>Crude-natural gas mix (5 kg/s total)</td>
<td>Ø0.9m pipe (9m and 15m)</td>
<td>TCs, calorimeters, radiometers</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>JFRT Validation programme</td>
<td>British Gas</td>
<td>OTO 96 055</td>
<td>4</td>
<td>Natural gas (3 kg/s)</td>
<td>UB 356x368x153, CHS Ø0.52m &amp; Ø0.22m</td>
<td>TCs</td>
<td>JSRT tests made for comparison</td>
</tr>
<tr>
<td>1996</td>
<td>Internal</td>
<td>British Gas</td>
<td>GRC R 0659</td>
<td>57</td>
<td>Natural gas (0.69-3.13 kg/s – up to 113 bar)</td>
<td>Horizontal deck 20m x 20m (2m – 6m)</td>
<td>TCs, calorimeters, pitot tubes</td>
<td>Parameters studied: mass flow rate, exit pressure, stand-off distance, wind and partial confinement</td>
</tr>
<tr>
<td>2000</td>
<td>BFETS Phase 2</td>
<td>British Gas</td>
<td>OTN 2000 042 (BGT R2961)</td>
<td>8 +21 further tests with water cut</td>
<td>Crude / propane / natural gas mix</td>
<td>Ø0.9m pipe (15m)</td>
<td>TCs, calorimeters, radiometers</td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>Programme</td>
<td>Conducted by</td>
<td>Reported in</td>
<td>Tests</td>
<td>Fuel (flow rate)</td>
<td>Target (distance)</td>
<td>Target instrumentation</td>
<td>Notes</td>
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<tr>
<td>2008</td>
<td>NATURALHY</td>
<td>British Gas Technology</td>
<td>R0051-WP2-R-0</td>
<td>6</td>
<td>Natural gas (3-20kg/s – 60 bar) and Natural gas &amp; hydrogen mix (as NG)</td>
<td>Ø0.9m pipe (9,15,22m)</td>
<td>TCs, calorimeters, radiometers</td>
<td></td>
</tr>
</tbody>
</table>
The following is a summary of information kindly provided by Barbara Lowesmith in private correspondence. 'Recent tests' refers to those discussed references [38] and [39].

Figure 22 includes data from 7 NG Shell tests and 6 NG BG tests involving impact onto the pipe target plus 53 tests where the jet fire was impacted onto a large flat surface. This partly informed the selection of the guidance values in Lowesmith et al, 2007.

Figure 17 shows data from more recent tests, conducted during the EC funded Naturalhfy project, 3 NG fires and 3 NG/H2 fires were conducted at nominal flowrates of 3, 10 and 20kg/s. The data on the pipe target was logged every 0.1s. It was then time averaged over a selected period of steady atmospheric conditions, typically at least 30s. A time plot is shown of some data from the NG test from a 20mm orifice for the calorimeters along part of the front of the target. In this case, the averaging period selected was from 50-90s, so 40s long.

Figure 23 is a plot of the measured heat flux values in the area of flame impact (defined as exceeding 50 kW/m2) compared with the guidance values, for the 6 tests conducted during Naturalhfy. From which you can see that values over 300 kW/m2 were measured even at the lower flowrate, although these will be limited to a small area spatially. Plus, of course, they represent the heat flux to a cooled target as the calorimeters were maintained at 60°C.

Figure 16 is a plot of the spatial variation of the time averaged fluxes from the NG test from a 20mm orifice. From this you could conclude that the maximum is over 300 kW/m2, however, as the area where this occurs is small, I think it would be excessively conservative to apply this all over.

Finally, can I remark that in my view the combination of explosion and jet fire testing is very valuable for PFP, as there is no point having PFP if it falls off in an explosion prior to a fire. I know that Spadeadam have performed many combined tests whereby the sample is first blast tested and then subjected to the standard jet fire test.
A review of the applicability of the jet fire resistance test method to severe release scenarios

When assessing safety cases for offshore installations, HSE may have to consider if the passive fire protection materials installed are suitable to protect against the events they may encounter. In situations where passive fire protection for structures and components could be subject to an intense jet fire, that suitability is judged by the results of testing to the ISO22899-1 international standard.

Within the offshore industry, it has been suggested that this standard test is not adequate for all fire situations. This has led to some protection products being tested to non-standard methods intended to create a higher heat flux in order to represent a more severe fire.

This report examines a range of jet fire scenarios and concludes that the standard test is representative of most but for certain scenarios may not always be applicable. However, simply increasing the heat flux may not produce a more onerous test.

In order to ensure that hazards from major jet fires are adequately controlled, large scale testing is needed to show how fire protection products respond to the actual fire events. Only with such information can validated, practical scale test procedures be produced, for any situations where the current standard test is not applicable.

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