

Chapter 7

Fire Risk Modelling

7.1 Overview

7.1.1 Cases with Opposite Results

It may be illustrative to consider the vast difference between two incidents in the North Sea that started in almost identical ways, within approximately 24 h, and ended very differently. These two events were presented in [Sects. 4.14](#) and [4.15](#):

- Explosion and fire on Brent A on 5 July 1988 ([Sect. 4.14](#))
- Explosion and escalating fire on Piper A on 6 July 1988 ([Sect. 4.15](#)).

The Piper A accident ended with a lost installation and is very well known due to the catastrophic development of the accident. The Brent A incident on the day before Piper A is virtually not known at all, except those involved, due to the benign consequences.

Both events occurred on mature installations, and started with a gas leak from a flanged connection. The gas leaks were both ignited and a gas explosion resulted with approximately the same peak overpressures. The protective systems onboard both installations were essentially the same. The main characteristics of the two events may be summarised as shown below:

	Piper A, 6 July 1988	Brent A, 5 July 1988
Leak source	Blind flange	Gasket in a flange
Ignition source	Ignition by unknown source	Probably by deluge
Explosion overpressure	Approximately 0.3 bar	Approximately 0.3–0.4 bar
Deluge	Not initiated, fire water supply unavailable	Started (inadvertently) on gas detection
Subsequent fire	Escalating immediately to other areas	Only few minutes fire duration

(continued)

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	Piper A, 6 July 1988	Brent A, 5 July 1988
Final consequences	Total loss	Significant damage to gas processing module
Consequences to personnel	167 fatalities	2 injuries

The main difference according to this simplified summary was the activation of the deluge system, but it is slightly more complicated than this. The Brent A gas leak occurred on the highest level far away from the accommodation area, whereas the Piper A gas leak occurred on a lower level below and next to the accommodation block.

7.1.2 Types of Fire Loads

This section gives an overview of accident scenarios that may result in fire loads on primary and secondary structures, (i.e. support structure, main deck structure and module structure). Two tables are presented, Table 7.1 for fixed and Table 7.2 for floating installations.

These tables show that uncontrolled hydrocarbon flow is the main reason for critical fire loads on the structure. It may be noted that dropped objects may also contribute, but only as a result of rupture of hydrocarbon containing equipment. It may be noted that falling objects have not caused hydrocarbon leaks in the Norwegian sector in the period 1996 until 2012, i.e. the period when detailed information about the leaks is available.

Structural failure and collision impact may under certain conditions lead to fires that may affect the structure. It should be noted that the failures that may lead to uncontrolled fire directly, usually dominate over those that depend on escalating sequences. The Mumbai High North fire in 2005 (Sect. 4.18) is an example of external impact from a vessel which caused a riser fire which escalated to an uncontrolled fire.

7.1.3 Structural Fire Impact

Calculating the fire loads on a structure and estimating responses involve these steps:

1. Calculation of release of hydrocarbon
2. Calculation of fire loads

Table 7.1 Overview of types of fire scenarios that may lead to structural fire loading, production installations

Type of accident	Conditions which may lead to structural effects	Structural elements typically affected	Criticality
Blowout	Difficult to control and combat, especially if ignited. Burning blowouts are usually of very long duration, thus very critical	Usually deck structure. May also be support structure, if burning on sea level	Usually highest contribution, if wellheads are on platform
Riser failure	Release may have extensive duration, if long pipeline is connected, and no isolation is possible	Deck structure, if riser is inside shaft. Also likely in later phases, when no shaft exists Likely if leak is below deck, and no shaft. Also likely if leak is subsea or in splash zone, thus causing burning on sea level	Usually significant contribution, unless riser is specially protected, or subsea isolation is provided
Pipeline failure	Release may have extensive duration, if long pipeline is connected, and no isolation is possible. Release needs to be close to structure and ignited on sea level, in order to be critical	Likely if leak is below deck, and no shaft. Also likely if leak is subsea or in splash zone, causing burning on sea level. Deck structure is likely in later phases	Usually insignificant contribution, because ignition is unlikely
Process equipment failure	Fires may have long duration through escalation to uncontrolled fire	Usually main deck structure	Dependent on likelihood of escalation
Dropped object	Through fire caused by rupture of hydrocarbon equipment	Usually main deck structure	Insignificant contribution

3. Calculation of structural time–temperature distribution
4. Calculation of structural response to temperature distribution.

For each of these steps, simplified methods or more comprehensive simulation tools may be used.

7.1.4 Fire and Explosion Loads on People

The assessment of the effects of fire explosion on people is parallel with the structural effects analysis, although in some respects considerably simpler.

Table 7.2 Overview of types of fire scenarios that may lead to structural fire loading, floating installation

Type of accident	Conditions which may lead to structural effects	Structural elements typically affected	Criticality
Blowout	Dry wellhead: Difficult to control and combat, especially if ignited. Burning blowouts are usually of very long duration, thus very critical	Usually deck structure. May also be marine structure, if burning on sea level	Usually highest contribution, if wellheads are on platform
	Subsea wellhead: Difficult to control and combat from platform. Ignited blowout will burn on sea, thus very critical	Usually marine structure, but may also be deck structure	Burning on sea level is less likely, compared with wells on deck. Unit may also reposition
Riser failure	Release may have extensive duration, if long pipeline is connected, and no isolation is possible	Marine structure, as leak is usually subsea	Usually significant contribution, unless subsea isolation is provided
Pipeline failure	Release may have extensive duration, if long pipeline is connected, and no isolation is possible. Release needs to be close to structure and ignited on sea level, in order to be critical	Marine structure, as fire is usually on sea level	Usually insignificant contribution, because ignition is unlikely
Process equipment failure	Fires may have long duration through escalation to uncontrolled fire	Usually main deck structure	Significance is dependent on likelihood of escalation
Dropped object	Through fire caused by rupture of hydrocarbon equipment	Usually main deck structure	Insignificant contribution

7.2 Topside Fire Consequence Analysis

The following section provides a brief overview of some of the important parameters that are used in the fire consequence analysis, including an overview of the fire types and their characteristic heat loads. For more detailed introduction, see for instance Lees (2004) or Fire Calculation Handbook (SINTEF 1992).

7.2.1 Mechanisms of Fire

Despite the fact that a fire originates from combustion reactions, the process of fire may be dependent on forces or factors that are not directly involved in combustion.

The overall process rate may be dependent on, or driven by, a step in the process other than the combustion reactions. It is therefore convenient to separate fires into different types:

- Ventilation controlled fires in enclosures (closed or partly closed)
- Fuel controlled fires in enclosures
- Pool fires in the open
- Jet fires
- Fires in running liquids
- Fire balls (BLEVE)
- Gas fires (premixed, diffuse).

All these scenarios are relevant in the case of offshore installations. Other types of fire that may occur are fires in electrical equipment and fire in equipment in the accommodation. These ‘non-hydrocarbon’ fires are not discussed. The fire loads are generally lower for these fires, but the smoke production may be a problem.

7.2.1.1 Combustion Reactions

All fires involve combustion in the gas phase except for smouldering combustion where the combustion reactions take place on the surface of the fuel.

Both exothermic and endothermic reactions take place during the combustion process. The overall reaction or process, is considered to be one reaction involving total, or 100 %, combustion or oxidation of the fuel.

The combustion reaction rate is dependent of the temperature in the combustion zone, the concentration of the reactants (oxygen and fuel) and the combustion products produced in the zone. If the concentration of the fuel is either too high or too low, or the temperature is too low, the reaction will not take place.

The dependence of the reaction rate on these factors is expressed by the parameters ignition temperature, flammability limits, and oxygen index. Other important properties are the flash point and the self ignition temperature. These properties can be found in a number of text books for different hydrocarbon products.

7.2.1.2 Heat Transfer to Object Within the Flames

The main heat transfer from a flame to an object in the flame occurs by radiation. In some situations, however, the convective heat transfer equals the radiative contribution. The radiative heat transfer can be expressed as:

$$q = \varphi \varepsilon \sigma \left(T_f^4 - T_o^4 \right) \quad \text{kW/m}^2 \quad (7.1)$$

where

φ = configuration factor

ε = emissivity/absorption factor for the system

σ = stefan Boltzmann's constant (56.7×10^{-12} kW/m² K)

T_f = flame temperature, K

T_o = temperature of the object, K.

If the object is totally enveloped in the flames we assume that is 1.0. If the thickness of the flames around the object is equal to or above 1, we assume that $\varepsilon = 1$. In general it is considered that in a pool fire the diameter of the flame must be larger than 3 m to create flame thickness equal to 1.

The temperature within the flame will vary from 500 °C at the top to 1600 °C locally in the flames. The value of 1100–1200 °C is often used to calculate the radiative heat transfer, but this value has been considered as conservative. Measurements from large scale tests have revealed that even higher temperatures may be generated in certain conditions, during a jet fire as well as a liquid fire. The following approach may be used for practical estimates:

1. The average flame temperature, where the flames totally envelop the objects, may be taken as 800 °C.
2. The product of φ and ε in Eq. 7.2 vary from 0.7 to 0.9, depending on the flame thickness and tightness around the object.

Using a value of $\varphi\varepsilon = 0.7$ and $T_f = 800$ °C, produces a radiant heat transfer of 52 kW/m² which may be regarded as a typical average value.

Consider a region of the flames equal to 2/3 of the total height of the visible flames. The convective heat transfer is high in this region in the beginning of the fire, if the pool diameter is large and flames stagnate on the object. The radiative heat is proportional to the temperature difference to the power four. The convective heat transfer is on the other hand linearly dependent on the temperature difference.

7.2.1.3 Heat Transfer to an Object in a Jet Fire

If an object is in a jet fire, the heat transfer to the object will be far greater than if the object were enveloped by flames controlled by natural convection. This is due to the very high gas velocities which result in 70–90 % of heat transfer by convection. In a jet fire the convective heat loads have locally been measured up to 350 kW/m² and average values of 300 kW/m² are possible.

Heat transfer from a pool fire in the open will normally have a maximum value of 150 kW/m². A jet fire will of course be far more local than a pool fire. In the BFETS programme (SCI 1998), the total incident heat flux onto targets was in general up to 200 kW/m², but local maxima could be up to 350–400 kW/m² under

certain conditions. This occurred for jet fires as well as pool fires in semi-enclosed areas.

The total heat transfer to an object within the flames of a jet fire can be estimated by calculating the radiation heat transfer ($\epsilon \approx 1$) and assuming this to be 30 % of the total.

7.2.2 Fire Balls

Fire balls may be the result of a Boiling Liquid Expanding Vapour Explosion (BLEVE). If a tank ruptures, the gas under pressure mixed with the condensed phase escapes immediately. The flash evaporation of the gas phase entrains liquids in the form of a fog which, when ignited, burns with the look of a ball or 'nuclear bomb mushroom'. The factors of interest are:

1. The hydrocarbon fractions released before combustion
2. The size of the fire ball
3. The duration of the fire ball
4. The radiation intensity from the fire ball.

The fraction participating in the combustion is suggested to be 30 %. Hasegawa and Sato (1977) have set up the following correlations of size and duration:

$$D_{\max} = 5.28 M_f^{0.277} \quad (7.2)$$

$$\tau = 1.1 M_f^{0.0966} \quad (7.3)$$

where

D_{\max} = maximum diameter of the ball, m

T = duration of the combustion, s

M_f = Mass of the involved fluid, kg.

7.2.3 Gas Fires

Gas fires and explosions are related phenomena, but it is important to distinguish between them. A gas fire will occur if the following three conditions exist at the same time:

- there is a mixture of gas and air within the flammability limits,
- there is a normal sized source of ignition energy, and
- the enclosure does not contain any flame front accelerating factors.

Flame front accelerating factors can be objects in the enclosure or any narrow passage way to neighbouring enclosures. If the flame front acceleration is sufficiently strong, a deflagration will develop (see [Chap. 8](#)).

The gas fire takes place with a flame front that propagates through the mixture at a speed of 0.5–2 m/s and the flow is laminar. The heat and overpressure loads from a gas fire are relatively small.

7.2.4 Air Consumption in Fire

The following figures are given in literature as the air requirements for burning the following fuels:

- Propane: 16 kg air/kg fuel
- Gasoline: 16 kg air/kg fuel
- Methane: 15 kg air/kg fuel.

These are theoretical values for complete combustion in diffusion flames. The air consumption required for jet fires is much higher than for an ordinary diffusion fire. In order for the jet to be maintained, excess air over that needed for the combustion reaction is needed. The jet fire air consumption is 400 % the ‘normal’ consumption, including both the combustion and excess air. For methane jet fires this means 60 kg air/kg fuel.

7.2.5 Choice of Calculation Models

There is a very wide range of available models which may be chosen for calculation of fire dimensions and loads. There are a number of simple, hand calculation models available, mainly based on empirical data. At the other extreme, there are several computational fluid dynamics (CFD) software packages available which enable very sophisticated calculations to be performed.

Using simplified tools is often a good starting point, in order to get some feel for how severe the fire loads are likely to be. If severe loads can occur, then it is wise to use more sophisticated tools (presumably with less uncertainty), to understand the situation better and thereby have a more precise basis for the engineering of protective measures.

An overview of simplified models is found in the *Fire Calculation Handbook* (SINTEF 1992). Some of the CFD-packages are briefly mentioned in Appendix A.

Table 7.3 Fire load characteristics

Jet fire	Diffuse gas fire	Pool fire	Fire on sea
Hole size	Release rate	Pool size	Spreading
Release velocity	Air supply	Air supply	Wind direction
Direction	Duration of leak	Wind direction	Wind speed
Duration of leak	Air supply	Duration of fire versus leak	Pool breakup

7.2.6 Analysis of Topside Fire Events

The main fire types are jet fire, diffuse gas fire, pool fire, and fire on sea. Table 7.3 summarises the main characteristics that need to be determined for these fire types.

7.2.7 Fire Simulations

Detailed analysis of fire loads would call for a number of fire simulations with CFD-tools (see Appendix A) for detailed production of fire loads. Table 7.4 presents the cases for CFD fire simulation for a large QRA study of a large production installation, reflecting the actual number of cases considered in the QRA study.

Results from the simulations may be viewed graphically for various parts and angles, with respect to various parameters, most typically the radiation flux at various levels.

The fire simulations for each of these cases are used for the calculation of the following probabilities:

- Probability of immediate fatalities
- Probability of fatalities during escape from area
- Probability of impairment of escape main safety function
- Probability of impairment of shelter area main safety function
- Probability of impairment of evacuation main safety function
- Probability of impairment of critical rooms main safety function
- Probability of impairment of main load-bearing structure main safety function
- Probability of impairment of escalation main safety function

A typical summary of radiation flux levels from the different simulation cases for three assumed lifeboat stations is shown in Table 7.5 (illustrative values, not from the study). A typical summary of immediate fatality probabilities in the areas where the accidents originate is shown in Table 7.6 (illustrative values, not from the study). These values reflect the radiation levels in the various modules, and would also reflect some evaluations based on the radiation levels.

Table 7.4 Fire simulation cases for QRA of a large production installation

Case	Module/area	Type of release	Direction	Mass flow (kg/s)	Wind direction	Wind speed (m/s)
11	M11	Jet fire	South	20	East	4
12		Jet fire	South	20	East	10
13		Jet fire	South	20	South-southeast	12
14	M12	Jet fire	North	10	North	2
15		Jet fire	North	10	East-northeast	2
16		Jet fire	North	10	North-northeast	10
17		Jet fire	North	20	North-northeast	10
18		Jet fire	North	20	North-northwest	10
19	M15 (well area)	Jet fire	East	10	East	2
20		Jet fire	East	10	South	8
21		Jet fire	North	5	East	8
22		Jet fire	North	10	East	8
23		Jet fire	North	10	East-northeast	8
24	Process area	Jet fire	North	10	East	6
25		Jet fire	North	5	North	8
26		Jet fire	North	5	North	8
27		Jet fire	North	10	East	6
28		Jet fire	South	10	East	2
29		Jet fire	South	10	East	10
30	Sea level	Pool fire	–	30	East	2
31		Pool fire	–	30	East	8
32		Pool fire	–	30	North-northwest	6
33		Gas plume	–	30	East	0.1
34		Gas plume	–	30	East	2
35		Gas plume	–	30	North	0.5
36		Gas plume	–	30	North-northwest	0.1
37		Gas plume	–	30	North-northwest	2
38	Drill floor	Jet fire	West	25	East	8
39		Jet fire	West	25	South	12

Table 7.5 Summary of radiation levels for three assumed lifeboat stations

Case	Lifeboat East			Lifeboat North			Lifeboat West		
	4 kW	15 kW	50 kW	4 kW	15 kW	50 kW	4 kW	15 kW	50 kW
11	x						x	x	
12							x	x	
13				x			x	x	X

Table 7.6 Summary of probability of immediate fatality in area where accident originates

Fire in area	Type of event	Leak rate category		
		Minor (0.1–1 kg/s)	Moderate (1–10 kg/s)	Large (>10 kg/s)
M11	Process fire	0.05	0.30	0.70
	Riser fire	0.20	0.50	0.80
M15	Process fire	0.10	0.40	0.75
	Blowout	0.20	0.65	0.85

7.3 Fire on Sea

A full rupture of a pressure (or storage) vessel containing a large amount of crude oil (e.g. from a separator) will cause the contents to be released more or less instantaneously on the platform. Due to the fact that the deck in process areas on offshore platforms usually comprises gratings, almost all the released oil will flow to the sea forming an oil slick which will rapidly increase in size. There are drain systems installed in order to prevent this scenario, but it is most likely that a significant proportion of the oil will flow to sea, in a major rupture, due to limited capacity of the drain system.

The lighter fractions of the oil will evaporate or flash off as the oil slick spreads on the sea surface. A release from a vessel containing the lighter as well as the heavier fractions will obviously produce a higher amount of gas. Fire on sea level may also occur due to blowout from a well (especially a subsea production well) or a pipeline leak.

It has been considered that very large pool fires (diameter > 40 m) would likely tend to split up into several flame plumes with smaller base diameter and, thus also attain significantly reduced flame heights compared to the height of a non-split-up flame. However, this has never been verified.

Immediate ignition of most crude oil releases on the sea surface will result in an oil slick fire in which the burning intensity will be in the range 0.03–0.08 kg/sm², depending on the fraction of light components contained in the oil. It appears that the maximum flame heights will be in the range of 25–50 m. Since the distance from the sea surface to the underside of the cellar deck or the Main Support Frame (MSF) of a typical fixed installation is usually in the range 25–30 m, most oil slick fires arising from a major release of crude oil will impinge on the MSF or underside of the deck. The most severe will engulf the deck and modules on top in flames and smoke. Floating installations have lower air gaps, which implies that heat loads will be higher.

It has traditionally been considered that heat loads from a sea level fire are lower than from a pool fire on deck. The lower burning intensities will result in a flame tip temperature of 500–600 °C, resulting in heat loads of 30–50 kW/m². The higher burning intensities will result in the upper part of the flame plume producing heat loads in the range 50–100 kW/m² at the MSF and deck, and heat loads

of 75–150 kW/m² on parts of the platform legs. In large scale tests (SCI 1998) flame temperatures up to 1250 °C have been measured.

The lack of actual experience data is one of the complicating factors in relation to fire on sea. Very few instances of fire on sea are publicly known. The Ekofisk field experienced one case around 1980, this was a very small amount and short duration, but caused severe panic on the installations. There are also rumours about other cases around the mid-1990s, in the North Sea and in Africa, but these are unconfirmed.

Another aspect of fire on sea, is the possible extensive cost impact if extensive passive fire protection of the structure is to be applied in order to protect against fire on sea level, this is further illustrated in Sect. 7.3.4.

Immediate ignition of an oil spill on the sea level is often caused by running or falling burning liquid droplets from the installation.

7.3.1 Delayed Ignition of an Instantaneous Release

Prior to ignition, the oil will spread on the sea surface due to changing spreading and retarding forces. Figure 7.1 shows the diameter of an unignited oil slick as a function of the elapsed time from the start of the release. This relates to an instant area release of 100 m³ of stabilised crude oil ignoring any effects of wind waves or currents. No immediate gas flashing or evaporation of light components is taken into account. A significant amount of gas flashing and evaporation would result in a smaller oil slick due to the reduced volume of oil.

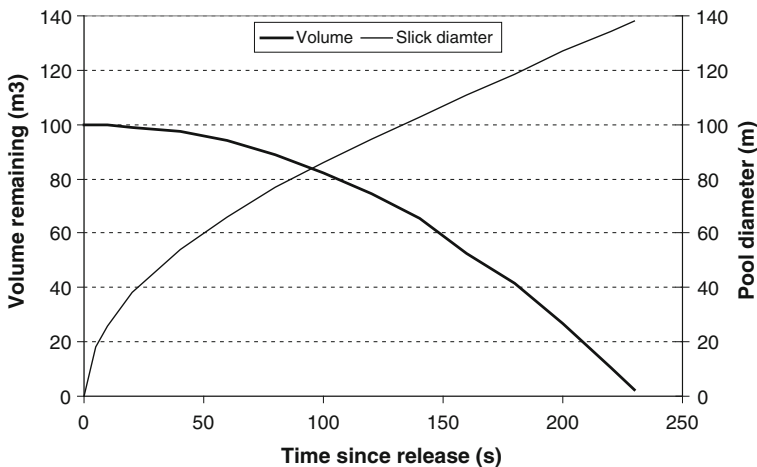


Fig. 7.1 Oil slick diameter as a function of time, provided there is no ignition of the oil (instantaneous release of 100 m³ of stabilised crude oil)

From Fig. 7.1 it can be seen that the diameter of the oil slick increases rapidly in the first 30 s after release, after which time the growth rate is slower. For example after 1–4 min, the oil slick diameter is approximately 65, 95, 120 and 140 m respectively. After 6 h the oil slick diameter is approximately 370 m. It is evident that if this oil slick is ignited after some minutes, huge flames may theoretically occur.

7.3.2 Ignition Probability of an Instantaneous Release

Due to the oil becoming less volatile with time, the ignition probability will correspondingly also decrease. The time to ignite an oil slick when subject to radiant heat will be longer if the oil has been on the water for some time and the thickness has decreased.

With heat radiation above 10 kW/m^2 the effects of delay and film thickness on time to ignition is hardly discernable. As time proceeds, light oil fractions evaporate, the oil cools down, the slick thickness decreases, and may to a certain extent be mixed with water. In this situation the possibility of igniting the slick decreases rapidly. Crude oil will thus attain ignition properties similar to those of diesel oil which cannot be ignited without the addition of a primer or without the presence of a significant heat source. An instantaneous release of fresh, unstabilised crude oil is easier to ignite the earlier the ignition source is introduced. The ignition probability of the stabilised crude oil in which all major light fractions are evaporated, is rather low. The flash point of such stabilised crude oil is as high as $125 \text{ }^\circ\text{C}$.

The temperature of the oil at the point of release may be as high as $90\text{--}100 \text{ }^\circ\text{C}$, but it will soon cool down by heat transfer to the sea and the ambient air. A major heat source has to be present to ignite a slick of stabilised crude oil some time after release. Such a heat source is unlikely to be present in most offshore situations except when there is already a significant fire on the platform.

On the other hand, if the ignition source is introduced approximately at the time of the release of fresh crude oil (i.e. immediate ignition), the oil is much more readily ignitable. Fresh, unstabilised crude oil has a flash point of $1\text{--}10 \text{ }^\circ\text{C}$. The fire point however, may be as high as $60\text{--}70 \text{ }^\circ\text{C}$, which usually is below the temperature at which oil is processed. Taking all these factors into consideration it may be concluded that the probability of immediate ignition of an instantaneous release resulting in a sustained fire is rather low.

7.3.3 What Determines the Likelihood of Fire on Sea?

Fire on sea is not a well documented event. In fact, very few events have explicitly been reported in the public domain. Blowouts are the main type of events where such occurrences have been known to occur. Even for blowouts, there are

relatively few cases where there has been fire on the sea. It is therefore essential to establish the circumstances which may result in fire on sea.

SINTEF (Opstad and Guénette 1999) has carried out a research project for several years examining fire on sea. This has included a series of large scale tests on Spitsbergen in 1994 as well as small scale laboratory tests in 1996–1997. A brief summary of some of the main findings from that work is presented in the following, related to the following main aspects:

- Flow of oil to the sea
- Oil composition
- Environmental conditions

These aspects will determine whether ignition of an oil slick is likely or not, and whether sustained fire can be expected. The aim of the project was to study the fire behaviour and thermal impact from fires on the sea surface, as input to management of safety in relation to fire on the sea level.

Experiments with fresh crude oil and oil water emulsions were carried out during the test programme. The maximum amount of oil in one experiment was 8 m³.

7.3.3.1 Flow of Oil to Sea

The full scale tests showed that the manner in which the oil reaches the surface of the sea is important. We may distinguish between oil which reaches the sea in a ‘plunge’ (i.e. free fall) from a ‘run’, where the oil runs down elements of the structure. The importance for fire on sea is as follows:

- Oil will ‘plunge’ if it falls freely from the platform. Even if it is burning when falling from the platform, it may be quenched through plunging into the sea.
- Oil may ‘run’ down the jacket legs, bracings risers etc., and may still be burning when it reaches the sea surface. Quenching is less likely under these circumstances.
- Oil released subsea can be regarded as ‘plunged’ oil, but is probably significantly more ‘weathered’ (emulsified). Ignition would then be dependent on whether a strong external source of ignition is in the area.

7.3.3.2 Oil Composition

Evaporation of the lightest fractions above the liquid surface is the main mechanism that determines the sustained burning ability. The laboratory tests carried out by SINTEF confirmed that a boundary layer still persisted in high wind conditions, if sufficient amounts of the lighter fractions are contained in the crude oil.

The other implication of this is that large differences in behaviour were identified between the different oils. Some oils had considerably more evaporation than others. Obviously condensates ignited most easily. SINTEF suggested that the flammability of the oil is dependent on the extent of flammable components with boiling points below 150 °C.

7.3.3.3 Environmental Conditions

Because of the obvious limitations, the testing of ignitability and sustained burning under different environmental conditions has been one of the most difficult aspects to study. The large scale tests at Spitsbergen were carried out in wind speeds up to 5–10 m/s. Air movement velocities up to 25 m/s were used in the laboratory tests. For the oils with the highest evaporation rates, there was a limited effect from the highest wind speeds. It should be noted that the laboratory air movement velocity of 25 m/s was measured only about 1 m above the surface, where as official wind speed is measured 10 m above the surface. A wind speed of 28–30 m/s at a point 1 m above the surface would probably correspond to a wind speed of 55–58 knots. This is close to a hurricane which begins at 64 knots.

Wave motions have not been studied in these tests, due to natural causes. The large scale tests were carried out partly in a basin (in the sea ice!) and partly in a sheltered lagoon. The possibility of significant wave actions in both scenarios was non-existent.

The overall effects of wave action on the burning of an oil slick will be most extensive for the thinnest slicks that are close to the critical minimum thickness for ignition. The minimum film thickness for sustained ignition will increase with the time as the oil is weathered. Non-breaking waves will introduce minor fluctuations in oil film thickness and this will affect a proportion of the slick area at any time. If the oil film is thick, this will not have any appreciable effect on the ignition properties other than to slightly enhanced the dilution of the vapour cloud above the slick. Breaking waves will disrupt the thinner areas of an oil slick. Although this will only affect a small proportion of the slick area at any one time, the thickness will not be reinstated. The cumulative effect of breaking waves will be to break up the sheen. This will effectively prevent flame spreading and sustained burning.

There is still considerable uncertainty about the effects of high wave actions, especially breaking waves and extensive sea spray, which would be quite common at high wind speeds. It is claimed that the evaporation rates will not be significantly changed in the high wind state but this remains an unsupported assumption.

However, there is a general agreement that intense burning and sustained fire is virtually impossible in high wind scenarios. This applies to both “weathered” and ‘fresh’ oil spills (i.e. where little or no weathering has taken place).

An indication of the results under different wind conditions is indicated in Fig. 7.2 (SINTEF 2005), which shows that the chance of ignition is virtually

Fig. 7.2 Heat transfer to the surface at the time of ignition in the laboratory tests (courtesy of SINTEF)

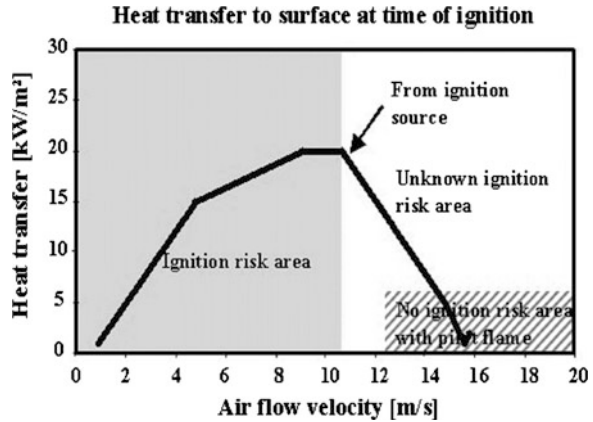


Table 7.7 Conditions for ignition and sustained burning for fire on the sea surface influenced by weather

Conditions	Type of oil		
	Condensate	Light crude	Crude oil
Minimum slick thickness (mm)	0.5	1	1–3
Maximum evaporative loss in (%)	>30	<30	5–10
Maximum water-in-oil emulsions (%)	Unknown	Unknown	<25
Maximum wind conditions (m/s)	25	20–25	15

independent of the heat transfer at low wind speeds, but much more dependent on the heat transfer at high wind speeds.

Table 7.7 (Opstad and Guénette 1999) presents a summary of the results from the tests carried out by SINTEF. It should be noted that the effects included are limited to wind effects, and are not the combined effects of wind and waves.

7.3.4 Loads from Sea Level Fire

The most severe fire loads from fire on sea level may have extensive cost implications in relation to the amount of passive fire protection that is needed to protect the structure. It is therefore important to consider the following parameters:

- Flame dimensions
- Fire duration (i.e. burn rates and inventory)
- Fire loads
- Smoke.

Consider, as an illustration, a floating production installation which was installed in the Norwegian sector some years ago. The following structural members were protected against sea level fire with passive fire protection:

- Support structure (columns)
- Deck support structure (beams).

The assessment of dimensioning loads was based on a conservative approach, which resulted in high fire loads, as follows:

- Columns
 - 250 kW/m², from sea level up to 15 m
 - 200 kW/m², 15 m upwards
- Main structural beams (support for topside modules)
 - 200 kW/m²
- All members protected for 2 h fire duration.

The total surface with protection was about 13,000 m². If we in current prices assume an average price of 600 USD per m², then the cost of passive fire protection of the structure is about 8 million USD. But even this may be a low value, if the protection has to be renewed on location. The cost of offshore reapplication would be several times higher.

7.3.4.1 Flame Dimensions

There are three phases of oil slick spreading (Fay 1969); gravity driven, viscous force limited and surface force limited spread. The diameter of a burning pool on the sea is dependent on the scenario that has created the burning pool, including a number of factors. All of the following need to be known in order to calculate the likely extent of a burning pool:

- Type of liquid, including its density
- Whether the spill is continuous or instantaneous
- Volume or leakage rate
- Time of ignition in relation to the start of the spill.

The laboratory tests (SINTEF 2005) demonstrated that upwind flame spread may occur, but not for the heaviest crude oils. The upwind flame spread may also be limited by strong wind. The crosswind flame spread velocity is also of the same order as the upwind velocity.

7.3.4.2 Fire Duration

The duration is first and foremost dependent on whether it is a continuous release or not. The fire will only last as long as the film thickness exceeds the minimum thickness.

7.3.4.3 Fire Loads

The large scale tests gave surprisingly high heat fluxes. Temperatures of certain regions inside the flames reached 1300 °C or more. The very hot regions are located where the turbulent eddies of the flames entrain sufficient amounts of air in order to allow complete combustion, and where the flames are optically thick.

Soot screening will trap some of the heat inside the fire plume, increasing the temperature and the heat load on an engulfed object. Therefore the fire load on objects inside a fire plume is of the same order as those found by experiments on land. An object enveloped in the flames may experience a fluctuating heat load, with peak values of approximately 400 kW/m². Average values may be in the order of 200–300 kW/m².

In high winds, heat exposure will mainly be on objects close to the surface, as long as no significant wind blocking from constructions occurs.

Fig. 7.3 Fire on sea level tests at Spitsbergen, 1994, photographed by the author



7.3.4.4 Smoke

This aspect does not affect structural elements, but rather has an impact on personnel which may be very severe. This may be seen from Fig. 7.3, which shows a sea level fire test using 8 m³ of stabilised crude oil. The spill was contained in a 10 m diameter ring when it was ignited, after which it was allowed to flow freely, increasing in diameter to almost 50 m, and burning for some 15 min. The height of the flames reached more than 60 m, but was pulsating with a period of some few seconds. The extent of the black smoke may be seen from the picture.

7.4 Analysis of Smoke Effects

7.4.1 *Methods for Prediction of Smoke Behaviour*

Smoke is one of the major hazards to personnel in fires, especially in oil fires. The reduced visibility due to thick black smoke is the first threat to people who want to escape from, or fight, a fire. Knowledge of smoke production, smoke flow and impact of smoke on people and facilities is available from literature, from laboratory tests, and from experience of real fires such as the fire on Piper Alpha platform (Lord Cullen 1990). A CFD-based computer code is needed for realistic modelling of smoke production and dispersion (Holen and Magnussen 1990).

The smoke generation in enclosed hydrocarbon fires is mainly governed by the properties of the fuel and the ventilation conditions. The nominal ventilation factor α the air-to-fuel ratio defines certain regimes of a fire from below stoichiometric conditions, characterised by oxygen starvation, through stoichiometric fires, to well ventilated fires.

7.4.1.1 Mass Flow Rate

An important fire scenario for offshore platforms is the enclosed fire. The estimated smoke production in this case is different from an open fire, since the combustion products can be recirculated into the flames. The enclosure itself may then be considered as a combustion chamber, and the mass and heat balance for the enclosure are the basis for estimating temperatures and determining smoke production rates and concentration of soot and gases.

A rough estimate of the smoke production rate in an enclosure may be obtained by multiplying the fuel burning rate by the amount of air needed for complete combustion. For most hydrocarbon fuels this is about 15 times the fuel burning rate. This number can be noted, k_a , the mass air-to-fuel stoichiometric ratio. In fires where the air supply is sufficient for complete combustion, the total mass rate of smoke can be calculated when the fuel burning rate is known. The total smoke production rate is:

$$\dot{m}_{tot} = \dot{m}_f + k_a \cdot m = (1 + k_a)\dot{m}_f \approx 16 \dot{m}_f \quad (7.4)$$

where

\dot{m}_{tot} = total mass flow of smoke from the flames

\dot{m}_f = fuel burning rate

k_a = mass air-to-fuel stoichiometric ratio.

This gives a first step estimate which gives an idea of the amount of smoke that is produced at high temperatures. The smoke produced by the fire is then mixed with entrained air, a process which goes on inside the fire module if excess air is available, or outside the module when the smoke escapes. This mixing process dilutes the smoke, leading to a reduction in temperature, soot concentration, and the concentration of toxic combustion products. The oxygen concentration in the smoke however, increases by mixing with the fresh air. The prediction of mass production rate of smoke is determined by the fuel burning rate, and the ventilation of the fire enclosure.

7.4.1.2 Temperature

The temperature of the smoke leaving a fire enclosure is a result of the burning conditions. If the ‘worst case’ fire severity is assumed, the maximum smoke temperature will be up to ≈ 1200 °C. A temperature significantly lower than this can be expected in most cases. It is not obvious that a ‘worst case’ fire development inside the fire enclosure leads to the worst smoke hazard to people on a platform. A very hot smoke plume developing from an opening in a fire compartment will have strong buoyancy and will tend to rise rapidly. In some cases this will be favourable, since smoke can flow above the platform. A cooler smoke plume will be more likely to follow the flow field of air around the platform and may conflict with escape routes and lifeboat stations at lower levels.

7.4.1.3 Soot Production

Soot production rates are given as soot yield, expressed as a ratio of soot production rate against fuel burning rate. The soot yield varies with fuel type, geometrical configuration of the fuel within the fire enclosure, and the air-to-fuel ratio of combustion.

Traditional building materials and furniture have a soot yield typically in the order of 1–2 %. Liquid and gaseous hydrocarbon fuels usually have characteristic soot yields significantly above this level.

7.4.1.4 Carbon Monoxide

The concentration of carbon monoxide (CO) in the compartment and at the outlet is typically less than 0.1 % for well ventilated fires. This is characterised by an air-to-fuel ratio above 50.

The concentration of CO in fires with limited air supply goes up to about 2 % when the air-to-fuel ratio becomes close to stoichiometric (15 kg/kg). CO concentration above 0.5 % can be found in fires with air-to-fuel ratio up to three times the stoichiometric ratio. For ventilation controlled fires and fires with oxygen starvation, CO concentrations of up to 35 % can theoretically occur. In practice, a CO concentration of 5 % at air-to-fuel ratios about half the stoichiometric ratio, has been measured in diffusion flames in poorly ventilated enclosures. This may be considered as a realistic maximum CO concentration in an offshore fire.

7.4.1.5 Carbon Dioxide

Carbon dioxide concentration varies with air-to-fuel ratio and a maximum concentration of 14 % has been measured at the outlet opening in experiments by SINTEF (1992).

7.4.1.6 Oxygen

Oxygen concentration at the outlet opening varies with air-to-fuel ratio from close to zero at the stoichiometric ratio, up to the concentration of ambient air at large for situations where excess air is available.

7.4.2 Smoke Flow and Dispersion

Smoke from fires in naturally ventilated areas will escape through openings and louvered walls. The hot gases are lighter than air and thus, buoyancy will create a smoke plume. The environment around the platform, characterised by wind direction and velocity, will influence the smoke plume. Both the smoke plume and the wind interact with the platform itself, creating areas with increased flow velocity and recirculating zones. Important questions to answer are:

- Can smoke be transported downwards after leaving an opening from the fire area, and be dragged below the platform?
- Can smoke flow upstream the wind direction?
- Will smoke enter the air intake for the accommodation areas ventilation system?
- Will smoke penetrate into a pressurised living quarter?

- How fast will smoke infiltrate a living quarter if ventilation systems are shut down?
- Which areas will be threatened by smoke in specified fire scenarios?
- What is the major impact of smoke on people?

The hazard of smoke is characterised by three factors:

- Reduced mobility
- Pain and injury to the personnel due to temperature of the smoke
- Incapacitation or death due to toxic or irritating components in the smoke.

The relative importance of these factors can be found by comparing the threshold values with the actual or predicted exposure in a fire scenario.

When soot concentration is determined by modelling of soot production rates and dispersion, this can be converted to a length of vision. Soot particles block the passage of light and visibility is determined by the intensity of the light source, the soot concentration, and the wavelength of the light.

The visibility of an object is determined by the contrast between the object and its background. Light emitting signs, for example, are two to four times easier to see than light reflecting signs.

7.5 Structural Response to Fire

7.5.1 Manual Methods

The simplest methods are directly based on results from fire tests, while the most sophisticated computer models calculate the temperature increase in a structural member based on a given temperature exposure curve and the thermal properties of the materials which are also temperature dependent.

7.5.2 Uninsulated Steel

When unprotected steel is exposed to fire, the temperature will in most cases rise to a critical level within minutes. A critical level is one at which the structural member is unable to fulfil its load bearing function. However, if the steel section is heavy and the temperature level is moderate, the structure may be able to carry adequate loads for a sufficient time without further fire protection. The temperature of an unprotected steel section may be predicted through an iterative process using Eq. 7.5 (SINTEF 1992):

$$\Delta T_s = \frac{h_{cr}}{c_{ps}\rho_s} \frac{A_i}{V_s} (T_g - T_s) \Delta t \quad (7.5)$$

where

ΔT_s = temperature increase in steel section ($^{\circ}\text{C}$)

T_s = temperature in steel section at time t ($^{\circ}\text{C}$)

$h_{cr} = h_c + h_r$, coefficient of heat transfer (includes both convective and radiant heat transfer) ($\text{W}/\text{m}^2 \text{ } ^{\circ}\text{C}$)

c_{ps} = specific heat of steel ($\text{J}/\text{kg } ^{\circ}\text{C}$)

ρ_s = density of steel (kg/m^3)

A_i/V_s = section factor of steel section (m^{-1}), where

A_i = area of the inner surface of the insulation material per unit length of the member (m^2/m)

V_s = volume of the member per unit length (m^2)

T_g = gas temperature at time t ($^{\circ}\text{C}$)

Δt = time interval (s)

This equation is based on the assumption of quasi-steady-state, one-dimensional heat transfer with the steel considered as heat sink. The heat supply to the section is considered to be instantaneously distributed to give a uniform temperature due to the high thermal conductivity of steel.

When the steel section is large, there may be considerable temperature gradients in the cross-sections. In such cases suitable computer codes should be used to predict the temperature response more accurately.

7.5.3 Insulated Steel

There are few methods suitable for the hand calculation of the temperature response of steel with passive fire protection. Those methods that are available are not applicable to all types of fire protection materials. These methods are simple iterative equations where the material properties of both steel and insulation materials are given as constants. However, the thermal properties of both steel and insulation materials may vary considerably with temperature, and the results from such calculations should be carefully checked with test results.

7.5.3.1 Simple Calculation Methods

Simple methods for the hand calculation of temperatures in an exposed insulated steel structure are limited to a one-dimensional approach. The calculation of the steel temperature increase ΔT_s of a member insulated with dry materials during a time interval Δt follows from Eq. 7.6 (SINTEF 1992):

$$\Delta T_s = \frac{\frac{\lambda_{ci}}{\delta_i}}{c_{ps}\rho_s} \frac{A_i}{V_s} \left[\frac{1}{1 + \frac{2\epsilon}{3}} \right] (T_g - T_s) \Delta t - (e^{\frac{\epsilon}{3}} - 1) \Delta T_g \quad (7.6)$$

$$\epsilon = \frac{c_{pi} \delta_i \rho_i A_i}{2 c_{ps} \rho_s V_s} \quad (7.7)$$

where

λ_{ci} = thermal conductivity for insulation (W/m °C)

δ_i = thickness of insulation (m)

c_{pi} = specific heat of insulation (J/kg °C)

ρ_s = density of steel (kg/m³)

c_{ps} = specific heat of steel (J/kg °C)

ρ_i = density of insulation (kg/m³)

A_i/V_s = section factor for steel member (m⁻¹)

T_g = ambient gas temperature at time t (°C)

T_s = steel temperature at time t (°C)

ΔT_g = increase of the ambient temperature during the time interval Δt (°C)

Δt = time interval (s).

These equations are valid for steel members insulated with dry materials. For wet materials the calculation of the steel temperature increase ΔT_s is based on the same equations with the following modifications:

- (a) Before reaching a steel temperature of 100 °C, Eq. 7.6 is used.
- (b) At a steel temperature of 100 °C, a delay in the steel temperature rise, Δt_v , is introduced. Methods for predicting the time delay are presented in SINTEF (1992).

When using hand calculation of temperatures in insulated steel structures exposed to fire, care should be taken when selecting the material data for the insulation material. First, the thermal conductivity varies with temperature. If the thermal conductivity is described with one single value, a relevant average value should be used. Secondly, all materials have an upper validity temperature, and calculations should not be undertaken outside this level. Thirdly, it is a good principle to try to validate calculations with test results.

7.5.3.2 Computer Calculations

There are many non-linear computer codes for temperature analysis of structural elements. Most computer codes can solve one and two-dimensional problems

although only a few codes are capable of solving three-dimensional problems. SUPER-TEMPCALC, and TASEF-2, are two codes which may be run on personal computers.

Both codes are based on the finite element method (FEM), and cover one and two-dimensional heat flow. The computer codes can analyse a cross-section of a linear structural element exposed to an arbitrary time/temperature curve. The cross-section can consist of different materials, and the thermal properties (λ , c_p) can be given as non-linear functions of temperature. The heat exposure is modelled either as a time/temperature-curve with a given convection and emissivity-value at the surface, or as a prescribed time-radiation relationship. Hollow sections can also be analysed.

The analysed cross-section is divided into an element mesh, and the governing transient heat conduction equation is solved at the boundaries of each element.

Figure 7.4 shows an element mesh for an insulated I-section steel column. The column is subjected to uniform heat exposure, and due to the two symmetry lines, only a 1/4 of the cross-section has to be analysed.

Results from a calculation should not be accepted unless the validity of the input-parameters is documented. Preferably the validity of the computer code should have been verified through comparison with appropriate test results.

When using manual methods, care should be taken when choosing the thermal parameters λ and c_p for the materials. For certain materials (gypsum and mineral wool) particular care should be taken into account, when using λ and c_p curves

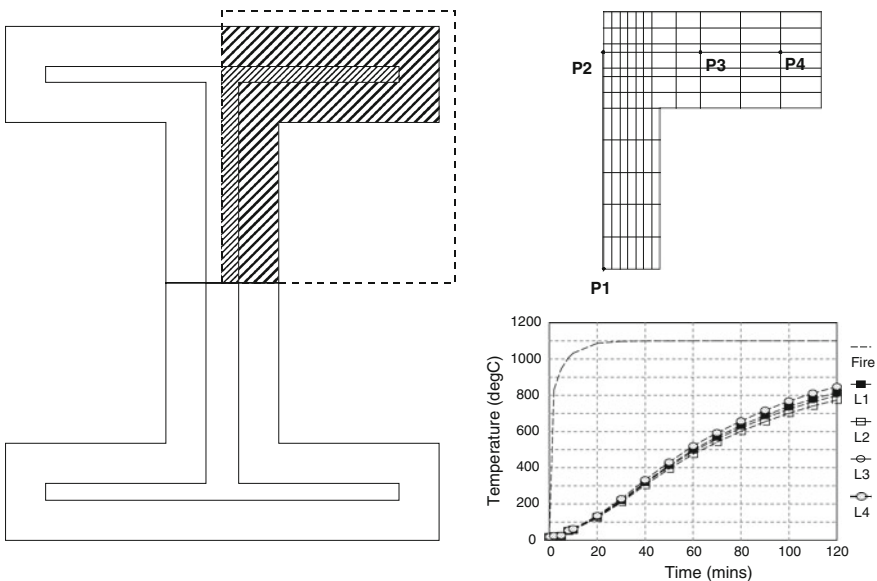


Fig. 7.4 Element mesh for an insulated I section steel column

outside certain ranges. When gypsum has reached a temperature of 600–650 °C the chemically bound water is released and evaporated, and a gypsum board will lose its strength and may fall off the protected structure. In calculations it is suitable to simulate this by a rapid increase in the conductivity curve at e.g. 600 °C.

Results from a temperature analysis with FEM computer codes may be presented as time/temperature curves for the individual nodal points, or as isothermal charts at given times.

7.6 Risk Reducing Measures

7.6.1 Overview

Measures to reduce risk in relation to the fire hazard have been the focus of the technical safety discipline for many years. There are several papers and reports published on these topics, and there is no need to go very deeply into these subjects. A full discussion of all relevant aspects is outside the scope of this book, which is focused on risk quantification.

The ISO 13702 standard was published in 1999 on these topics (ISO 1999), ‘Control and Mitigation of Fires and Explosions on Offshore Production Installations—Requirements and Guidelines’. The following are sections of the ISO 13702 standard that are relevant to the fire risk reduction:

5. Installation layout

- Leak prevention
 - Welded connections
 - Flange types with reduced leak probability
- Leak detection
 - Gas detection
 - Fire detection
 - Emergency shutdown system
 - Blowdown system
- Ignition prevention
 - Hot work procedures
 - ‘Ex’-protected equipment
 - Maintenance of electrical equipment
- Escalation prevention
 - Installation layout
 - Segregation of areas
 - Active fire protection
 - Passive fire protection.

6. Emergency shutdown systems and blowdown

7. Control of ignition

8. Control of spills

9. Emergency power systems

10. Fire and gas systems
11. Active fire protection
12. Passive fire protection
15. Inspection, testing and maintenance.

If the logic of a typical event tree is followed (see, for instance, Fig. 6.10), then the risk reducing measures may be structured as follows:

7.6.2 Recent R&D Experience

The most extensive R&D effort has been performed through the so-called ‘Blast and Fire Engineering for Topside Systems’ programme (BFETS), SCI (1998). This programme has included both fire and explosion research, the explosion related experience is discussed in Sect. 9.1.2. With respect to the fire related research, some of the main issues have been:

- Realistic fire loads have been established for jet fires as well as pool fires. Some of these fire loads are somewhat higher than anticipated.
- Pool fires in ventilated enclosures have been found to give almost as high heat loads as jet fires.
- Use of active fire protection, for instance deluge water systems, has been found to be even more effective than anticipated, especially in ventilated enclosures.

7.7 Dimensioning of Structural Fire Protection

7.7.1 Case Illustration

The case chosen to illustrate the dimensioning of structural passive fire protection (PFP) concern the upgrading of the deck structure of an existing installation. The deck structure in question is a module support structure consisting of trusses with box section members. There is a limited amount of process equipment installed inside the structure, which is relatively open.

The case study will demonstrate the calculations and risk evaluations necessary to determine whether the most severely affected parts of the structure can be effectively protected by PFP and how this may be efficiently accomplished.

7.7.2 Dimensioning Fire

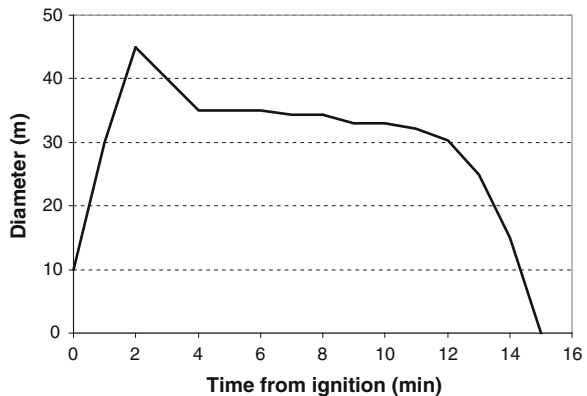
The previous requirements for design against fire in the Norwegian regulations for Fire and Explosion protection of offshore installations (NPD 1992a) and the regulations on structural design and protection (NPD 1992b) have been replaced by requirements in NORSOK N-001 (Standard Norway 2012) and N-003 (Standard Norway 2007). The requirements are the same, in the sense that adequate fire protection of load-bearing structures is required in relation to the dimensioning fire. Therefore, it is important to establish what a dimensioning fire is and what are the associated fire loads.

It should be noted that whenever PFP is used, it shall also have the capability to withstand the dimensioning explosion load, to protect against a scenario where fire follows an explosion. PFP therefore also needs to have explosion resistance. This is also addressed in a later section. The main characteristics of a dimensioning fire are:

- Heat loads
- Dimensions of fire
- Duration of fire.

The use of constant values for these three parameters will sometimes be too simplistic. The following example may illustrate this. If the contents of a liquid filled vessel (stabilised crude oil) spilled onto the deck is not taken care of by the drain system, a liquid pool on the deck of, say, 20 m diameter may result. The resulting fire will then have the same diameter, and a height of about the same value. More realistically, the height will be limited by the space between decks. The time averaged heat loads will depend on the ventilation rate and air supply to the flames, but may typically be 150 kW/m^2 . If the initial spill is 50 m^3 , the diameter is 20 m, and the average burning rate is 3 mm/min, then the average thickness of the pool is 0.159 m, and the duration of the fire is slightly above 53 min.

Fig. 7.5 Diameter of burning pool on sea surface as function of time since ignition



In theory, the diameter and height of flames should be constant during the duration of the fire. In practice, however, experience shows that the size of the pool will shrink, and the flame height reduce (unless it is limited by other constraints, such as distance between decks). In a full scale test with crude oil burning on the sea surface, the size of the unconstrained pool on the sea varied as shown in Fig. 7.5. The pool in that test was physically limited to 10 m, before ignition, after which it was unconstrained. The behaviour in the initial phase must be considered in the light of these constraints.

As a start, it will often be reasonable to assure that the fire dimensions and fire loads will be constant. In that case, the only variable to consider is the duration of the fire.

7.7.3 Fire Duration Distribution

If we make the approximation that all variables except duration are constant, we end up with a ‘one-dimensional problem’. Thus the assessment of the integrity of a structure subject to a dimensioning fire is limited to an analysis of fire response under the applicable loading as a function of time. The critical aspect will be to determine whether failure occurs before the fire has subsided. It is recognised that it is impossible to define the fire ‘Design Accidental Event’, based on the theoretical definition of DAE. Various practical considerations are therefore used, involving consideration of the following factors:

- Volumes of ESD segments
- Depressurisation capacities and times
- PFP applied on equipment and structures.

Figure 7.6 presents the exceedance frequency function for the cellar deck (inside the support structure) as a function of the duration of the fire, for the case study installation referred to in Sect. 7.7.1.

Fig. 7.6 Exceedance frequency distribution for fire duration on cellar deck

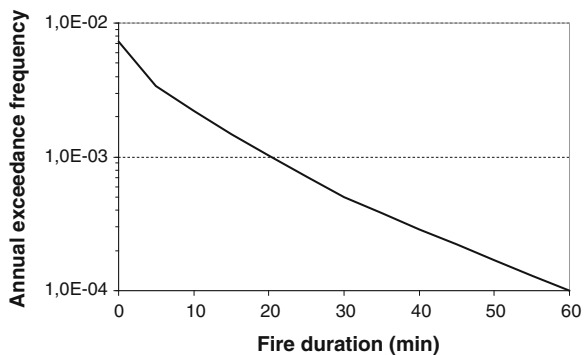
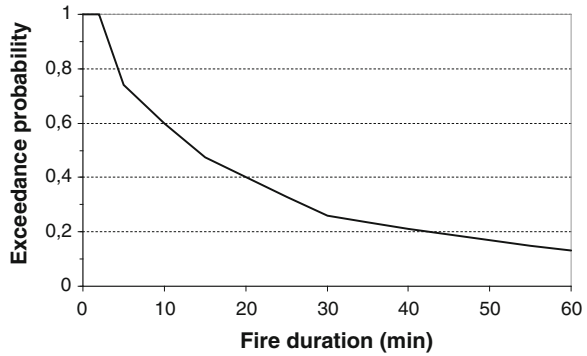


Fig. 7.7 Fire duration distribution on cellar deck



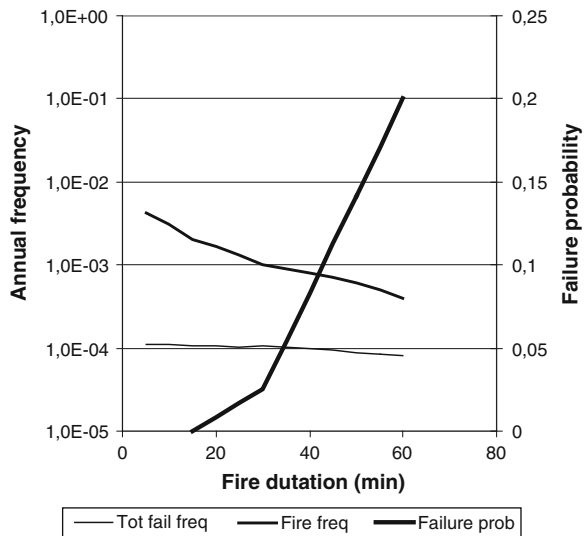
The frequency of all fires (exceeding 0 min) is 7.3×10^{-3} per year, whereas the annual frequency of fires that exceed 20 min duration is 10^{-3} . The duration that corresponds to 10^{-4} exceedance frequency is 60 min. 10^{-4} exceedance frequency shall be used as design basis for structural design, according to NORSOK S-001 (Standard Norway 2008).

The same distribution is presented in Fig. 7.7, where the conditional exceedance probability is presented for the same fire durations. The conditional probabilities are based on occurrence of fire within cellar deck.

It is shown that there is about 70 % probability that fires will last longer than 6 min. The probability that the fire duration exceeds 15 min is 50 %, where as the probability that the fire exceeds 40 min is 20 %.

There is no accepted way to interpret these curves in order to define the duration of the dimensioning fire. If the median value in the conditional distribution is chosen, then this would imply a duration of the dimensioning fire of 15 min.

Fig. 7.8 Occurrence frequencies for fire and system failure, and resulting exceedance frequency for system failure



7.7.4 Definition of Dimensioning Fire

Equation 7.8 presents the definition of a dimensioning fire according to the previous NPD regulations for load-bearing structures (NPD 1992b). A dimensioning fire is defined by the following equation:

$$p(\text{system failure}) = P(\text{system failure}|\text{fire}) \cdot P(\text{fire}) \leq 10^{-4} \quad (7.8)$$

This definition is applied to the exceedance probability curve in Fig. 7.8. The fire duration corresponding to a 10^{-4} exceedance probability, is approximately 37 min. The figure gives the frequency of fire as well as the probability of failure for the fire durations shown, as well as the resulting exceedance frequency function.

7.7.5 USFOS[®] Modelling

The program USFOS[®] is tailored for progressive collapse analysis of jackets and topside structures under extreme environmental and accidental loads such as ship collision, fire and explosions. The program is based on general continuum mechanics principles and accounting for non-linear geometry and material effects include several special features facilitating efficient non-linear static or dynamic analysis. The basic idea behind the formulation is to use one finite element to model each structural component and still obtain a realistic representation of the non-linear material and geometry effects.

Due to the choice of displacement interpolation functions, USFOS[®] predicts the exact buckling load of an axially compressed member with arbitrary end conditions and nodal forces. Non-linear material behaviour is accounted for by introducing yield hinges at the beam ends and mid-section. The plasticity model is formulated in the force space based on bounding surface theory. The thermal load effects presently accounted for include thermal expansion and reduction of yield stress and E-modulus at elevated temperatures. The effect of temperature loading on an elastic element is to produce forces related to axial expansion and bowing due to temperature gradients over the cross-section. Thermal expansion and reduction of E-modulus yields consistent nodal forces. Within the boundary

- South-west corner Diffuse gas fire, 18 m diameter sphere, truncated by distance between decks
- South-east corner Condensate pool fire, 24 m diameter sphere, flame height restricted by distance between decks
- Frame structure around top of shaft Diffuse gas fire, 18 m diameter sphere, truncated by distance between decks

Table 7.8 Typical fire loads according to fire type and fire water application

Fire type	Typical loads according to use of fire water (kW/m ²)	
	With fire water	No fire water
Diffuse gas	150	200
Liquid pool	100	150

surface concept both the yield and bounding surface contracts (at different rates) for increasing temperatures reflect the degradation of cross-sectional capacity.

7.7.5.1 Application in Risk Reduction Context

A comprehensive USFOS[®] analysis has been performed in order to provide further insight into the fire performance of the module support frame and the possible effects of installing PFP on selected members. Three locations are considered, referred to as the following cases:

- South-west corner
 - South-east corner
 - Frame structure around top of shaft.
- Failure of support structure considered to occur when relative movements exceed 0.3 m in any direction.

The South East corner is particularly critical, because this part of the MSF supports a heavy module. The fire loads on the MSF are as defined below:

The PSA regulations require that active fire protection (water spray systems) is not considered when PFP is calculated. On the other hand, in the QRA, the combined effect of both active and passive systems may be considered. In the present cases, the loads as shown in Table 7.8 are utilised as typical loads.

The values used in the study are different from those recommended in NORSOK S-001 (Standard Norway 2008). These values are discussed in Sect. 13.6.1.4. It should be noted that the USFOS FIRE[®] package has a module that may be used for calculation of the detailed fire loads as a function of fuel supply ventilation and time.

A detailed and specific analysis will be especially important when the modules are either considerably under- or over-ventilated. The typical values shown in Table 7.8 are otherwise usable (somewhat conservative) when ventilation is around the stoichiometric ratio (15–16 kg air per kg hydrocarbon fuel), typically in the range 10–20 kg air per kg hydrocarbon fuel. It should be noted that the following failure criterion was used in the analysis:

Table 7.9 Main loads from USFOS® analysis

Area	Time to failure (min)	Deluge accounted for	Comments
South-west corner	7	No	Fire size conservative for area
	10	Yes	Conservative fire size Model slightly conservative
	>150	Yes	Realistic fire size Most optimistic location
Top of column	16	No	Standard fire size used
South-east corner	22	Yes	Calculated with realistic fire size and heat load
	45	Yes	PPF on selected members

Please note that such movement may not necessarily imply collapse, but is likely to cause secondary rupture of piping, vessels, etc. Such mechanisms may supply extra fuel to the fire, and fire water systems may fail.

7.7.5.2 USFOS® Results

The results from the USFOS® analysis are presented in Table 7.9 for the three areas considered. The last case also includes the effects of providing PFP on selected trusses in the South-east corner. The details are discussed in a later subsection.

The last calculation, reflects the condition where PFP has been applied to the truss members beneath module support points. Under one module support two members are insulated while under the other supports only one of the members is insulated. This point, although it is the most highly loaded, is not likely to be subjected to high fire loads (only far field radiation), whereas the first support point would be engulfed by flame in most fire scenarios.

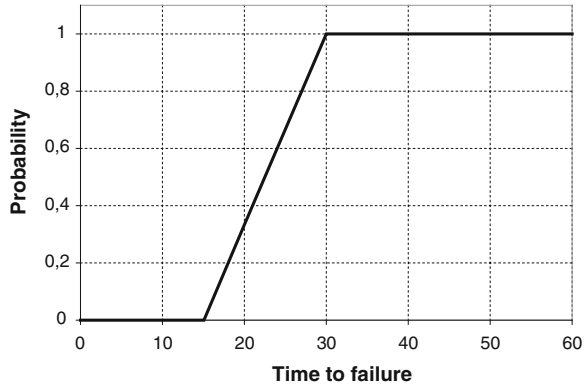
7.7.6 QRA Modelling

The initial failure model of the deck used in the QRA is shown in Fig. 7.9. It should be noted that:

- The curve is the overall average failure function for all decks and areas.
- The performance of the module support frame members is likely to be in the lower probability range.

This is a simplistic model which does not pretend to be accurate in any sense, but useful for the QRA modelling. The implications of the model are as follows:

Fig. 7.9 Base case failure probability model used for decks and areas in QRA



- Structural failure (to an extent that it gives escalation of the fire from one deck to that above) is impossible up to 15 min.
- Escalation of the fire through deck failure is certain after 30 min.
- It is assumed (as a simplified model) that the failure probability increases linearly between 15 and 30 min.

The definition of the curve may be expressed mathematically as follows:

$$P_f = \begin{cases} 0, & t < 15 \\ \frac{t}{15} - 1, & 15 \leq t \leq 30 \\ 1, & t > 30 \end{cases} \quad (7.9)$$

where

t = duration of fire (in minutes).

It is important to note that the USFOS[®] studies seen in the context of the QRA may be characterised as follows:

Fig. 7.10 Revised failure probability model to reflect vulnerability of structure when unprotected

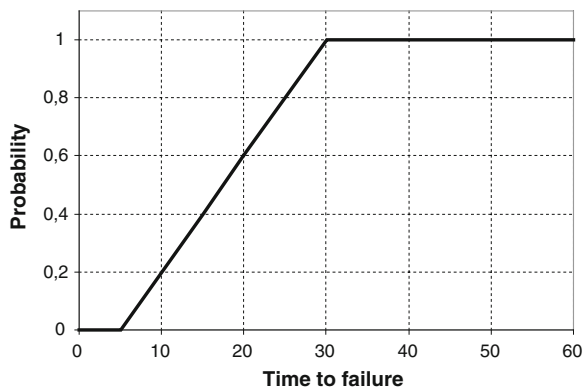
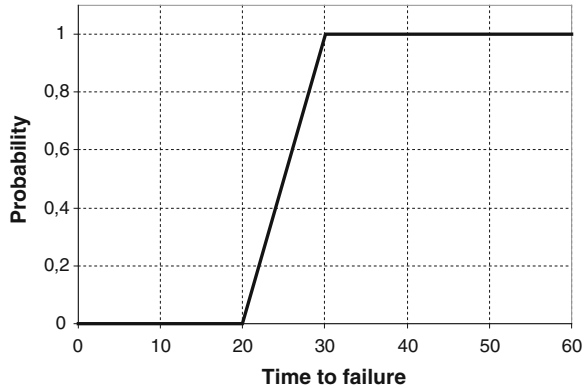


Fig. 7.11 Structural failure model after improvement of structural fire protection



- They provide ‘snapshots’ i.e., they provide a single deterministic calculation of one case out of a myriad of possible cases.
- They provide a specific time to failure in defined areas under given fire and structural loading.
- Since the USFOS[®] studies are normally conducted for the most critical areas in the most severe circumstances, they are inclined to define the lowest starting point of the failure curve.

For the evaluation of USFOS[®] results with respect to the QRA, the following should be noted:

- For the ALARP analysis, active and passive fire protection can be considered in combination, even though the regulations do not allow active fire fighting to be accounted for, when passive fire protection is dimensioned.

Following the results from the USFOS[®] studies, the failure model in Fig. 7.9 was revised as shown in Fig. 7.10.

This failure curve is similar to that defined by Eq. 7.9, except that the failure probability starts to increase above zero after 5 min rather than 15 min. The failure probability is less than 1.0 until the fire duration reaches 30 min, at which the probability of failure is 1, as with the previous model.

Lastly, Fig. 7.11 presents the failure function assumed to model the situation when the structure was protected with Passive Fire Protection in the most vulnerable areas.

The implication of Fig. 7.11 is that even in the most critical areas the structure will not fail for 20 min. In this case there would be only limited variations between the different parts of the structure.

These two modelling cases (represented by the failure models in Figs. 7.10 and 7.11) were selected to represent a conservative approach to the ALARP demonstration, in that a limited protection by PFP in one area could not improve the situation more extensively than is implied by these two diagrams, probably less extensively.

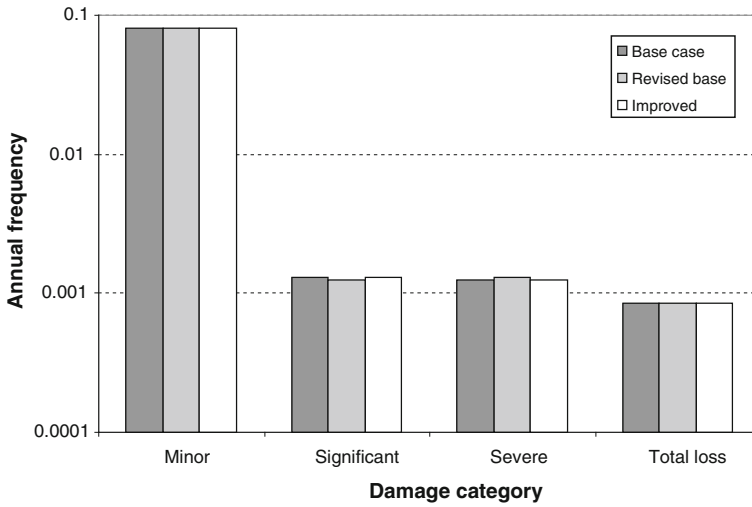


Fig. 7.12 Overall results for material damage risk

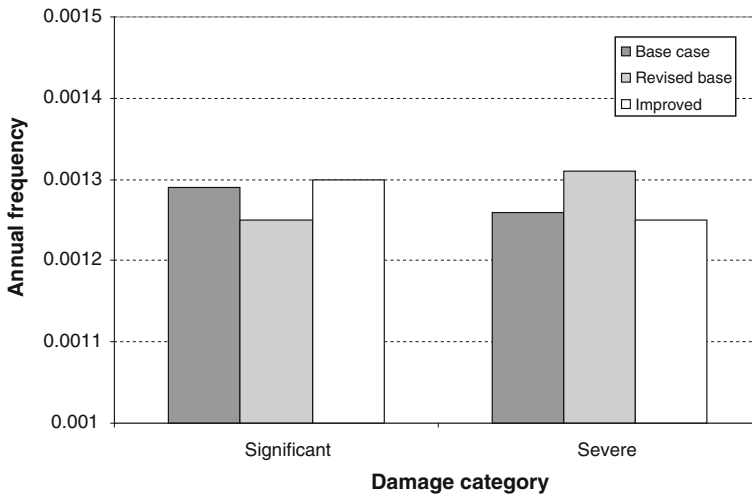


Fig. 7.13 Material damage results only for significant and severe damage

7.7.7 QRA Results

Figures 7.12 and 7.13 present the results for four categories of risk of material damage to the assets.

It can be observed that the influence on the material damage risk is very small, only in the order of 3–4 % change of frequencies for significant damage (one

module damaged) and severe damage (damage to two or more modules). This is interpreted in the following way: when the fire protection of the structure is improved, some of the scenarios that earlier would escalate to a second module, will be contained within one module. Therefore, the frequency of the most severe damage is reduced, while the lowest category is correspondingly increased.

7.7.8 Observations

The case study discussed in this section has shown several aspects of the use of advanced non-linear structural analysis in combination with QRA. The main observations that may be drawn from this case are the following:

- The non-linear analysis will enable reflection of the differences in structural sensitivity according to which structural members are affected.
- The analysis with the USFOS[®] (and associated software) allowed significant improvements to be identified from a very limited application of PFP on the structural members. Thus a realistic case for improvement could be defined and implemented. More extensive PFP application would not have been practical, neither from a technical nor economical point of view.
- The limited effect on risk levels from the improvement of structural fire protection is mainly due to the fact that no accommodation facilities are provided on the installation in question.

7.8 Blast and Fire Design Guidance

Steel Construction Institute, in collaboration with British Gas and Shell, and supported by a number of sponsors, issued in 1992 the following document:

- Interim Guidance Notes for the Design and Protection of Topside Structures against Explosion and Fire (SCI 1992).

This guidance document has been undergoing revision for a number of years, and a Revision 2 has been prepared for some years. The following is the status of the different parts (see <http://www.fireandblast.com>):

- Fire and explosion guidance: Part 0—Fire and explosion hazard management, Issue 2, October 2003 (Oil and Gas UK 2007).
- Fire and explosion guidance: Part I—Avoidance and mitigation of explosions, Issue 1, October 2003 (Oil and Gas UK 2007).
- Fire and explosion guidance: Part II—Avoidance and mitigation of fires, Final draft, February 2006 (Oil and Gas UK 2007).

The final version; Fire and Explosion Guidance (Oil and Gas UK 2007) is published by Oil and Gas UK (see <http://oilngasuk.co.uk>).

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