FIRE CFD MODELLING APPLIED TO OFFSHORE DESIGN

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1. INTRODUCTION

Fires on offshore platforms contribute to a major part of the total risk. Nevertheless, the methodologies that are used to estimate fire risks and design fire protection and mitigation means may be coarse and based on subjective opinions and standard solutions.

Prediction of fires and radiation impact could be performed using free field models. These models are based on fires in open terrain, and work fine for the far-field which is a typical situation of interest for most onshore installations. However, in an offshore module, the fire is constrained by walls and decks and confinement which will completely change the location and impact of the fire. The free field models usually apply constant surface emitting powers from the flame surface. This radiation flux is largely varying dependent on the flame thickness and temperature, causing the free field model to have a considerable uncertainty compared with a more detailed CFD (Computational Fluid Dynamic) model.

In the deterministic method, a credible fire scenario is defined as the fire which the structure needs to withstand. The selection of this scenario needs to be done very carefully because it ultimately will decide where to locate the PFP (Passive Fire Protection). The size of the selected scenario may vary considerably, indicating the uncertainty of the PFP coverage estimate may be significant. Normally, when a selection of the credible scenario is performed, some conservative assumptions are made due to the uncertainties involved. This results that the PFP coverage is generally larger than actually needed. In comparison, the accuracy of the probabilistic approach is improved because a larger number of scenarios are involved (see also Fernandez & Carretero, 1994, regarding the same topic for nuclear plants). Also, as a result of the present investigation, the scenarios which have the most influence on the fire impact are used in the probabilistic approach. Furthermore the proposed probabilistic approach uses a risk acceptance criterion to decide where to locate the PFP. This greatly improves the consistency of the method. By using a common risk acceptance criteria in the fire analysis, this analysis can be performed together with the other accident analyses (explosion, ship collision, dropped object, etc.) and the resources for prevention of accidents can be applied using the means where the risk reduction is highest.

PFP also causes inspection and maintenance to be more difficult resulting in a higher probability of failure, or the need for more inspection hours. This causes more personnel in the process area, which also represents an added ignition source.

Prior to the present development, Det Norske Veritas (DNV) has developed a probabilistic explosion procedure (Huser and Kvernvold 2000, Huser et al 2000, 2001, 2002) and a combined QRA (Quantitative Risk Analysis) analysis using CFD (Vianna 2005 and Vianna 2007). These procedures are based on the NORSOK (2001) procedure which is adopted by all operators in the North Sea. The present development is performed using the same principles as in the explosion procedure, and is a continuation of the work performed by Dalheim at al (2002).

An essential part of these probabilistic procedures is to use CFD methods to simulate the dynamics of the fire. In the explosion analysis, the FLACS (from Gexcon, Norway) explosion software is applied, and in the present analysis, KFX (Kameleon Fire Modeling) and FAHTS (structure heat-up) are applied. This combination of CFD and finite element tools uses state-of-the-art technology, and are also designed for use in often short deadline offshore projects. For example, the geometry model needs only to be made once for the FLACS and KFX programs. This geometry model is usually obtained by converting from existing CAD geometry models. It is also possible to transfer results directly from KFX fire calculations to FAHTS steel heat-up calculations, and further from FAHTS (Fire and Heat Transfer Simulations) to USFOS collapse analysis. FAHTS and USFOS are Finite Element (FE) programs which models the framework structure. These FE models are also imported from most standard FE structure packages.

2. NUMERICAL MODELLING

In the present work, the fire phenomena have been modelled using the principle of conservation applied to mass, momentum, enthalpy, mass fraction of fuel, turbulent kinetic energy and the dissipation rate of turbulent kinetic energy. Analysis of the differential equations describing the conservation laws for these quantities indicates that the Favre-averaged variables obey a generalized equation (equation (1)), in which φ represents the dependent variable u_i; h; Y_i; k; ε; and Γ_φ represents the turbulent exchange coefficient for that variable and S_i represents the corresponding source term:

$$\frac{\partial(\beta_v \rho \phi_i)}{\partial t} + \frac{\partial(\beta_j \rho U_j \phi_i)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho \Gamma_\phi \frac{\partial \beta_j \phi}{\partial x_j}\right) + S_i \tag{1}$$

Combustion is modelled based on the Eddy Dissipation Concept (EDC) of Magnussen 1976. Further information on the combustion model is described by Magnussen 1976. The porosity technique is applied in the modelling and it is represented in the equation by β. Volume porosities and area porosities are considered. A detailed discussion about porosity modelling in reacting flows can be found in Vianna 2010.

The radiation is solved by an enhanced version of the Discrete Transfer Model by Shah and Lockwood 1979.

The steel heat up is modelled using FAHTS (Fire and Heat Transfer Simulations). The code is tailored to form a link between the CFD fire modelling from KFX and the mechanical response simulations from USFOS. FAHTS is a finite element program using implicit tine integration scheme. The code is based on a general formulation but it is specially designed to be used in connection with USFOS. The Fourier equation (equation 2) is resolved for the entire system. More detail about FAHTS can be found in the code manual.

$$\frac{\partial(\rho c T)}{\partial t} = \frac{\partial}{\partial x}\left(K_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z}\right) + q \tag{2}$$

Where *c* is the heat capacity and *k* is the thermal conductivity in x, y and z direction.

3. DEVELOPMENT OF THE PROCEDURE

A systematic investigation of a large number of fires was performed prior to development of the procedure. This involved simulation of a large set of jet fires in a separator area. The purpose of this investigation was to determine which parameters are most important for the severity of the fire, emphasizing on the collapse of steel structure and equipment. Main results from this exercise are detailed information about how complex 3D transient heat loads can be reduced and applied in the probabilistic procedure, as well as information about which parameters needs to be considered in the probabilistic procedure.

3.1. DYNAMICS OF OFFSHORE FIRES

It is found that the dynamics of the fire is important to consider in order predict when and where collapse occur. The fact that the hottest zones move during a fire gives a considerable relief for the structure. The movement of the flames is illustrated with an example of a horizontal jet shown in Figure 1. Here, the flames are shown (with colors) for two different snapshots of the jet fire; the initial leak (96 kg/s) and after 5 minutes (24 kg/s). The heat flux is measured on a horizontal pipe running in the x-direction, shown in Figure 1, crossing in front of the leak at about 30 metre from the leak. The heat flux received by this pipe is plotted in Figure 2, indicating that for the initial fire, there are two hot regions with 500 kW/m2, one on each side of the centerline of the jet. When the leak rate has been reduced to 24 kg/s and 6 kg/s, the hottest point on the pipe is at the centerline of the jet.

Due to this dynamic movement of the flames, the hottest spots on the pipe will also move. The first minute of the fire when the leak rate is 96 kg/s, the pipe receives the maximum heat flux of 500 kW/m2. However, after 5 minutes, the same spots only receive 130 kW/m2. At 5 minutes, the hottest spot has moved about 2 metres to the West and here the flux is 240 kW/m2. For this example, the worst heat fluxes on the pipe are found, as show in Figure 3. Here, the overall maximum heat flux at any place on the pipe is compared with the physical location that is worst early and the physical location that is worst late. This example shows a central point of the new fire procedure. Only heat load on fixed locations is used when the time to collapse is estimated.
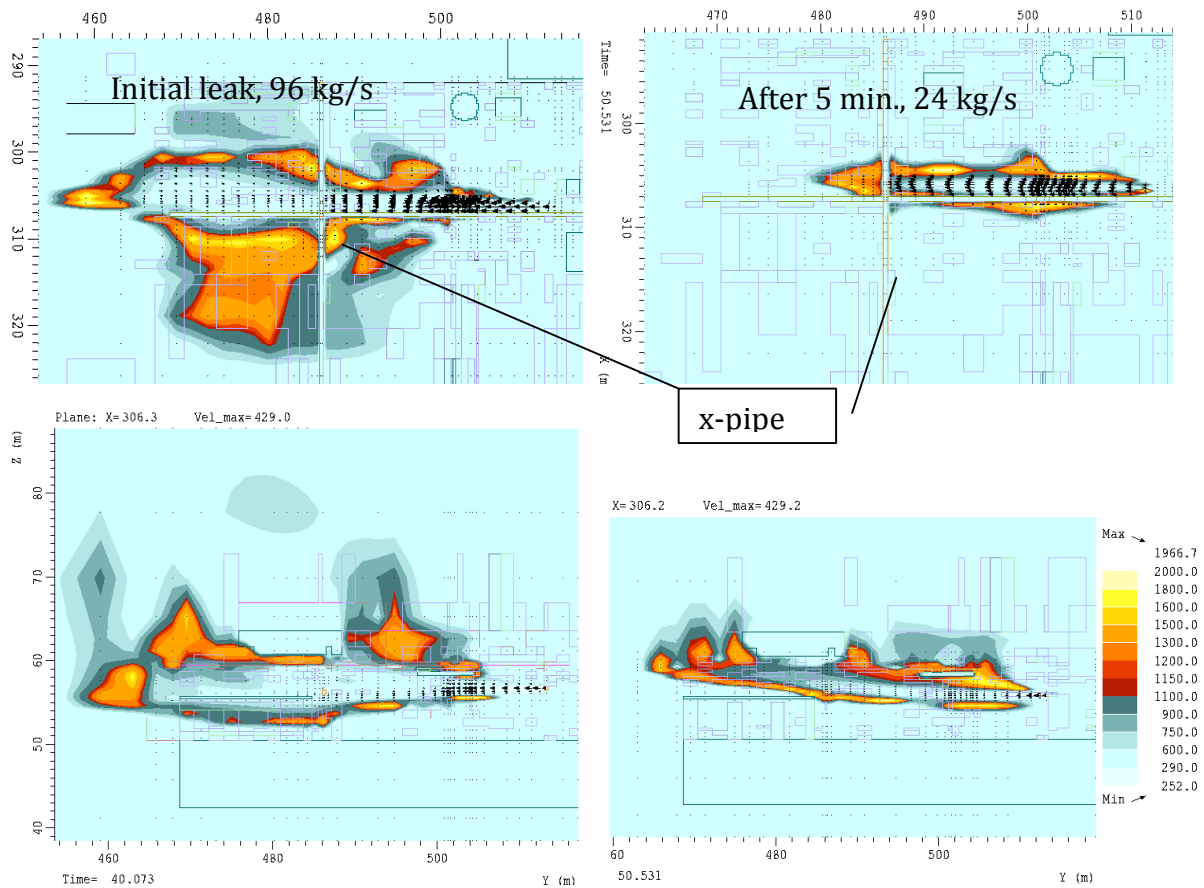
Figure 1. Temperature contour plots (K) of the jet fire at two times; initially, with 96 kg/s (left); and after 5 minutes, 24 kg/s. Horizontal cuts through the x-pipe (upper two plots) and vertical x-plane through the leak. Platform North is to the right in all plots.

3.2. PARAMETERS THAT NEED TO BE CONSIDERED

The parameters, wind speed, wind direction, leak rate, jet direction and leak location were varied by running different KFX simulations. From each case were taken out heat loads on several elements in the module. When analyzing the results, it was found that the most important parameters were the leak direction, leak location, whether the jet hit an obstruction or not, the initial leak rate and the duration of the leak. All these parameters are considered in the new procedure. The wind speed and wind direction are normally not causing significant impact on the results for jet fires.
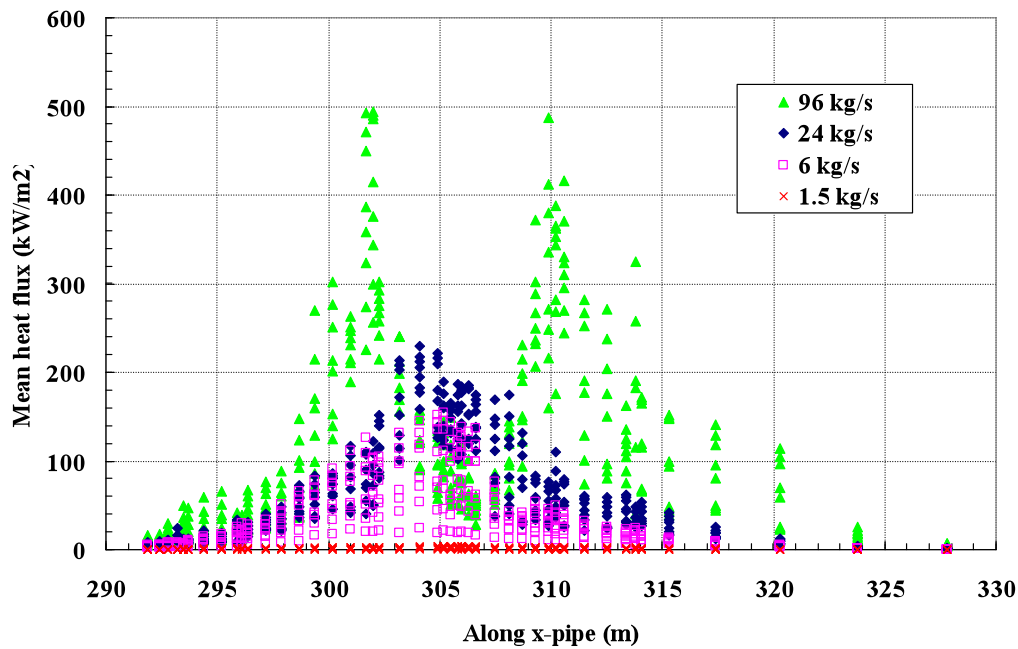
Figure 2   Incoming heat flux (radiation plus convection) on the surface of the x-pipe for 4 leak rates. Each x-coordinate has a value on 8 angle locations.
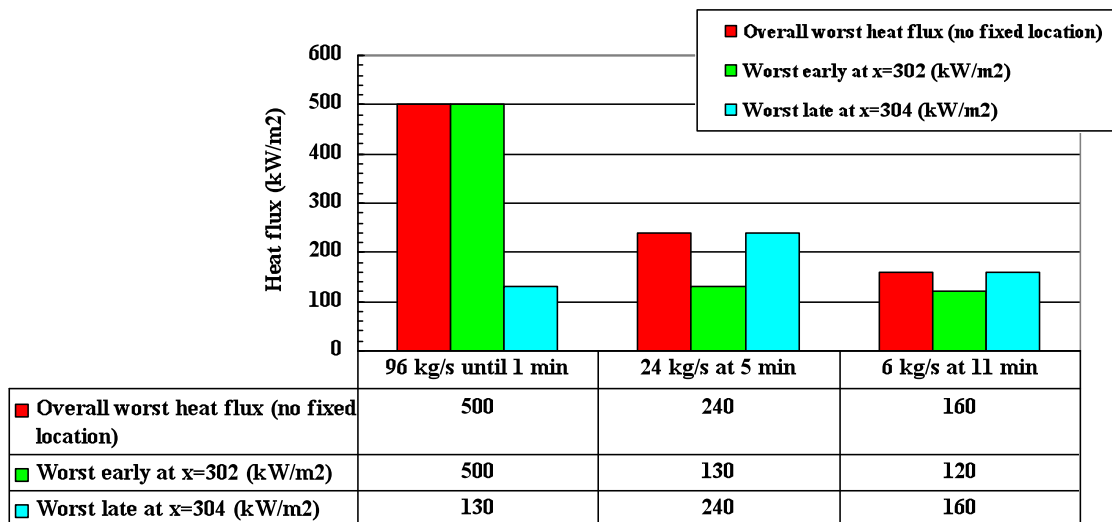

	96 kg/s until 1 min	24 kg/s at 5 min	6 kg/s at 11 min
■ Overall worst heat flux (no fixed location)	500	240	160
■ Worst early at x=302 (kW/m2)	500	130	120
■ Worst late at x=304 (kW/m2)	130	240	160

Figure 3 Heat flux at pipe surface. Comparing overall worst load with dynamic heat load.

4. PROBABILISTIC PROCEDURE

A general detailed probabilistic procedure is developed based on the findings from a large set of fire simulations with CFD. The procedure is based on the same principles as the NORSOK Z13 procedure for explosion analyses. However, the explosion procedure is somewhat simpler since its result is primarily the dimensioning load on a given wall;

therefore, only a single number. The results from the fire analysis are primarily the locations of Passive Fire Protection (PFP) as well as the degree of covering. The results are presented as detailed maps showing which beams or equipment need PFP.

The new probabilistic procedure is performed in 3 main steps as indicated in Figure 4:

1. Run KFX dynamic fire simulations. A number of pool and/or jet fire scenarios are defined based on selected leak segments, initial leak rates, leak profiles, leak locations and leak directions. Results from each scenario are taken out as dynamic heat flux series on the most critical locations (as illustrated in Figure 3), and volumes that receives dynamic heat flux above set levels. These two parameters (flux and volumes) are required to define the severity of the fire.

2. Run EXPRESS FIRE probabilistic analysis. This program is an extension of EXPRESS, Huser et al (2000-2002) which also calculates exceedence curves for fire load. The fire load is more complicated than the explosion load because it is a function of the dynamic heat flux, the duration of the fire, as well as the volume of the fire. Therefore, the fire load exceedence curves are more involved. The exceedence curves show, however, the frequency of exceeding a given fire load. Using a risk acceptance criterion, the exceedence curves can be used to select the Dimensioning Accidental fire Load (DAL). The construction must hence be dimensioned to withstand all fires that has up to this load.

3. In this step is used the DAL fire load to run the steel heat-up and collapse analysis with FAHTS and USFOS. Actual fires from the KFX simulations are selected and used as input to the FAHTS simulations. There may be several fires that fall inside the DAL size, some with different locations, and some with different intensity and durations. Therefore, several FAHTS and USFOS simulations must be performed. During the first run, no PFP is added. The collapse analysis will then show if there is collapse or not. If collapse occurs, PFP is added to the structure model on all elements that are collapsing for all DAL scenarios. Then the cases are run again. If collapse is not occurring, the procedure is stopped.
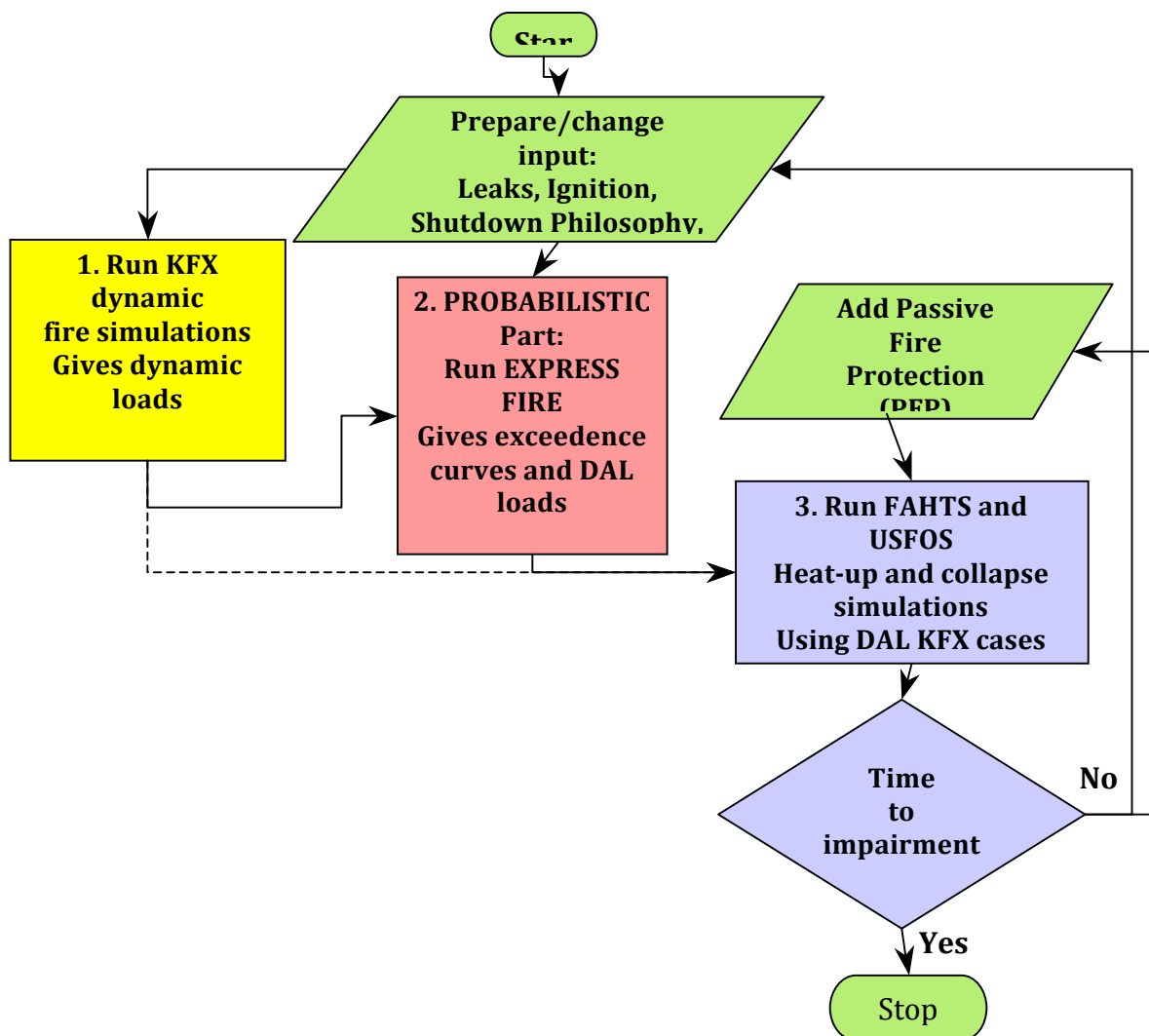
Figure 4   Flow diagram new detailed probabilistic fire procedure.

5. FIELD EXAMPLE

A field example is described in order to highlight the main points of the probabilistic procedure. The example is taken from an existing platform where two new gas risers and a pigging station are predicted to be installed (Vianna 2004). The pigging station is located on the West side of the lowest deck. The objective of the analysis was to decide where PFP coverage was needed (if needed) in the lower deck area, caused by fires in the new pigging station. This area reaches over the entire lower deck of the platform. This example only considers leak from the new pigging station, and the other pipes and equipment in the same area is not included as leak sources, hence the analysis is reduced compared to a complete analysis in an area. A Quantitative Risk Analysis (QRA) was also performed together with this PFP study. Results in terms of scenario definitions, leak frequencies and ignition probabilities from the QRA are applied in this example. It is here shown, one deterministic and one probabilistic result.

5.1 Deterministic approach

Three leak scenarios are selected from the scenarios defined in the QRA. The selected scenarios are the small, medium and large leaks from the largest segment in the new pigging

station. The jet direction is towards the interior of the platform. The three scenarios were simulated using KFX for the fire simulations and FAHTS to simulate the heat-up of the primary structure. It was found that the large scenario was reaching longest inside the new deck. Therefore, this scenario was used to decide how far inside the deck needed PFP. The FAHTS steel heat-up simulations in Figures 6 and 7 shows that the temperature reaches above the critical temperature that will cause collapse until Row D. Hence, the PFP need to cover until Row D. Figure 5 shows the construction from above, indicating the locations of the rows.

5.2 New Probabilistic approach

A simplified version of the probabilistic procedure presented above is applied in this example. The first step involves both KFX fire and FAHTS heat-up simulations. The second step is further performed using results from the steel heat-up calculations. The 3rd step, which involves USFOS collapse simulations, is omitted. The assumption that has to be made when using this simplified probabilistic approach is the criterion for collapse. In this example is used a collapse criterion based on the temperature in the steel. Typically the modulus of elasticity is reduced by 50% when the temperature reaches $500^{o}C$. This temperature is used as a criterion of when collapse occurs. Note that this is a conservative approach, since the actual stress in beams and the redundancy in the framework is not considered.

The main steps that are performed are described as follow:

First, a number of fire scenarios are defined from the two ESD segments in the new pigging station. For each scenario, all leak directions that can cause collapse are simulated. These are leak directions towards the interior of the lower deck, as well as up and down. The defined scenarios are simulated using KFX which gives the extent of the fire and the transient heat flux in the 3D domain. In this example, FAHTS heat-up simulations were also performed prior to the probabilistic assessment. Results from KFX are imported directly into the FAHTS model ensuring that the true dynamic loads are applied for the steel heat-up simulations.

Results from all KFX and FAHTS simulations are used in the probabilistic routine. Each scenario has now an expected frequency and a consequence. The consequence is in this example defined as the distance inside the lower deck that will collapse without PFP coverage. This distance is obtained from steel temperature plots as shown in Figures 6 and 7. It can be seen from these plots that a medium fire reaches to Row C, and a large fire to Row D. Note that in the general procedure, the consequence is instead defined as a heat load, including duration and volume. Result from this step is a plot showing the frequency as a function of the distance inside the lower deck that needs coverage (Figure 8). This plot is used together with an acceptance criterion to decide which distance inside the lower deck shall be protected. The acceptance criteria used here is 2E-5 per year. A typical acceptance criterion for impairment of safety functions caused by fires is 1E-4 per year, NPD (2002). However, using this criterion it is necessary to consider all leak sources in the area. In this example, only a part of all process equipment in the area is considered. It was found that the new pigging station consists of approximately 20% of all equipment in the lower deck. Therefore, the acceptance criteria for accidents in the pigging station was assessed to be 2E-5 per year. Using this criterion, it is found that PFP coverage is needed until Row C.

In comparison with the deterministic approach, it is shown that the PFP coverage can be reduced when using a probabilistic approach. The total cost savings by reducing the PFP from Row D to Row C is estimated to 1.5 mill US$, using typical cost of PFP as 500 US$ per m2, and assessing that the area that needs to be covered between Row C and D is approximately 3000 m2.
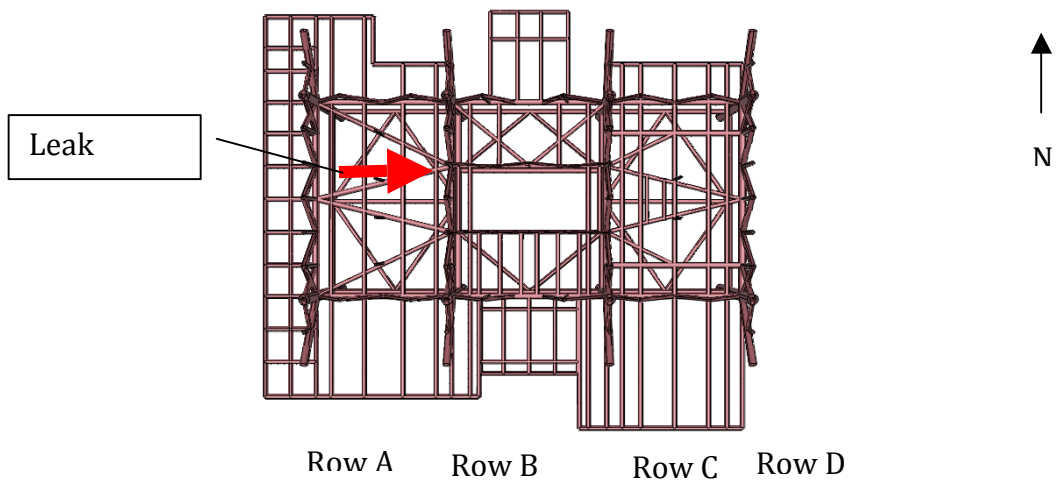
Figure 5   FAHTS Finite Element model used to the primary structure heat-up calculations.
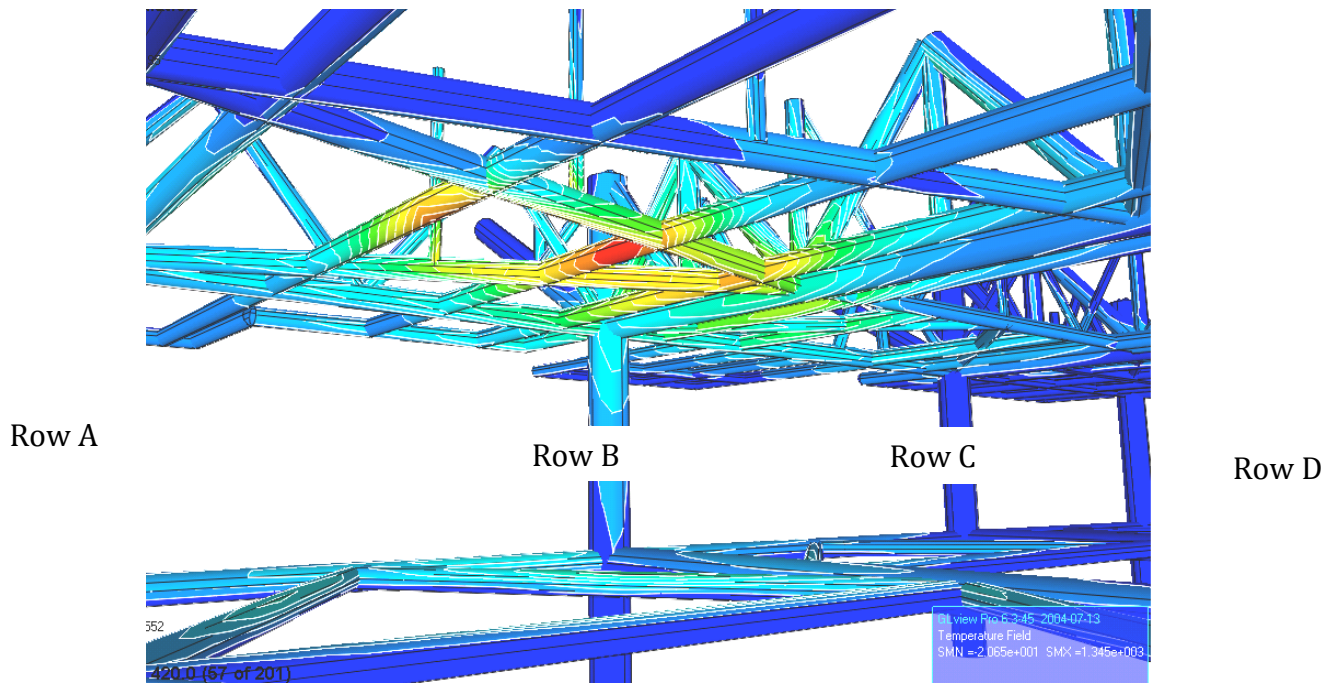

Figure 6. Medium fire, jet towards East. Temperature (C) in primary structure at the time of maximum temperature. View from southwest close to the leak location towards the 4 columns on the north side. Legend is shown in Figure 7.
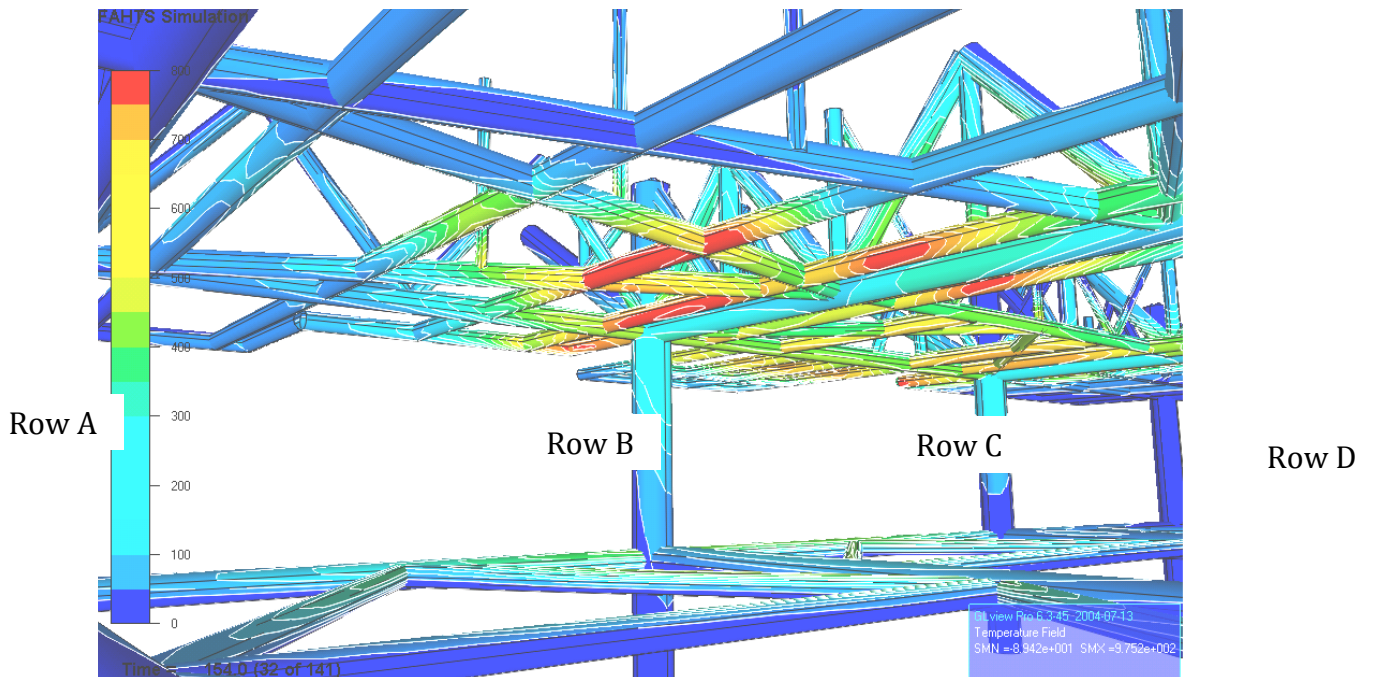
Figure 7 Large fire, jet towards East. Temperature (C) in primary structure at the time of maximum temperature. View from southwest close to the leak location towards the 4 columns on the north side.
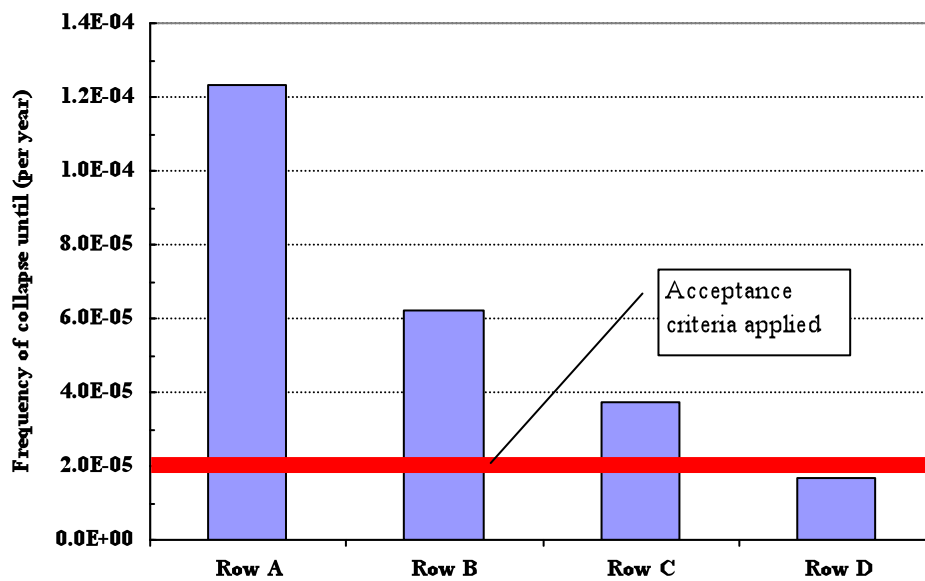

Figure 8 Frequency of collapse of primary structure as a function of distance from the fire. Row A is closest to the fire (see Figure 5).

6. CONCLUSIONS

A probabilistic procedure for the design of Passive Fire Protection (PFP) coverage has been developed and presented. The procedure relies on detailed Computational Fluid Dynamics (CFD) calculations for the prediction of fire and radiation impact, and on detailed Finite Element (FE) structure calculations for the prediction of steel heat-up and collapse. As a part of the development, the most important effects that influence the fire has been identified. These are the dynamic effects of the fire, the leak directions and leak location as well as the initial leak rate and the leak duration. All these effects are considered in the new procedure.

The procedure was applied on a field example together with a conventional deterministic approach. In comparing the final results it is found that considerably less PFP is needed when using the probabilistic approach. The savings obtained using the probabilistic approach is of the order 1-2 mill US$. This was obtained considering only one area of the platform. It is expected that an even more significant PFP cost reduction can be obtained with the application of the probabilistic approach for the whole platform in comparison with the results of the deterministic approach.

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