공학석사 학위논문

Study on a Probabilistic Fire Risk Analysis and Structural Safety Assessment of FPSO Topside Module

FPSO 상부구조에 대한 확률론적 화재 위험도
해석 및 구조 안전성에 관한 연구

2014 년 02 월

서울대학교 대학원

조선해양공학과

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이 논문을 공학석사 학위논문으로 제출함

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2014 년 2 월

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Abstract

Study on a Probabilistic Fire Risk Analysis and Structural Safety Assessment of FPSO Topside Module

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Many offshore platforms are usually exposed to the flammable oil & gas circumstances; hence hydrocarbon fire is a big threat to the offshore platforms. Fire accident on the offshore platform occupies a major part of the total risks. Nevertheless, former procedures of fire

risk analysis used in the industry are still not intact enough to evaluate the risks related to fire accident. For this reason a new procedure of fire risk analysis is established in this paper to overcome the deficiencies in the former FRAs.

In the new FRA procedure, the key parameters used for constructing fire scenarios are carefully considered and discussed for fear of the too much conservative judgment. Some of the parameters are considered in a probabilistic way or by using historical database and even sometimes based on the information of P&ID and PFD. CFD fire simulation is carried out based on the identified representative fire scenarios. In the fire simulation, the dynamic effect of hydro carbon fire determined by the inventory condition is also properly reflected by applying an effective method called 'snapshot'. Furthermore, for investigating the structural response under the fire, heat transfer analysis and non-linear structural analysis are both included in the new FRA procedure.

In the former FRAs, a concept of exceedance curve with certain physical variable is generally used in the frequency analysis for combining the results of fire simulation and fire frequency calculation. The purpose of using exceedance curve is for deciding a DAL, which is used for structure design against the fire accident or determination of proper PFP application area. Whereas, in the new FRA procedure, a new concept of structural cumulative failure frequency is presented to take place of the conventional exceedance curve. The purpose of using cumulative failure frequency in the new FRA can be summarized as two aspects. One is to solve the connection problem between the determined design load and structure analysis existed in the former FRAs, and other one is to have the determination of PFP application area become more intuitively and precisely.

Generally, in the offshore platform PFP (Passive Fire Protection) is the most common and useful measure to reduce the failure of offshore structure under the hydro carbon fires. However, wide use of the PFP leads to a considerable increase of total project cost and this indicates that minimizing or optimizing the application areas is quite important. In that sense, cumulative failure frequency presented in this paper can be a quite useful tool to determine the proper PFP application areas for the structures. Furthermore, in order to demonstrate more detail of the new FRA procedure, an example with FPSO separation module is presented at last.

Keywords : QRA(Quantitative Risk Assessment), FRA(Fire Risk Analysis), PFP(Passive Fire Protection), CFD, Snapshot

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Contents

List of Figures

List of Tables

NOMENCLATURE

DAL	Design accidental load
ESD	Emergency shutdown
EDP	Emergency depressurization
FRA	Fire risk analysis
FAHTS	Fire and heat transfer simulator
HC	Hydro carbon
HSE	Health and Safety Executive
HCRD	Hydro carbon release database
KFX	Kameleon FireEx
OGP	Oil & Gas producer
PFP	Passive fire protection
PFD	Process flow diagram
QRA	Quantitative risk assessment
SDV	Shutdown valve

1. Introduction

1.1. Research Background and Objective

Facing with the rapid development of society and industry, energy consumption and requirement have been increasingly grown in the last few decades. In the past, the main source of human fuel comes from the crude oil buried underground but now it has been changed. The increasing energy requirement forces the resource exploitation activity to expand to the sea floor, driving the whole energy industry into a new era. The development of drilling & subsea techniques provides a significant possibility of exploiting the crude oil & gas buried under the sea floor, and also many different shapes of offshore platforms are designed to provide a stage to ensure the availability of drilling & exploitation activity for deeper and deeper water.

However, because most of the offshore platforms are exposed to the flammable oil & gas circumstance, hydrocarbon fire accident is a big threat to the offshore platform. Typically, there are 3 types of offshore hydrocarbon fire, respectively jet fire, pool and BLEVE (Boiling liquid expanding vapor explosion). All of these fires could possibly weaken the strength of offshore structures or safety equipment and result in a considerable disaster.

Fig. 1 Piper Alpha accident

One of the typical offshore platform fire & explosion accidents in the history is the well-known Piper Alpha disaster in 6^{th} June, 1988. The disaster was begun with an error of maintenance routine procedure. During the work shift, the primary propane condensate pump was failed, but none of the shifted workers were aware that a vital part of the equipment had been removed and decided to start the backup pump. Gas products escaped from the hole left by the valve at a high pressure and ignited. Afterward, the fire spread most of the platform, destroyed some oil lines and a large quantity of stored oil burned out of control. The whole accident took place only in 22 minute, and caused the loss of 167 crewmen and $ 3400 million.

Fig. 2 Deep Water Horizon accident

Another typical accident is the Deepwater Horizon disaster occurred in 20th April, 2010. The accident was caused by a HC blowout from the well which resulted in an explosion and fire on the rig later. 11 people lost their lives during the accident, and the whole rig sank after the 36 hours of struggling. Moreover, during the accident the whole well control system (including BOP) was failed, and leakage from the well continued for 87days even though several interventions were tried to stop the situation. Nevertheless, the considerable amount oil spill still left a giant damage to the surrounding environment in the end.

As above two accidents reflected, explosion & fire accident is quite deathful to an offshore platform even though it has a very little frequency of occurring; hence the risk management should be carried out to guarantee the survival of offshore plant as far as possible from those destructive accidents.

QRA (Quantitative risk assessment) is the most advanced method of managing all types of possible accidents on the offshore platform, and the main purpose of QRA is evaluating the quantified risk which is defined as the product of consequence and frequency. Quantified risk is usually used for determination of the prevention and mitigation measures against the accidents. QRA for an offshore plant is consisted of many sub-parts according to different types of risk, and FRA (fire risk analysis) is one of the sub-parts for evaluating the risk related to fire accident.

However, existing methods of fire risk analysis used in the industry are lack of standard procedure, therefore those FRAs appeared in the past offshore projects were not unified. Practical details associated with the methodologies involved in the former FRA procedures are quite diverse and ambiguous because they were independently carried out by different engineering companies. Furthermore, according to the different levels of accuracy or interesting targets, the physical variable used in the procedure for calculating the DAL is different (e.g. flame size, heat dose, heat flux etc.), and this could probably influence the methodology of FRA.

Facing with above problems of former FRAs, a new scenario based probabilistic FRA procedure is established in this thesis. The purpose of the new FRA procedure can be sorted out as two aspects. One is regulating a general procedure to reduce the variances and uncertainties in the former FRAs, and the other one is constructing an unprecedented FRA procedure, which is focusing on the connection problem between fire simulation and structural consequence analysis to identify the failed structure members that need certain protection. In the former FRA procedures, the analyses are normally ended up with calculating DAL (design accidental load), and no more detail procedure is described for how to use the determined DAL to perform the structural consequence analysis. This is because the determined DAL is usually expressed by certain physical variable, which is quite difficult to be used in structural consequence analysis. Therefore in the former FRA studies, the part of structural consequence analysis is always either omitted or considered with an uncertain procedure. To solve this, a lot of efforts are paid in this thesis to think about the way how to probabilistically reflect the result of structural consequence analysis in the FRA studies, and the answer is the cumulative structural failure frequency. By using the cumulative structural failure frequency, structural response under the fire can be easily connected to the frequency analysis, which makes possible to probabilistically identify venerable parts of topside structure and optimize the area of PFP application or deluge system.

1.2. Research Status

FRA (Fire risk analysis) is defined as a course of study, which determines the threats of potential fire scenario to the offshore plant and its associated facilities through proper number of fire simulations as well as structural consequence analysis if needed. The results and finding of FRA will be used as input to an overall quantitative risk assessment (QRA). The specific objectives fire risk analysis can be summarized as followings. First, identify a series of representative fire scenarios that can be enough to stand for the potential fire accidents on the offshore plant. Second, quantify the identified scenarios with certain physical values (e.g. flame size, heat dose, heat flux etc.), which are used for calculating DAL (design accidental load). Third, identify the vulnerable targets to the fire scenarios and evaluate their consequence under the fires. Forth, identify the potential escalation of each fire accident and the possible damages to the asset, and lastly determine the possible requirement for additional risk reduction measures to help prevent and/or mitigate the effects of the identified fire scenarios.

Typically, fire accidents on the offshore plant is quite deathful even though they happen rarely, so directly using the fire simulation results to assess the risks is seemed to be very conservative. To avoid this, commonly probabilistic methodology is involved in the FRAs. Generally, the fire scenarios identified in the FRA are consisted of several parameters, and most of the parameters are considered in a probabilistic approach for calculating the fire scenario frequency as well as DAL. However, some of the parameters are naturally quite difficult to treat in a probabilistic way; hence for these parameters, simple assumptions or expert's judgment were more plausible in the former FRAs. Also, as mentioned in the previous section, the physical variable concerned about in the FRA study influences its methodology. The purpose of using certain physical variable is for quantifying the impact of identified fire scenarios in the FRA. Fire simulation result is usually used as input for the overall QRA, thus it must be reflected by some quantified variables to measure its damages or impacts. Typically, there are several types of quantified physical variables were mainly selected in the former FRAs, for example, flame size, heat dose, heat flux contour, temperature etc, and among those physical variable, flame size and heat dose are typically to be used. When using the flame size, the accuracy level of FRA is just limited to roughly judge the failure of critical targets with flame size, and no further detailed analysis about fire simulation and structural consequence is included. The critical target is defined as some important parts of offshore plants whose failure probably can cause a significant loss (e.g. Module supports, ESDVs, Crane Pedestal, Flare KO drums etc.). Conversely, when using the heat dose, the accuracy level of FRA is much higher since detailed fire simulation is involved to calculate the DAL. The detail of both methods will be accounted particularly in this paper.

2. Generic Outline of Fire Risk Analysis

Fire risk analysis is a sub-part of QRA (Quantitative risk assessment), which mainly evaluates the fire related risks on the offshore platform. The generic outline of former fire risk analysis and the new proposed one both can be consisted of 3 phases, each of them are presented in Fig. 3. In the outline only key steps are sorted out; hence it can be regarded as a foundation and the specific methodologies used in each FRA are all started from the outline.

2.1. Phase 1

Phase 1 is a preparation stage for the following fire simulation. Identically, for both generic outlines, the phase 1 is made up with two parts, one is fire scenario identification and the other one is frequency calculation.

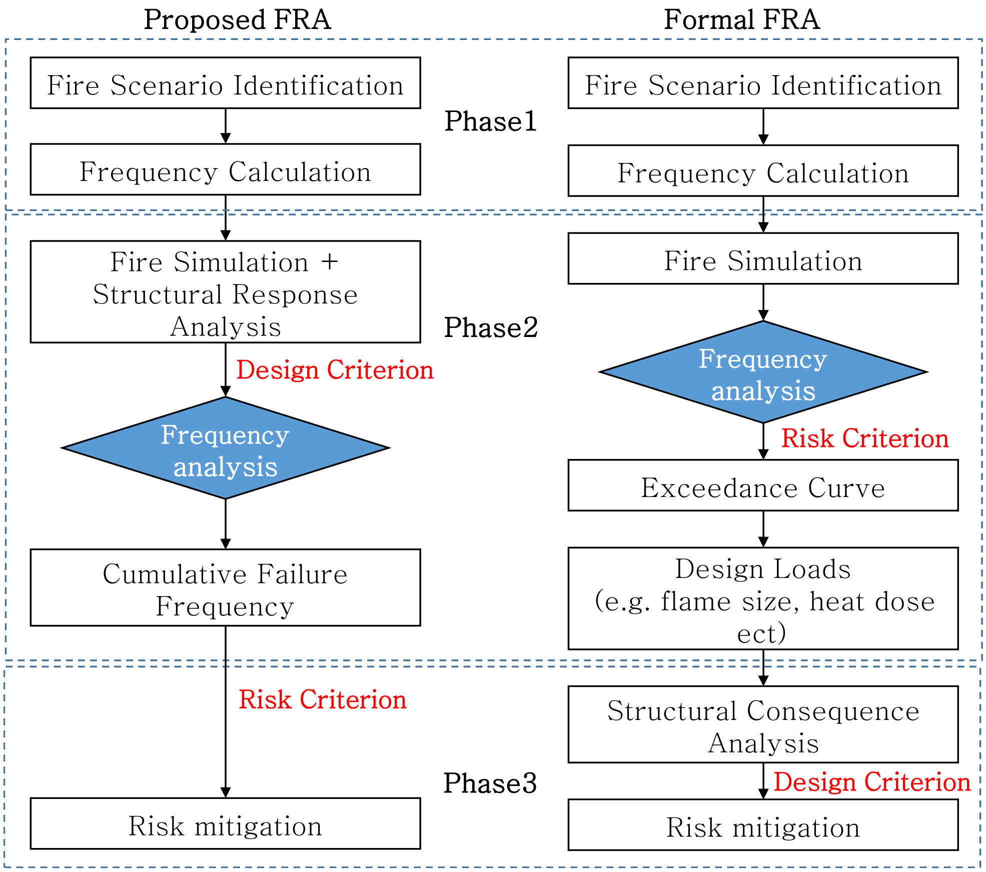


Fig. 3 Generic outline of fire risk analysis

2.1.1. Fire Scenario Identification

Typically, several fire control parameters are considered during the scenario identification, and they are summarized below:

- Leak rate
- Leak duration
- Leak direction
- Leak location
- Leak frequency
- Ignition probability

Among these parameters, leak rate, duration, frequency, ignition probability are predictable by various source of data, whereas, leak location and direction is not easy to determine, because they are quite random variables. For this reasons, usually conservative assumption or expert's judgment is the most practical ways to consider the two parameters. Furthermore, in order to identify the scenarios more efficiently, usually the whole process is divided into several isolatable segments, and each segment should be bounded by SDV (shutdown valve) or ESDV (Emergency shutdown valve). For FPSO, each module in the process area is isolated by SDV or ESDV, thus each module can become an isolatable segment.

2.1.2. Leak frequency

Hydrocarbon leaks from process equipment make a significant contribution to the risks of offshore plants. When risk management options are determined using QRA, the frequency of HC leaks is an input to the study and it will have a major influence on the estimated risk. Leak frequency in FPSO process area is usually calculated based on historical leak database (e.g. HCRD by HSE). Following figure is showing the generic HSE release statics from 1996 to 2013. The data is plotted based on 3 levels respectively, minor, significant and major. More detail about the leak frequency calculation is instructed in chapter 4.

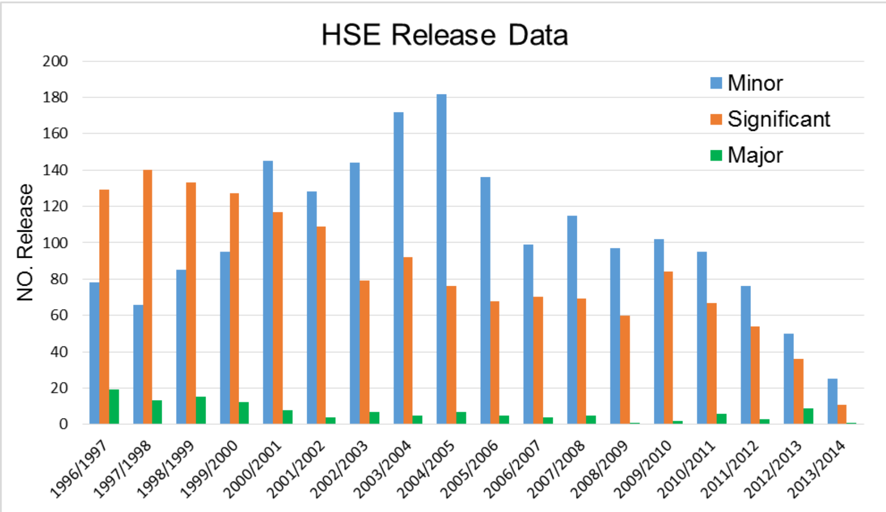


Fig. 4 HSE hydro carbon leak data (1996−2013)

Table 1 Three levels of HSE leakage

	Leak rate	Duration
Major	>1kg/s	> 5min
Significant	0.1~1kg/s	2~5min
Minor	0.1kg/s<	2 min <

2.2. Phase 2

Phase 2 is made up with two key parts, one is fire simulation and the other one is frequency analysis. Usually the structural consequence analysis is placed after the step of frequency analysis, and this sequence was normally used in the former FRAs (Right one in the Fig. 3). However, in the new proposed method, the step of structural analysis changes to be placed before the step of frequency analysis (Left one in the Fig. 3). Determination of design load in the former FRAs is based on an exceedance curve with certain physical variable. The purpose of using the variable is for quantifying the impact of identified fire scenarios. Fire simulation results in the FRA are usually used as input for the overall QRA, and this indicates that they must be reflected by some quantified variables to measure their damages or impacts. Typical quantified variables used in the existing FRAs are respectively flame size, heat dose, heat flux contour etc. Commonly, the quantified variables are quite useful during frequency analysis to extract the design load of fire accident. However, since the extracted design load is usually expressed by a single variable; hence using such design load to analyze the structural response is quite difficult. This is the reason why most of the former FRAs are stopped at the step of determining design load, and cannot provide no more specific details about how to use the design load to perform the structural consequence analysis. Facing with above problems, in the new proposed FRA, structural consequence analysis is added before frequency analysis by using a full of fire simulation results, and the cumulative failure frequency is developed to take place of conventional exceedance curve aiming at a probabilistic evaluation of structural safety.

2.3. Phase 3

Phase 3 is mainly focusing on the risk mitigation measure according to the results of several previous analyses. Typically, there are two types of effective risk measures for offshore structures, one is passive fire protection and the other one is deluge systems. In this thesis, the new procedure is mainly customized for determining the proper PFP application area, but the simulation results still can be used for other QRA studies.

3. Former Fire Risk Analysis

There are typically two main physical variables were usually used in the former FRAs. One is flame size and the other one is heat dose. When using the flame size, the level of FRA is just limited to roughly judge the failure of critical targets, and no further detailed analysis about fire simulation and structural response is included. Conversely, when using the heat dose, the level of FRA is much higher, and detailed fire simulation is involved to calculate the design fire load.

3.1. FRA with Flame Size

Using flame size in the FRA is a simplified method that usually carried in early stage of offshore structure design. It is used for roughly judging the impairment of identified critical target, PFP range as well as sub−deluge zone. The critical target is defined as some important parts of offshore plants whose failure probably can cause a significant loss (e.g. Module supports, ESDVs, Crane Pedestal, Flare KO drums etc.).

Fig. 5 is the detail flowchart of FRA procedure using flame size.

First of all, based on P&ID, PFD drawings divide the process of objective FPSO into several isolatable segments, and in the each segment identify the main inventory according to operation conditions as well as contained hydrocarbon component.

Then, generate representative fire scenarios for carrying out the fire simulations. Leak location position is usually assumed as the center of the module. Fire frequency is calculated through multiplying the leak frequency by ignition probability. Fire simulation is only carried out by 2D simple fire simulation tool e.g. Phast, and the actual CAD data of objective process module is not reflected in the simulation.

After that, flame size exceedance curve is calculated using the results of simulation, and design flame size is determined according to the exceedance curve. At last, failure of critical target is judged by using the design flame size. In other words, draw a circle using the design flame size at each time interval and check if the interested critical target locates in the circle. Following is an example of the procedure.

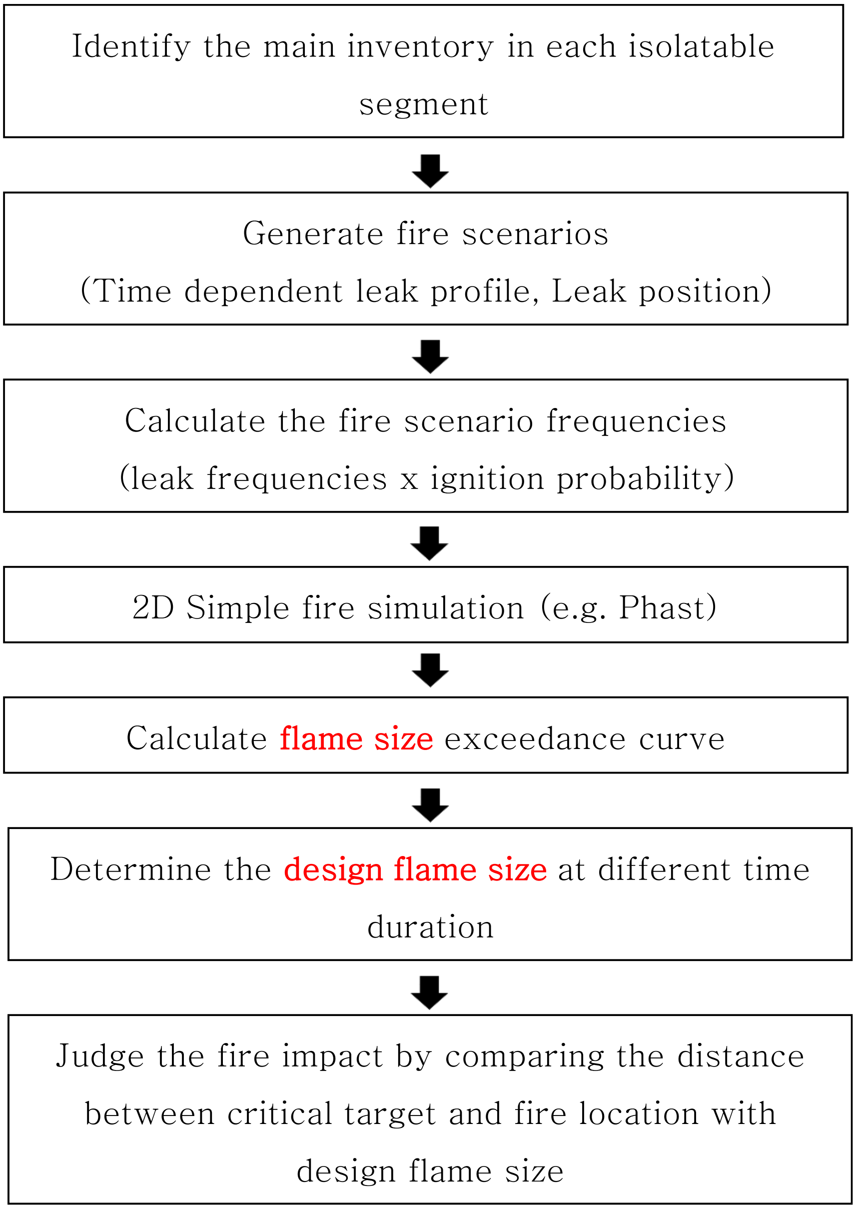


Fig. 5 FRA Diagram using flame size

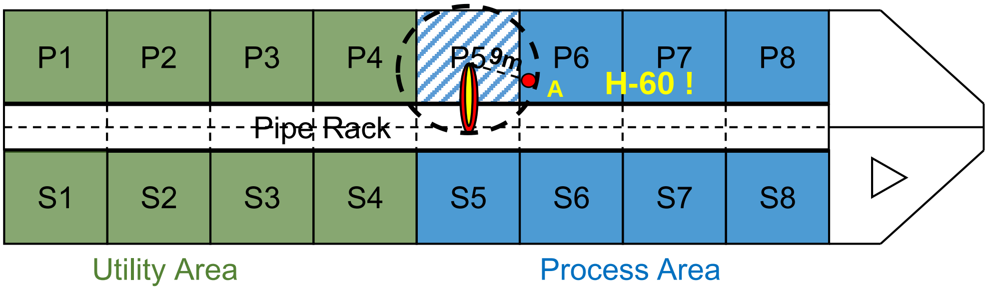


Fig. 6 Example of FPSO module layout

Fig. 6 is module layout of FPSO used in the example. The objective module is P5, and the identified segments, scenarios, fire simulation results are listed in the Table 3. In this example the flame size exceedance curve is calculated for 5 different time durations, and two of them are presented in the Fig. 7. When the risk criterion (e.g. 1.0E−04) is applied to each exceedance curve, then the design flame size is determined as showed in Table 4. Table 2 is showing the required time of critical target A becomes failed when it is continuously exposed to the fire. The distance between A and center of P5 is 9m, and this is much bigger than the magnitude of design flame size for the first 5 min. This indicates that the critical target A is probably to be failed if it does not get any protection. Subsequently, another design flame size is selected to determine the rate of PFP. In the example, before 60 min the design flame size is entirely bigger than the distance between A and module center, and this illustrates that the PFP required for A should sustain its protection at least for 60min. Consequently, the minimum rate of PFP for critical target A is determined as H60.

Table 2 Failure time of critical target A

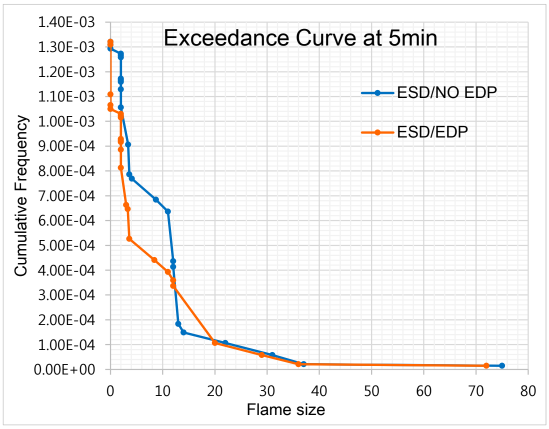
Time to failure (min)	5
Flame size (m)	23

Table 3 2D fire simulation results of identified segments

Segment	Flame Length	Frequency	ESD/No EDP					ESD/EDP				
			5min	10min	30min	60min	120min	5min	10min	30min	60min	120min
MA2 (Oilgocene production manifold)	S	2.30E-05	12	12	12	12	12	12	11	8.8	5.2	5.1
	M	6.10E-06	37	36	34	6	0	36	34	29	22	6
	L	7.00E-06	2	0	0	0	0	2	0	0	0	0
	Full	7.90E-06	2	0	0	0	0	2	0	0	0	0
SAG (O9 MP separator gas)	S	8.50E-05	4.1	4.1	4.1	4	3.8	3.6	3	2	0	0
	M	3.40E-05	13	12	9.9	7.3	3.7	11	9	3	2	0
	L	4.80E-05	22	2	0	0	0	20	2	0	0	0
	Full	8.60E-05	2	0	0	0	0	2	0	0	0	0
SAL (O9 MP separator liquid)	S	2.30E-04	12	12	12	12	12	12	12	9.8	6.5	6.5
	M	3.70E-05	31	30	30	29	27	29	26	18	8.1	7.8
	L	1.50E-05	75	0	0	0	0	72	0	0	0	0
	Full	1.20E-05	0	0	0	0	0	0	0	0	0	0
CDG (Piping from MP separator to MP compression)	S	1.70E-05	3.6	3.1	2	0	0	3	2	2	0	0
	M	6.20E-06	2	0	0	0	0	2	0	0	0	0
	L	6.60E-06	2	0	0	0	0	2	0	0	0	0
	Full	3.00E-05	2	0	0	0	0	2	0	0	0	0
SBL (Piping to crude oil inlet manifold)	S	2.00E-04	11	10	9.2	8.4	7.6	0	0	0	0	0
	M	4.30E-05	14	10	7.8	7.8	1	0	0	0	0	0
	L	1.60E-05	0	0	0	0	0	0	0	0	0	0
	Full	2.00E-05	0	0	0	0	0	0	0	0	0	0
MCG (UM gas production manifold)	S	1.20E-04	3.4	3.4	3.2	2.9	2.4	3.3	3.2	2.5	2	0
	M	4.80E-05	8.7	6.8	2	0	0	8.4	6.3	2	0	0
	L	7.30E-05	2	0	0	0	0	2	0	0	0	0
	Full	1.50E-04	2	0	0	0	0	2	0	0	0	0

Table 4 Design flame size for each time duration with successful ESD/EDP

Time (min)	5	10	30	60	120
Flame size (m)	23	20	16	7.8	7.5



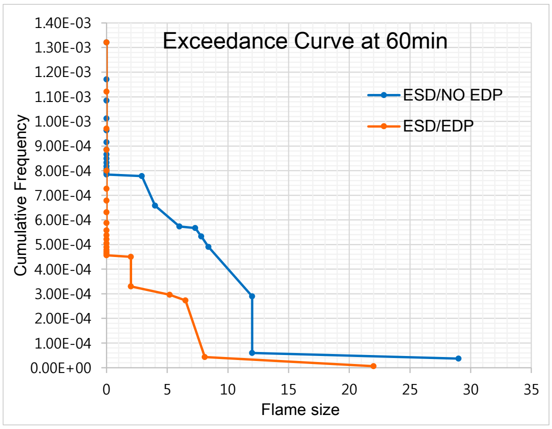


Fig. 7 Exceedance curve of flame size

The most critical problem in the flame size method is using 2D simple fire simulation. In actual conditions, most of jet fires occur inside of process module are hindered by surrounding structures or facilities, and this type of fire is named as impinged fire. However, in 2D fire simulation, CAD data is not considered, and this indicates that 2D simple fire simulation cannot precisely reflect the result of fire but roughly predict the magnitude of flame size.

Furthermore, even if 3D fire simulation is added to replace the 2D fire simulation, the flame size method still cannot be reasonable. Because when the 3D CAD data is considered, the size of flame cannot keep identical in all direction due to the different magnitudes of geometry congestion. This indicates that the circle showed in Fig. 6 is not possible to mapping on the module lay out any more. In summary, the FRA using flame size is a simple but rough method which is only limited to the initial design stage, and if additional structural response is required to investigate, other advance FRA method is much more suitable.

3.2. FRA with Heat Dose

Method of using heat dose is detailed sorted out in FABIG Technical Note 11 which is fitted for probabilistically checking the structural consequence. In this method, another physical variable named heat dose is used for calculating the exceedance curve. Heat dose is defined as the time integral of heat flux. Figure 8 shows the detail flowchart of FRA procedure by using heat dose.

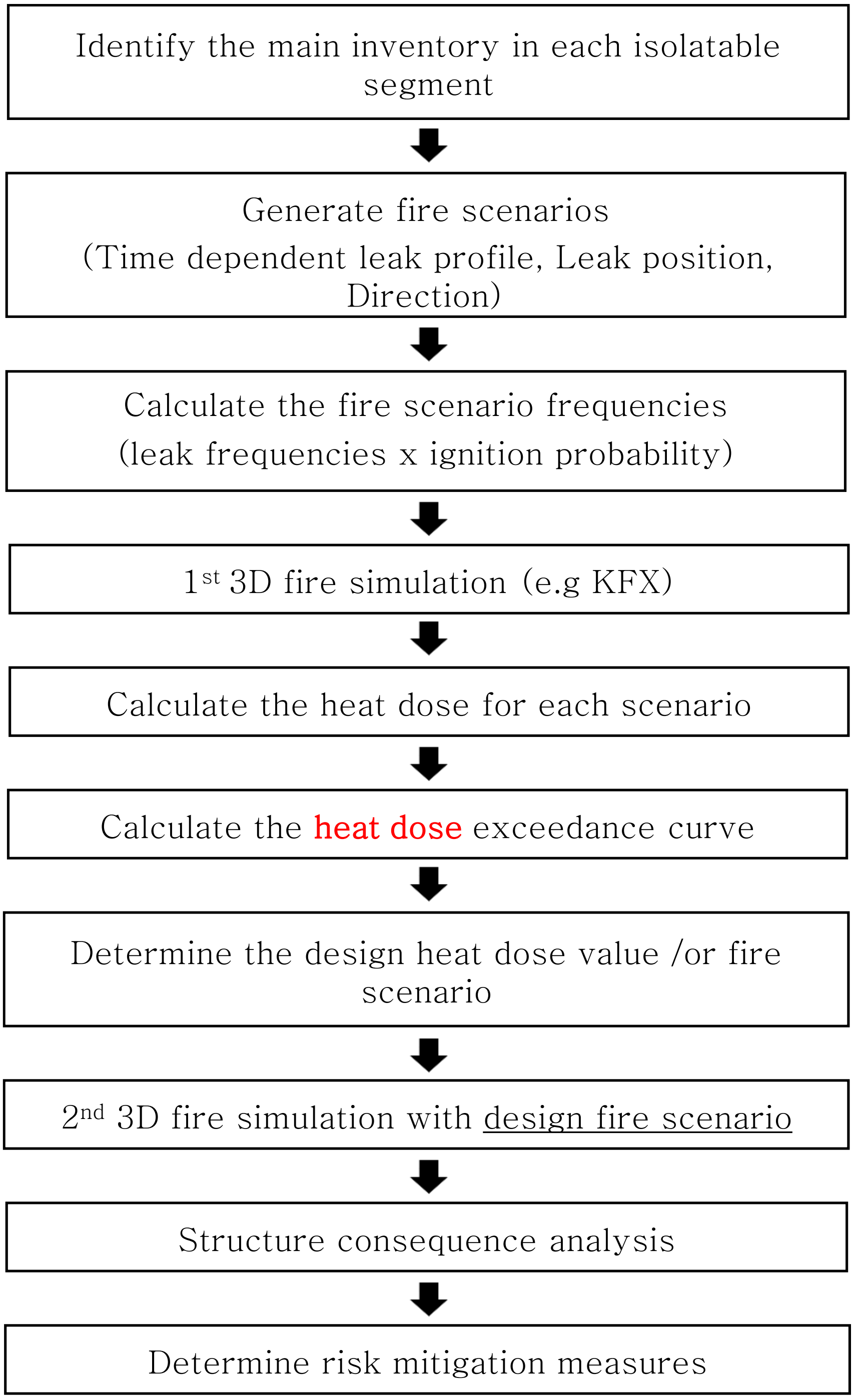


Fig. 8 FRA diagram using heat dose

In the flowchart the first three steps are almost identical to the ones in the previous procedure. The only difference is that leak direction is more intentionally considered in this method and moreover 3D fire simulation is applied to improve its accuracy. Several specific points are picked up for calculating the heat dose, and design heat dose or corresponding fire scenario is determined through the exceedance curve. Then, structural consequence analysis is carried out using the design fire scenario, and risk mitigation measures are determined based on the results of structural response analysis at last. Following is an example of the procedure using heat dose variable.

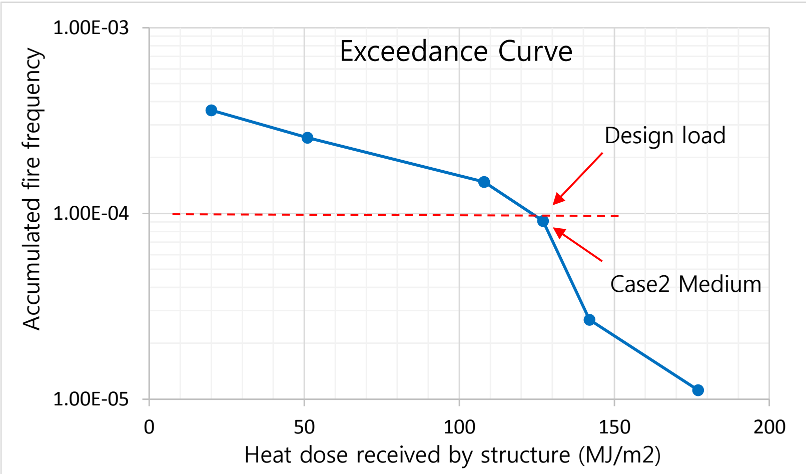


Fig. 9 Exceedance curve of heat dose

Table 5 Inventory data for each segment

Segment	Case name	Leak Medium	Inventory of gas in segment (kg)
Case1	LP stage	gas	558
Case2	HP stage	gas	1342

Table 6 Results of heat dose calculation with identified fire scenarios

Segment	Size	Heat dose (MJ/m^2)	Fire frequency
Case1	Large	20	1.04.E-04
	Medium	108	5.71.E-05
	Small	142	1.56.E-05
Case2	Large	51	1.07.E-04
	Medium	127	6.44.E-05
	Small	177	1.12.E-05

Table 5 & 6 illustrates the information of identified segment, especially Table 6 lists the fire scenarios considered in the example as well as their heat dose calculated by using the 3D fire simulation result.

In the example, heat dose is calculated by integrating the heat flux history at all grid points, and the maximum integral is subsequently selected as the one for plotting exceedance curve. Deservedly, the point that has the maximum heat dose usually locates at the center of flame, and this indicates that only the hottest point inside the flame is reflected in the design load.

Then, through the exceedance curve showed in Fig. 9 a design load is determined, however, as previously mentioned the design load is only expressed by the heat dose and it is difficult to analyze structural consequence with it. Therefore, instead of using the heat dose, corresponding fire scenario is selected for the structural analysis. When using a fire scenario as the design load, the actual input for structural analysis is an entire 3D heat flux distribution obtained from the fire simulation. In the example the design scenario is medium fire size of case2 whose magnitude of heat dose is 127 MJ/m^2.

Furthermore, two times of fire simulation are involved in the flowchart of Fig. 8, and following two pictures explain how the fire simulations are different from each other. In the first time of fire simulation, the leak direction is simply determined with several orthogonal vectors starts from the center of module, and its purpose is only for calculating heat dose to quantify the result of fire simulation for each scenario. However, in the second time, the determined design fire scenario is not directly put into the simulation, instead, they are redefined to have the scenario cause the worst condition to the module. The right picture in Fig. 10 shows the worst combination of leak direction and location which brings significant damage about the module. Obviously, it is concluded that the determined design fire scenario almost become useless in the second fire simulation except for reflecting the information of leak rate and duration.

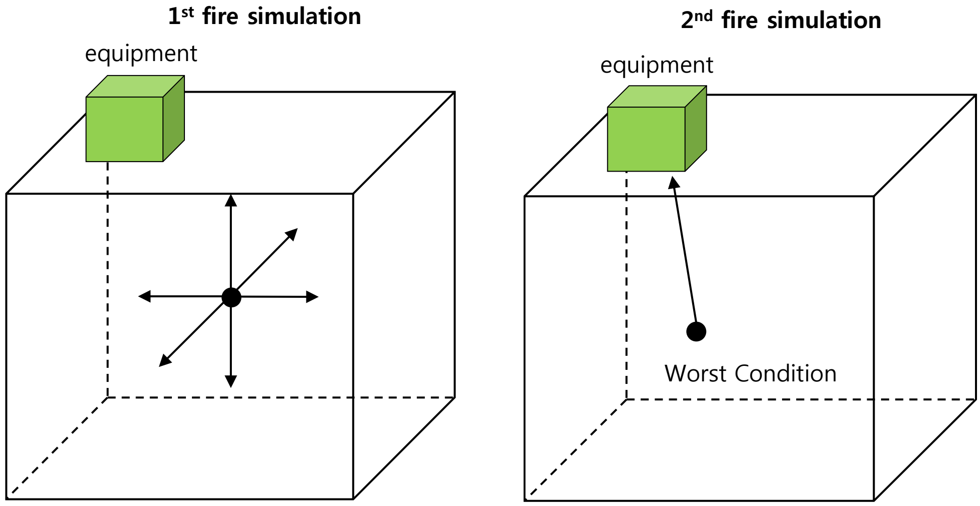


Fig. 10 Two times of fire simulation

In summary, compared with the FRA using flame size, method of using heat dose is much more progressive since it uses the 3D fire simulation. However, the way to decide the heat dose for each scenario is still too weak to properly reflect the whole domain of fire accident. Also, during heat dose calculation as well as structural analysis, the inconsistent consideration of leak direction and location not only leads to two times of fire simulation but also breaks the original intention of using heat dose.

4. Proposed FRA Procedure

Following Fig. 11 shows the details of new FRA procedure proposed in this thesis. The whole procedure is composed of 7 steps, and each of them will be discussed in the following sections. Also, some important methods or key consideration are noted under the box of each step.

4.1. Fire Scenario Identification

Different from previous FRAs, leak location is particularly considered in the new procedure through analyzing the PFD, P&ID diagram. Normally, the most probable leak position in FPSO process comprises the flange, valve and pipe connection, however, the number of these components in a process module is significant, and when all of them are considered together with leak direction, the work of fire scenario identification seems impossible to be accomplished. To solve this problem, an approximation method is applied in the new procedure to efficiently determine the leak location. Following three figures are the equipment layout drawings of the test separation module introduced in chapter 5.

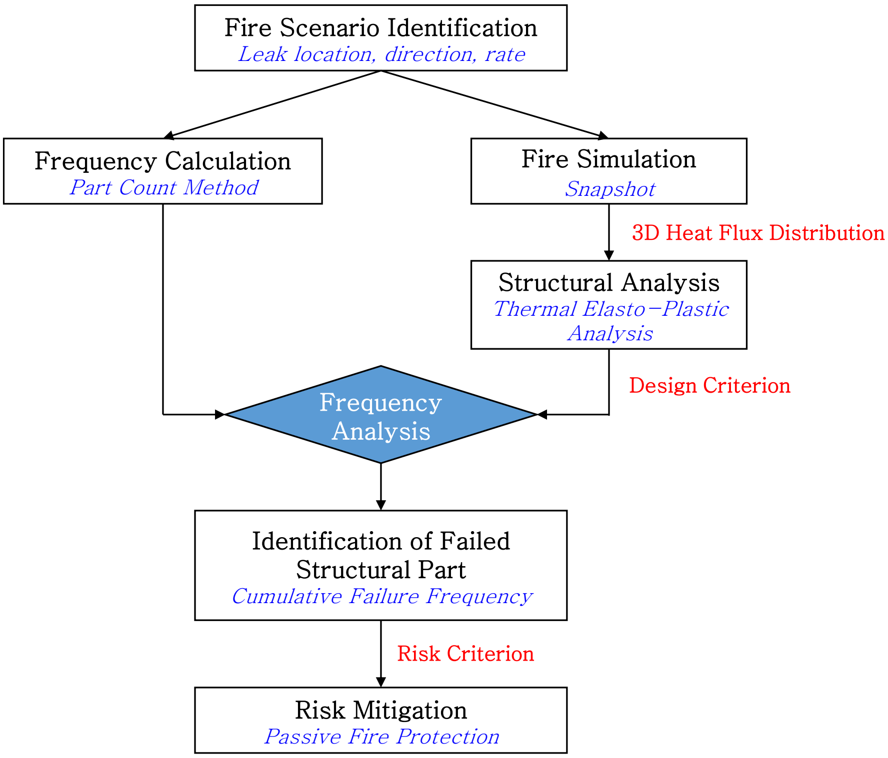
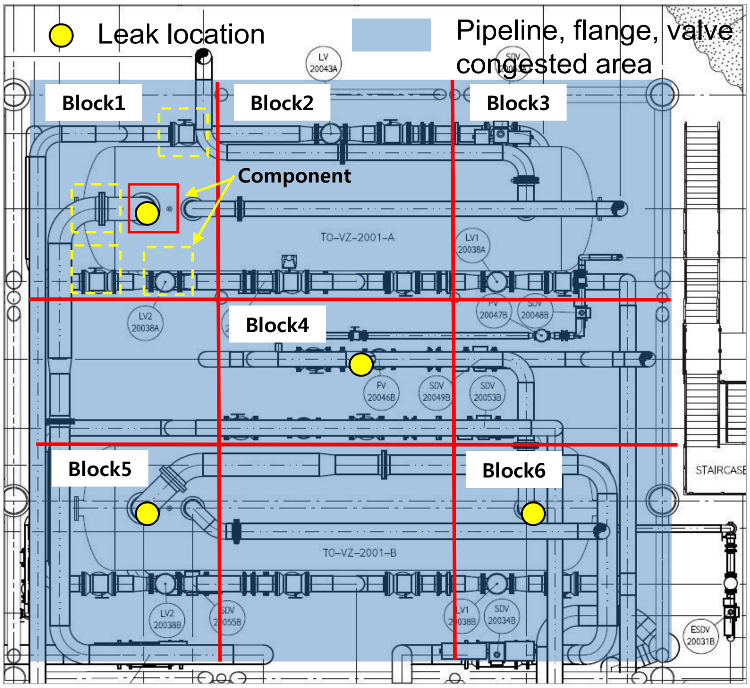
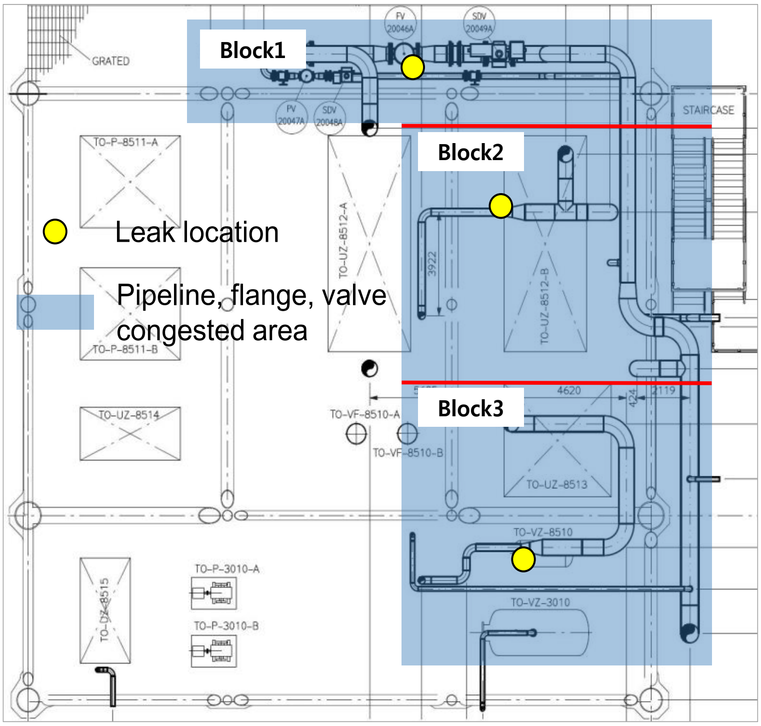


Fig. 11 Diagram of new FRA procedure

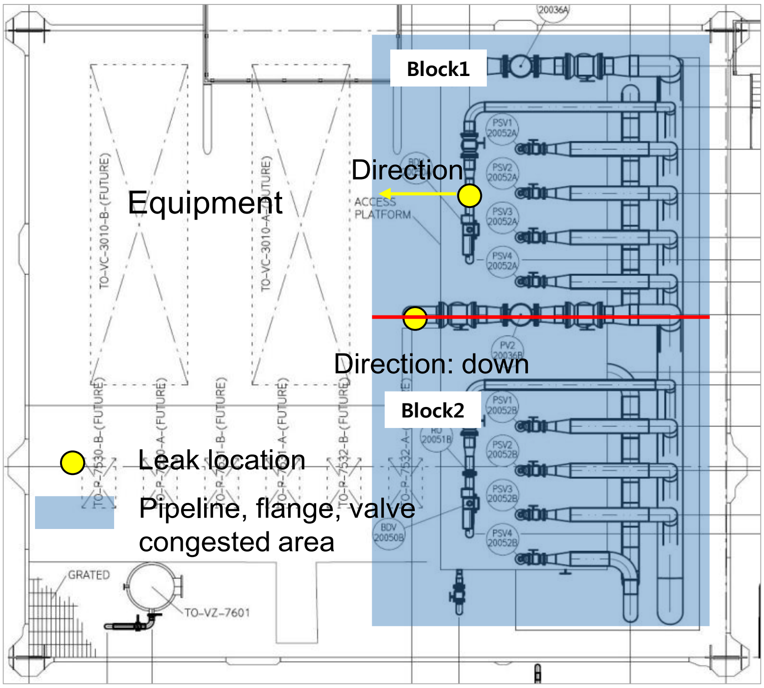
The first step of determining leak location in the new FRA procedure is identifying the pipeline, flange, and valve congested area. In the following figures, the shading area represents the congested area. Then, divide the congested area into several blocks according to its shape. There are several types of component in each block, and among them leak location is selected as the one which is not only close to the center of block but also itself connected to the identified main inventory.



(a) Process Deck



(b) Upper Deck



(c) Top Deck

Fig. 12 Equipment layout of test module

For example, in the figure (a) there are 5 components identified with dash line in block 1, and among them, the one outlined with full line is selected as the leak location since it simultaneously satisfies the two requirements mentioned above.

Furthermore, in the new procedure, leak location is determined together with leak direction. Similar to the previous FRA procedure using heat dose, leak direction is only considered with the vulnerable parts of structure. This is the reason why there is not any leak location identified in block 3 of process deck.

Leak direction has a quite random characteristic; therefore it is impossible to consider all kinds of the directions at each identified leak location. However, the original purpose of FRA is to evaluate the threats of fire accidents to the structure or associated facilities, and this indicates that the identified leak directions should at least comprise the cases that hydro carbon leaks directly towards the vulnerable parts of the structures. In this thesis, vulnerable parts of structure is defined as the ones who locally bear the weights of process equipment, and the leak direction is only considered with them. Although the approach seems to be very conservative, at least it guarantees the safety of structure since it takes all of the vulnerable parts into consideration.

Leak rate is a time dependent parameter, which controls the dynamic effect of fire accident. Following Fig. 13 is the considered leak rate profile for the test module in chapter 5. The actual fire on the FPSO topside usually has a time dependent leak rate, which decays over the time, and it is commonly named as the dynamic fire (Sávio Vianna, Asmund Huser, 2010). The dynamic effect of actual fire must be considered since it influences the accuracy of fire simulation. However, if the whole duration of actual dynamic (transient) fire is considered, the time required for simulation is too much. As a result, an effective method called snapshot is used in the new procedure for purpose of reducing the required simulation time. Fire simulation with snapshot is concretely accounted in section 4.3.2.

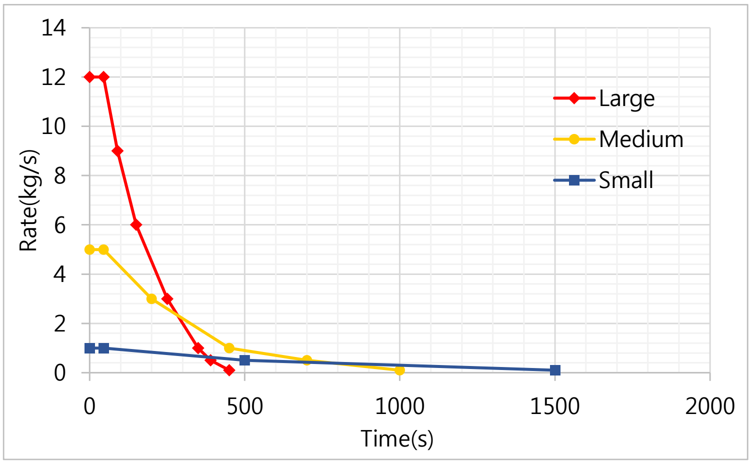


Fig. 13 Time dependent leak rate

4.2. Frequency Calculation

4.2.1. Historical Leak Frequency Data

As mentioned in the previous section, leak frequency is usually calculated based on the historical database. HCRD by HSE has become a standard source of leak frequencies for offshore QRA studies. The data allows 78 separate types and sizes of process equipment to be distinguished. However, for certain types and sizes of process equipment, there is relatively little leak experience, and the statistical differences of leak frequency between them are also too small to be used for distinguishing them. Such deficiencies may probably lead to conservative assessment of risk. To avoid this, modification of the HSE database is a common practice. Usually, different analysts use different approaches and assumptions in modifying the data, but these different types of modification can lead to the frequencies used by analysts being inconsistent despite being based on the same HCRD dataset (Andreas Falck, 2011). Therefore, standardizing the approach of modifying the HCRD is an urgent need.

DNV developed a methodology (Andreas Falck, 2011) for obtaining leak frequencies from HCRD. The methodology consists of the following three steps:

- **Grouping data for different types and sizes of equipment**, where there is insufficient experience to show significant differences between them.
- **Fitting analytical frequency functions to the data**, in order to obtain a smooth variation of leak frequency with equipment and hole size.

- **Splitting the leak frequencies into the different leak scenarios**, in order to promote compatibility with different approaches to outflow modelling in the QRA.

Following table 7 shows the HCRD leak statistics from 1992 to 2006. There are two different equipment types mentioned in the table, one is DNV equipment type and the other one is HCRD equipment type. Since some of the equipment types and sizes in HCRD have little leak experience; hence they have been merged into one type and this process results in the DNV equipment type.

Table 7 Leak statics for HCRD 1992−2006

	DNV EQUIPMENT TYPE	HCRD EQUIPMENT TYPE	All leaks	Leaks excluding < 1 mm	Exposure
1	Steel process pipes	Piping, steel (3 sizes)	700	646	5,958,814 pipe metre years
2	Flanges joints	Flanges (3 sizes)	327	298	3,368,520 flange joint years
3	Manual valves	Valve, manual (10 types & sizes)	175	154	1,498,038 valve years
4	Actuated valves	Valve, actuated, non-P/L (18 types & sizes)	264	221	329,562 valve years
5	Instrument connections	Instruments (including connecting tubing)	528	442	749,786 instrument years
6	Process (pressure) vessels	Pressure vessel (14 types)	42	37	17,494 vessel years
7	Pumps: Centrifugal	Pumps, centrifugal (2 seal types)	126	110	14,564 pump years
8	Pumps: Reciprocating	Pumps, reciprocating (2 seal types)	21	19	2,652 pump years
9	Compressors: Centrifugal	Compressors, centrifugal	40	33	3,110 compressor years
10	Compressors: Reciprocating	Compressors, reciprocating	43	36	507 compressor years
11	Heat exchangers: Shell & Tube, shell side	Heat exchangers, HC in shell	18	14	3,398 exchanger years
12	Heat exchangers: Shell & Tube, tube side	Heat exchangers, HC in tube	26	21	6,165 exchanger years
13	Heat exchangers: Plate	Heat exchangers, plate	31	30	2,865 exchanger years
14	Heat exchangers: Aircooled	Fin fan coolers	5	2	1,069 exchanger years
15	Filters	Filters	48	47	12,495 filter years
16	Pig traps	Pig launchers & pig receivers (4sizes)	29	28	3,994 pig trap years

Following equation is the analytical function used in DNV methodology, which represents the variation of leak frequency depended on leak hole size, equipment type and diameter.

$$F(d) = C(1 + aD^n)d^m + F_{rup}$$, Andreas Falck(2011)

F(d)	= Frequency per year of leaks exceeding size d (mm)
D	= Equipment diameter
D	= Hole size
F_{rup}	= Rupture frequency per year
C,a,m,n	= Constants specific to the equipment type and leak scenario

Hence the frequency of holes within any range from d_1 to d_2 is:

$$F(d_1) = C(1 + aD^n)(d_1{}^m - d_2{}^m)$$, Andreas Falck (2011):

In this thesis leak frequency is referred to an open source released by the Oil & Gas Produce. OGP is a third party who modifies the original HSE's HCRD by using the DNV methodology and releases an open source of leak frequency database in a general tabulated form showed in table 8. Table 8 is an example of the leak frequency data for steel process pipe in the OGP leak frequency source.

Table 8 Example of OGP leak frequency data – steel pipe

Equipment Type: (1) Steel process pipes

Definition:

Offshore: Includes pipes located on topsides (between well and riser) and subsea (between well and pipeline).
Onshore: Includes pipes within process units, but not inter-unit pipes or cross-country pipelines.
The scope includes welds but excludes all valves, flanges, and instruments.

(a) All piping release frequencies (per metre year) by pipe diameter

HOLE DIA RANGE (mm)	2" DIA (50 mm)	6" DIA (150 mm)	12" DIA (300 mm)	18" DIA (450 mm)	24" DIA (600 mm)	36" DIA (900 mm)
1 to 3	9.0E-05	4.1E-05	3.7E-05	3.6E-05	3.6E-05	3.6E-05
3 to 10	3.8E-05	1.7E-05	1.6E-05	1.5E-05	1.5E-05	1.5E-05
10 to 50	2.7E-05	7.4E-06	6.7E-06	6.5E-06	6.5E-06	6.5E-06
50 to 150	0.0E+00	7.6E-06	1.4E-06	1.4E-06	1.4E-06	1.4E-06
>150	0.0E+00	0.0E+00	5.9E-06	5.9E-06	5.9E-06	5.9E-06
TOTAL	1.5E-04	7.4E-05	6.7E-05	6.5E-05	6.5E-05	6.5E-05

(b) Full piping release frequencies (per metre year) by pipe diameter

HOLE DIA RANGE (mm)	2" DIA (50 mm)	6" DIA (150 mm)	12" DIA (300 mm)	18" DIA (450 mm)	24" DIA (600 mm)	36" DIA (900 mm)
1 to 3	5.5E-05	2.6E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05
3 to 10	1.8E-05	8.5E-06	7.6E-06	7.5E-06	7.4E-06	7.4E-06
10 to 50	7.0E-06	2.7E-06	2.4E-06	2.4E-06	2.4E-06	2.3E-06
50 to 150	0.0E+00	6.0E-07	3.7E-07	3.6E-07	3.6E-07	3.6E-07
>150	0.0E+00	0.0E+00	1.7E-07	1.7E-07	1.6E-07	1.6E-07
TOTAL	8.0E-05	3.8E-05	3.4E-05	3.3E-05	3.3E-05	3.3E-05

(c) Limited piping release frequencies (per metre year) by pipe diameter

HOLE DIA RANGE (mm)	2" DIA (50 mm)	6" DIA (150 mm)	12" DIA (300 mm)	18" DIA (450 mm)	24" DIA (600 mm)	36" DIA (900 mm)
1 to 3	3.1E-05	9.9E-06	8.1E-06	7.8E-06	7.7E-06	7.6E-06
3 to 10	1.5E-05	4.9E-06	4.0E-06	3.8E-06	3.8E-06	3.7E-06
10 to 50	1.3E-05	2.5E-06	2.0E-06	1.9E-06	1.9E-06	1.9E-06
50 to 150	0.0E+00	3.2E-06	5.2E-07	5.0E-07	4.9E-07	4.9E-07
>150	0.0E+00	0.0E+00	2.4E-06	2.4E-06	2.4E-06	2.4E-06
TOTAL	5.9E-05	2.0E-05	1.7E-05	1.6E-05	1.6E-05	1.6E-05

(d) Zero pressure piping release frequencies (per metre year) by pipe diameter

HOLE DIA RANGE (mm)	2" DIA (50 mm)	6" DIA (150 mm)	12" DIA (300 mm)	18" DIA (450 mm)	24" DIA (600 mm)	36" DIA (900 mm)
1 to 3	3.7E-06	3.2E-06	3.1E-06	3.1E-06	3.1E-06	3.1E-06
3 to 10	2.7E-06	2.3E-06	2.3E-06	2.3E-06	2.3E-06	2.3E-06
10 to 50	6.0E-06	1.9E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06
50 to 150	0.0E+00	3.4E-06	7.7E-07	7.6E-07	7.6E-07	7.6E-07
>150	0.0E+00	0.0E+00	2.6E-06	2.6E-06	2.6E-06	2.6E-06
TOTAL	1.24E-05	1.07E-05	1.06E-05	1.05E-05	1.05E-05	1.05E-05

4.2.2. Leak Frequency Calculation

Leak frequency in FPSO process area is usually calculated based on historical leak database, and one of the common calculation method is called part count. Part count method is generally based on counting the number of equipment that have the possibility of HC leaks in the oil & gas process. A simple example of part count method is presented in the following with a segment showed in the Fig. 14.

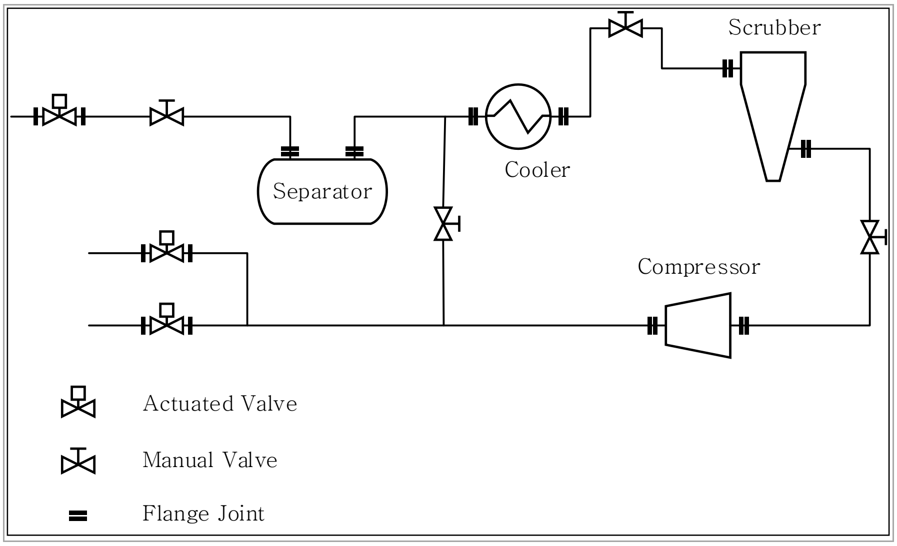


Fig. 14 Sample of process segment

In the Table 9, the quantity of each equipment type is counted according to the diagram of sample segment, and the total frequency is calculated through multiplying it by the frequency per equipment obtained from leak frequency database.

Table 9 Example of part count method

Equipment	Quantity	Equipment size	Frequency per equipement year[1)]	Total
Process vessel	1.5	6"	1.70E−04	2.55E−04
Compressor	1	6"	1.10E−04	1.10E−04
Heat Exchanger	1	6"	1.20E−04	1.20E−04
Flange joint	9.5	6"	1.10E−04	1.05E−03
Actuated Valve	1.5	6"	6.20E−04	9.30E−04
Manual Valve	4	6"	1.30E−04	5.20E−04
Pipe	20	6"	7.40E−05	1.48E−03
Total				4.46E−03
1) Frquency per equipment is referred to OGP data				

When counting the number of equipment, there are some matters need to be taken carefully.

- The segment is bounded by actuated valves, thus only half of these valves should be counted.
- Only half of the separator should be counted since its bottom is not connected to the pipe.
- Flange in the figure is considered as a joint which comprises two flange faces. Also similar with the actuated valve, only one side of flange joint should be counted.

Leak frequency of the test separation module is calculated in a similar way and the results are presented in chapter 5.

4.2.3. Fire Frequency Calculation

Fire frequency of each identified scenario is calculated by using the original leak frequency and several probabilities of fire control parameters. Following is the general formulations used in this thesis for fire frequency calculation.

$$F_{fire,i} = \frac{F_{leak}}{n} \cdot P_{ign} \cdot P_{ESD} \quad , \quad \text{for failed ESD \& EDP}$$

$$F_{fire,i} = \frac{F_{leak}}{n} \cdot P_{ign} \cdot (1 - P_{ESD}) \quad , \quad \text{for successful ESD \& EDP}$$

$F_{fire,i}$	=	Fire frequency of scenario i
F_{leak}	=	Total leak frequency of certain hole size for each segment
P_{ign}	=	Ignition probability
P_{ESD}	=	Failure probability of ESD & EDP
n	=	Total number of leak location in each segment
ESD	=	Emergency shutdown
EDP	=	Emergency depressurization

During the calculation of leak frequency for example module, three sizes of leakage are considered for each type of equipment, and leak frequency is separately calculated for each deck by using the part count method. Furthermore, the total leak frequency of each deck is split for each leak location according to the number of it considered in section 4.1. In the actual condition, the leak frequency of each leak location may be variable, but for simplicity in the example it is given equally by dividing the total leak frequency of each deck with its number of leak location n.

Ignition probability used in this thesis is developed by Cox, Lee & Ang. The ignition model is dependent on leak rate, and it is plotted in Fig. 15

$$P_{ign} = 0.0158 \cdot R^{0.6415} \quad \text{Cox et al. (1990)}$$

P_{ign} = Ignition probability

R = Leak rate

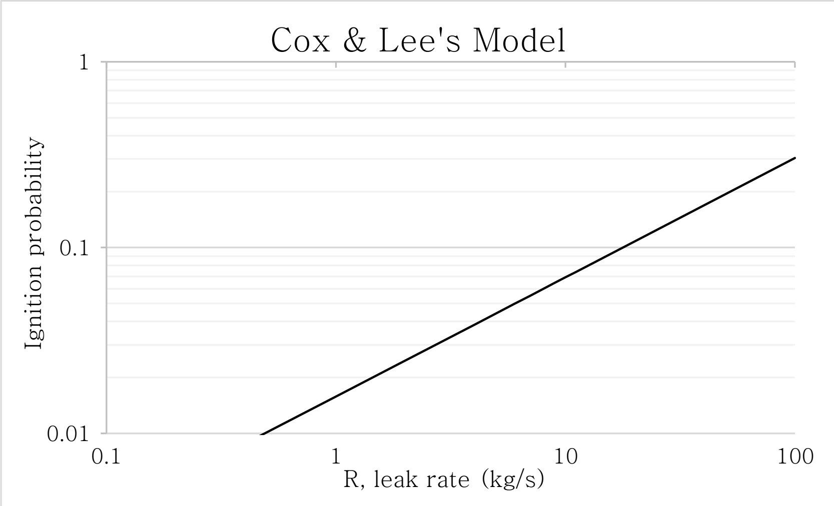


Fig. 15 Ignition model of Cox, Lee & Ang

4.3. Fire Simulation

4.3.1. Radiation Calculation

In thesis, fire simulation is carried out by using the KFX (Kameleaon FireEx) program. When a fire accident occurs, the surrounding gas mixture composed of CO_2, H_2O, Soot may participate in radiation heat transfer. At moderate temperatures the gas mixture heats up itself by absorbing the radiation emitted from the flame, and conversely at high temperature it also emits the radiation to surroundings at the same time. The emission and absorption characteristic of a mixture gas is usually dependent on its temperature, pressure as well as chemical composition. Furthermore, since the mixture gas belongs to fluid, its fluidity should also be simultaneously considered with the radiation process.

KFX can be called as the most advance fire simulator which is available to reflect the turbulent combustion flow using the Eddy Dissipation Concept proposed by Magnussen and Hjertager (1976), and simultaneously calculate the radiation heat flux by using Discrete Transfer Model proposed by Shah and Lockwood (1979). Following equation describes the radiation transfer along a path through an absorbing and emitting medium which is a basis of the DTM. Radiation intensity I for certain direction is defined as a rate of radiation energy emission or absorption per unit area normal to the direction and per unit solid angle of the direction. DTM is used for calculating the radiation intensity for all directions and furthermore the obtained radiation intensities are used for calculating radiation heat flux through proper mathematical integrations. In KFX radiation heat flux calculation is accomplished by using the bullet monitor. Bullet monitor is a virtual small ball spread over the whole calculation domain and its surface is discretized by proper number of solid angle for logging the entire radiation intensities. Radiation intensity and solid angle is illustrated in Fig. 16 and they are also defined by the following equations.

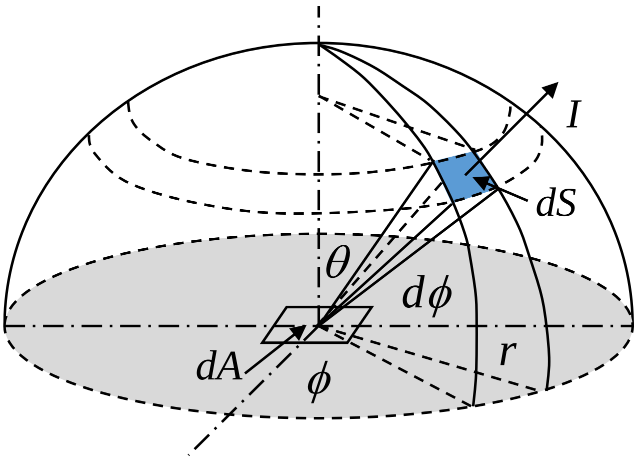


Fig. 16 Radiation intensity and solid angle

Solid Angle:

$$d\Omega = \frac{dS}{r^2} = \sin\theta d\theta d\varphi$$

Radiation Intensity:

$$I(\theta,\phi) = \frac{d\dot{Q}}{dA\cos\theta \cdot d\omega} = \frac{d\dot{Q}}{dA\cos\theta \cdot \sin\theta d\theta d\phi}$$

Radioactive Transfer Equation:

$$\frac{dI}{dx} = -\alpha I + \frac{\alpha\sigma T_g^4}{\pi}$$

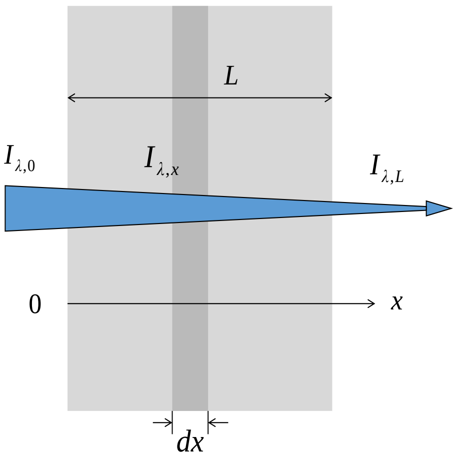


Fig. 17 Beer's law

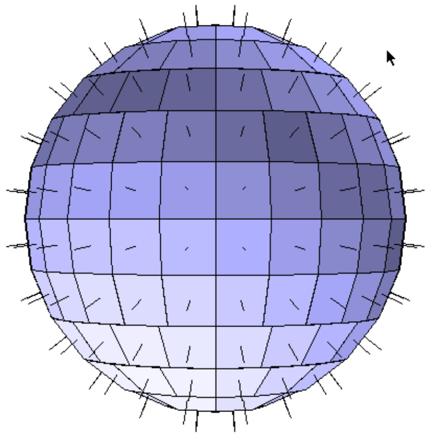


Fig. 18 Bullet monitor

Incident Radiation Heat Flux:

$$q_{in} = \int I \cdot d\Omega = \sum_{n=1}^{N} I_n \cos\theta \sin\theta \cdot d\phi \cdot d\theta$$

Ω = Solid angle

I = Radiation intensity

κ_λ = Spectral absorption coefficient

α = Absorptivity

n = Number of solid angle

T_g = Gas temperature

λ = Wave length

4.4. Snapshot

When a fire accident occurs on the FPSO, the leak rate of hydro carbon becomes smaller with time. This is because the shutdown or depressurization system installed on the process intervene the flow of hydro carbon. Therefore dynamic effect of leakage must be considered in QRA studies; otherwise it results in an over estimation of the risk. Unfortunately, since considering the dynamic effect of leakage in a CFD based fire simulation requires a significant amount of time consuming, thus it always becomes an issue in QRA studies. In order to reduce the time needed for simulating dynamic fire accidents a concept of snapshot is appeared to properly approximate the actual fires without simulating the whole fire accidents. Literally, snapshot is a moment of an actual fire accident and it is only bound with a unique leak rate. Commonly, 3 different sizes of leakage are commonly considered in FRA studies i.e. small, medium, large fire. In the new FRA procedure, several snapshots are specified simultaneously for the 3 sizes of fire scenario at each identified leak location. The specified snapshots are bundled together to construct a virtual compressed leak profile, the one which is actually reflected in the carried out fire simulations.

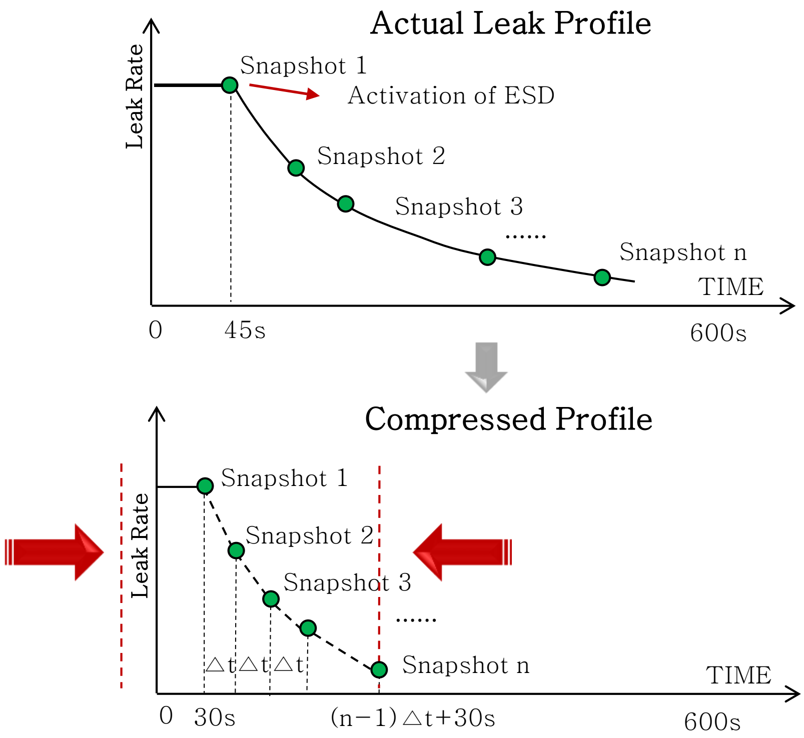


Fig. 19 Compressed virtual leak profile

Fig. 19 distinctly shows the how to construct a compressed virtual leak profile with the snapshots. In the compressed profile, the key thing is the time interval between each snapshot. This must be specified with enough time to reduce the difference of simulation results between the actual and compressed one. For instance, in the actual leakage showed in Fig. 19, the snapshot 1 stands for the moment after 45 seconds pass from the starting of leakage, and it is also an actual starting point of the ESD activation. However, in the compressed leak profile, the time interval from starting point of leakage to the activation of ESD is reduced as 30 seconds, this is because when the time is over 30 seconds the result of fire simulation almost becomes consistent until the activation of ESD. Consequently, the proper time interval from starting of leakage to snapshot 1 is determined as 30 seconds and this make the simulation save around 15 seconds at the first stage of leak within snapshot 1.

Following Fig. 20 shows a detail procedure of using snapshot for the test separation module introduced in chapter 5. In this case the snapshots are specified together by simultaneously considering the 3 different sizes of leakage, i.e. the ‘compress’ step in Fig. 20. As a result of the fire simulation, a 3D heat flux distribution is bound to each snapshot, and these heat flux distributions are later used as inputs for the structural analysis. However, before using these 3D heat flux distributions for structural analysis, the time interval between each of them must be recovered to an actual condition, i.e. the ‘Recover’ step. Most of the snapshots are repeatedly used in the 3 sizes of leakage with different time intervals since the 3D heat flux distributions of snapshot are almost identical as long as their associated leak rates are equal to each other in the 3 considered leakages. In summary, if use the snapshot, the time required for fire simulation is significantly reduced from 2950 seconds to 90 seconds in the example.

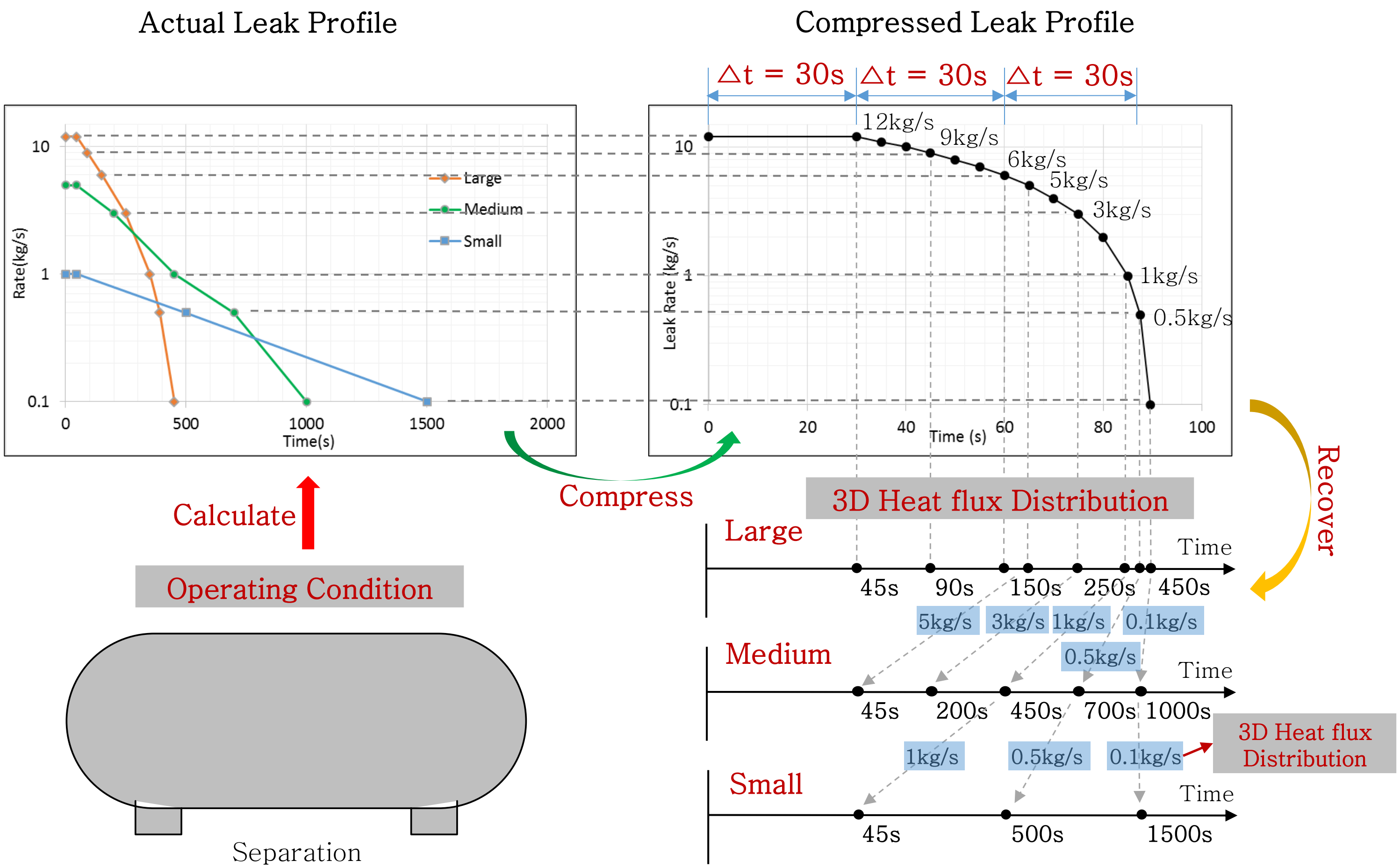


Fig. 20 Detail procedure of using snapshot

4.5. Structural Consequence Analysis

The structural response under the fire is assessed by using thermal elaso−plastic analysis. This analysis is composed of two parts, one is heat transfer analysis and other one is nonlinear structural analysis within the calculated temperature loads. In following two sections both of them are discussed respectively in detail.

4.5.1. Heat Transfer Analysis

In thesis, heat transfer analysis is carried out by using the FATHS program. FATHS is an interface face program between the KFX and USFOS which is aimed at transferring the fire loads to structure analysis. As mentioned in previous section, the compressed time of 3D heat flux distributions must be recovered before they are put into the heat transfer analysis, and the work is easily accomplished by editing the result files generated during the fire simulation. The result of heat transfer analysis is temperature distribution and it is used for the following non−linear structural analysis.

4.5.2. Non-Linear Structural Analysis

In this thesis, non−linear structural analysis is carried out by using the USFOS program. Since material property of steel is usually dependent on the temperature, the variation must be considered in the non−linear structure analysis. In that sense, the purpose of heat transfer analysis mentioned in the previous section has no other reasons than to calculate the increased structural temperature for modifying its material property. In this thesis the material property of each structural element steel is modified according to the following graph.

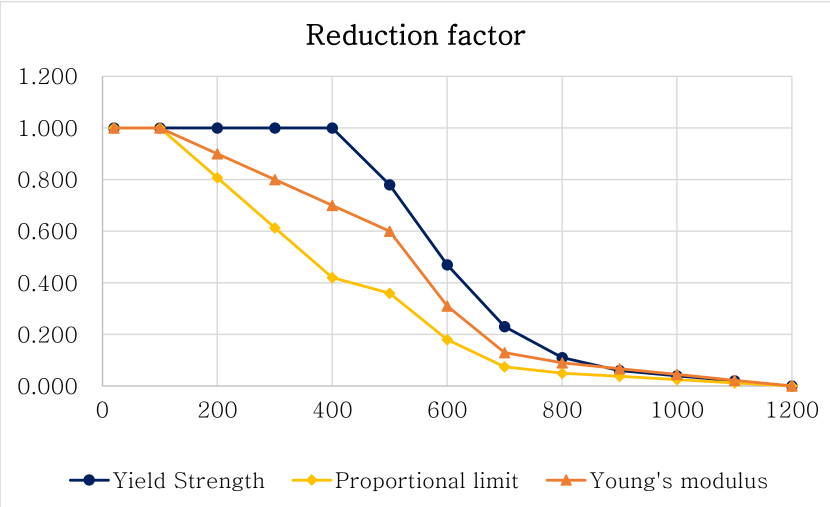


Fig. 21 Time dependent material property reduction factor

Furthermore, instead of using a normal transient structural analysis with considering the whole temperature history, a simplified static analysis is selected in the new FRA procedure. Different from other research fields, which need a high quality of structural analysis, structural analysis in general FRA studies is just aimed at globally checking and estimating the failure of structure; hence the static analysis seems is advisable enough.

In static analysis the reduced material property is specified per structural element according to its maximum temperature during the whole fire accident.

4.6. Cumulative Failure Frequency

4.6.1. Identification of Failed Element

Prior to calculate the structural cumulative failure frequency, the failed structural element must be identified for each fire scenario. Commonly, there are two different types of criteria used in FRA studies for checking the failed elements, and both of them are presented in the following figures. For simplicity, sometimes the structural response under the fire is assessed only by using the result of heat transfer analysis, and in that case the temperature criterion is used to judge the failure of element.

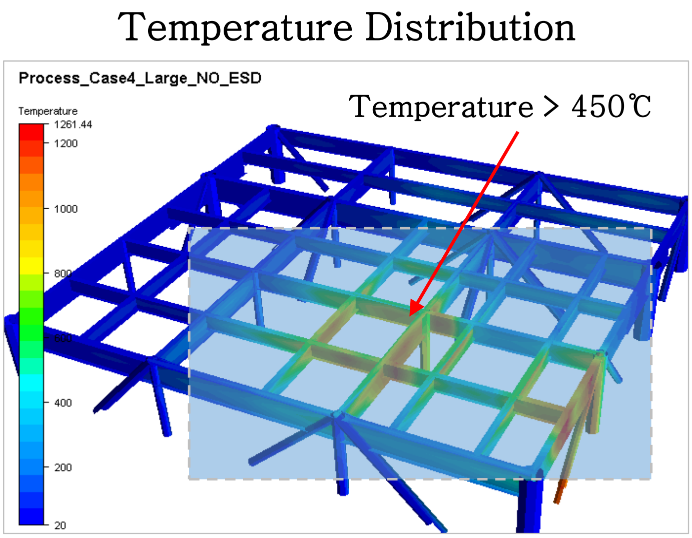


Fig. 22 Failure criterion with temperature

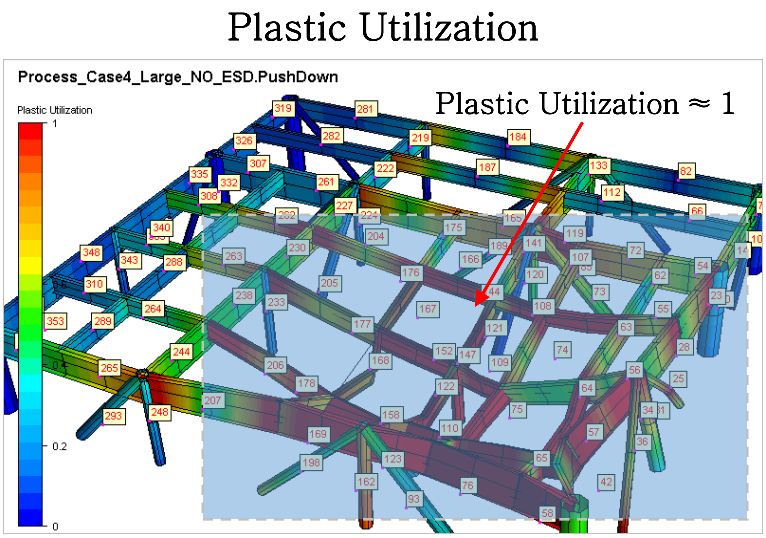


Fig. 23 Failure criterion with plastic utilization

4.6.2. Calculation of Cumulative Failure Frequency

Cumulative failure frequency of structural element is the most central part in the new prosed FRA procedure. It is generally obtained by combing the result of frequency calculation and structural response analysis. In order to distinguish the failed elements identified in the previous section from the safe ones an index I is used to quantify the element's condition. Following is the formulae used for calculating cumulative failure frequency of structure with index I

<u>Radioactive Transfer Equation:</u>

$$F_{failure,j} = \sum_{i=1}^{m} F_{fire,i} \cdot I_i$$

$F_{failure,j}$	= Cumulative failure frequency for element j
$F_{fire,i}$	= Fire frequency of scenario i
I_i	= Index of element j at scenario i
	$I_i=1$ for failed, $I_i=0$ for safe
i	= Scenario number

When the risk criterion is applied to the cumulative failure frequency of structural element, the element that has a high possibility of failure in the identified fire scenarios is easily found out.

5. Example of Proposed FRA

5.1. Scenario Identification and Frequency Calculation

As showed in Fig. 24, 25, a FPSO separation module is taken as the test model in this chapter for demonstrating the new FRA procedure in more detail. The test module is composed of 3 decks, and the scenario identification as well as frequency calculation is carried out by each deck. More detail about them has already discussed in chapter 4. The results of both leak frequency and fire frequency calculation are showed in Table 10 ~ 12.

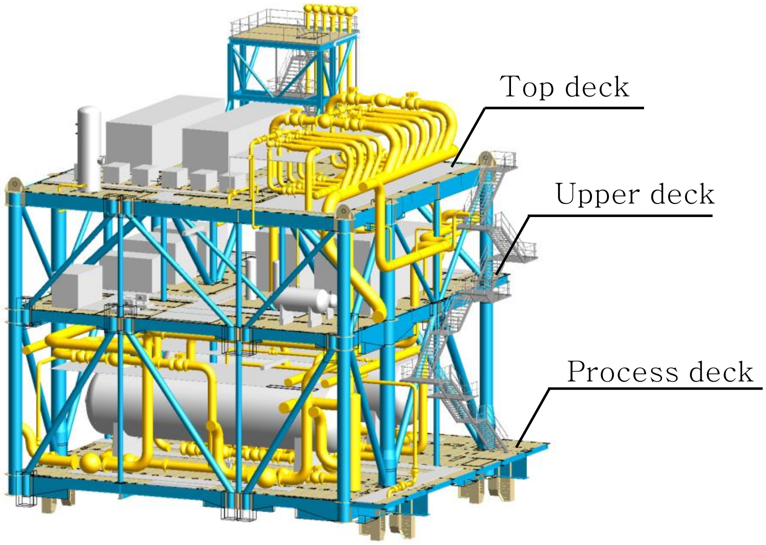


Fig. 24 Test separation module

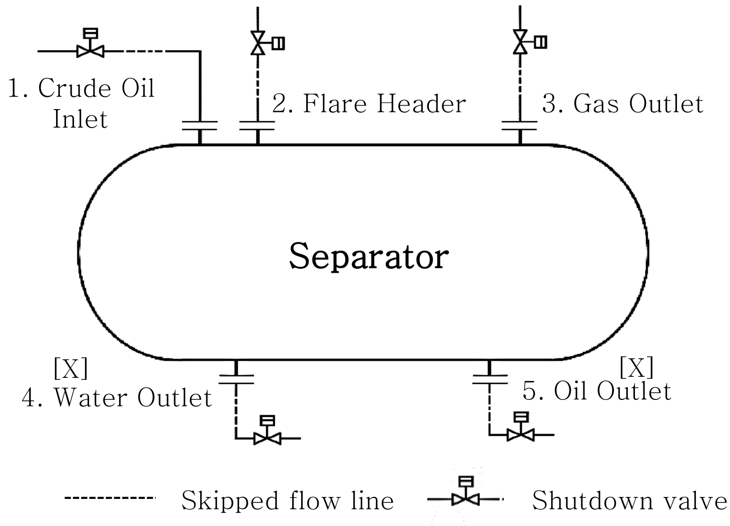


Fig. 25 Separator in test module

The main inventory in the test module is a great deal of oil & gas contained in the separators. There are 5 nozzles connected to each separator, but two of them are separated water and oil outlets, which hardly cause a fire accident. Therefore, only the rest three flow lines associated with nozzle 1~3 are considered during the scenario identification. Following figure 26 shows the total number of cases considered in the example under the condition of both successful and unsuccessful activation of ESD & EDP system. Furthermore, for each case three types of initial leak rates i.e. large, medium, small are also taken into consideration and each of them is called as a fire scenario.

Table 10 Leak frequencies for 3 hole sizes on process deck

Type	Diameter	Process Deck			Quantity	Modification factor	Large	Medium	Small
		Large [65mm]	Medium [46mm]	Small [6mm]					
Flange	30"	6.00E−06	2.95E−05	7.35E−05	6	1.5	5.40E−05	2.66E−04	6.62E−04
	24"	5.10E−06	2.50E−05	6.20E−05	6	1.5	4.59E−05	2.25E−04	5.58E−04
	20"	4.43E−06	2.23E−05	5.47E−05	23	1.5	1.53E−04	7.69E−04	1.89E−03
Actuated Valve	20"	1.15E−05	5.50E−05	1.35E−04	0	1.5	0.00E+00	0.00E+00	0.00E+00
	24"	1.10E−05	5.40E−05	1.30E−04	1.5	1.5	2.48E−05	1.22E−04	2.93E−04
Manual Valved	20"	7.53E−06	2.80E−05	5.20E−05	2	1.5	2.26E−05	8.40E−05	1.56E−04
Pipe [mm]	30"	1.40E−06	6.50E−06	1.50E−05	13305	1.5	2.79E−05	1.30E−04	2.99E−04
	24"	1.40E−06	6.50E−06	1.50E−05	51715	1.5	1.09E−04	5.04E−04	1.16E−03
	20"	1.40E−06	6.50E−06	1.50E−05	90475	1.5	1.90E−04	8.82E−04	2.04E−03
Vessel	30"	2.80E−04	3.50E−04	5.60E−04	2	1.0	5.60E−04	7.00E−04	1.12E−03
Total							1.19E−03	3.68E−03	8.17E−03

Table 11 Leak frequencies for 3 hole sizes on upper deck

Type	Diameter	Upper Deck			Quantity	Modification factor	Large	Medium	Small
		Large [65mm]	Medium [46mm]	Small [6mm]					
Flange	30"	6.00E−06	2.95E−05	7.35E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	24"	5.10E−06	2.50E−05	6.20E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	20"	4.43E−06	2.23E−05	5.47E−05	7	2.0	6.20E−05	3.12E−04	7.66E−04
Actuated Valve	20"	1.15E−05	5.50E−05	1.35E−04	0.5	2.0	1.15E−05	5.50E−05	1.35E−04
	10"	1.10E−05	5.40E−05	1.30E−04	0	2.0	0.00E+00	0.00E+00	0.00E+00
Manual Valve	20"	7.53E−06	2.80E−05	5.20E−05	2	2.0	3.01E−05	1.12E−04	2.08E−04
	10"	6.14E−06	2.13E−05	4.00E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
Pipe [mm]	30"	1.40E−06	6.50E−06	1.50E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	24"	1.40E−06	6.50E−06	1.50E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	20"	1.40E−06	6.50E−06	1.50E−05	58170	2.0	1.63E−04	7.56E−04	1.75E−03
Vessel	30"	2.80E−04	3.50E−04	5.60E−04	0	1.0	0.00E+00	0.00E+00	0.00E+00
Total							2.67E−04	1.24E−03	2.85E−03

Table 12 Leak frequencies for 3 hole sizes on top deck

Type	Diameter	Top Deck Large [65mm]	Top Deck Medium [46mm]	Top Deck Small [6mm]	Quantity	Modification factor	Large	Medium	Small
Flange	30"	6.00E−06	2.95E−05	7.35E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	24"	5.10E−06	2.50E−05	6.20E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	20"	4.43E−06	2.23E−05	5.47E−05	12	2.0	1.06E−04	5.35E−04	1.31E−03
Actuated Valve	20"	1.15E−05	5.50E−05	1.35E−04	0	2.0	0.00E+00	0.00E+00	0.00E+00
	10"	1.10E−05	5.40E−05	1.30E−04	0	2.0	0.00E+00	0.00E+00	0.00E+00
Manual Valve	20"	7.53E−06	2.80E−05	5.20E−05	6	2.0	9.04E−05	3.36E−04	6.24E−04
Pipe [mm]	30"	1.40E−06	6.50E−06	1.50E−05	22000	2.0	6.16E−05	2.86E−04	6.60E−04
	24"	1.40E−06	6.50E−06	1.50E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	20"	1.40E−06	6.50E−06	1.50E−05	10000	2.0	2.80E−05	1.30E−04	3.00E−04
Vessel	30"	2.80E−04	3.50E−04	5.60E−04	2	1.0	5.60E−04	7.00E−04	1.12E−03
Total							8.46E−04	1.99E−03	4.02E−03

Table 13 Probability of ignition and ESD & EDP

ESD & EDP			Cox & Lee Model		
Failure Probability on Demand			Ignition probability		
L	M	S	L	M	S
12kg/s	5kg/s	1kg/s	12kg/s	5kg/s	1kg/s
0.05	0.05	0.05	0.0778	0.0444	0.0158

Table 14 Leak frequency for each leak location

	Total Leak Frequency on Each Deck			Leak Frequency per Leak Location		
Size	L	M	S	L	M	S
Process	1.19E−03	3.68E−03	8.17E−03	1.98E−04	6.14E−04	1.36E−03
Upper	2.67E−04	1.24E−03	2.85E−03	8.88E−05	4.12E−04	9.51E−04
Top	8.46E−04	1.99E−03	4.02E−03	4.23E−04	9.94E−04	2.01E−03
Total	2.30E−03	6.90E−03	1.50E−02	7.10E−04	2.02E−03	4.32E−03

Table 15 Fire frequency with successful activation of ESD & EDP

Fire Frequency per Leak Location for Sucessful ESD & EDP			
Size	L	M	S
Process	1.46E-05	2.59E-05	2.04E-05
Upper	6.57E-06	1.74E-05	1.43E-05
Top	3.13E-05	4.19E-05	3.01E-05
Total	5.25E-05	8.52E-05	6.49E-05

Table 16 Fire frequency with unsuccessful activation of ESD & EDP

Fire Frequency per Leak Location for Unsuccessful ESD & EDP			
Size	L	M	S
Process	7.69E-07	1.36E-06	1.08E-06
Upper	3.46E-07	9.14E-07	7.52E-07
Top	1.65E-06	2.21E-06	1.59E-06
Total	2.76E-06	4.48E-06	3.41E-06

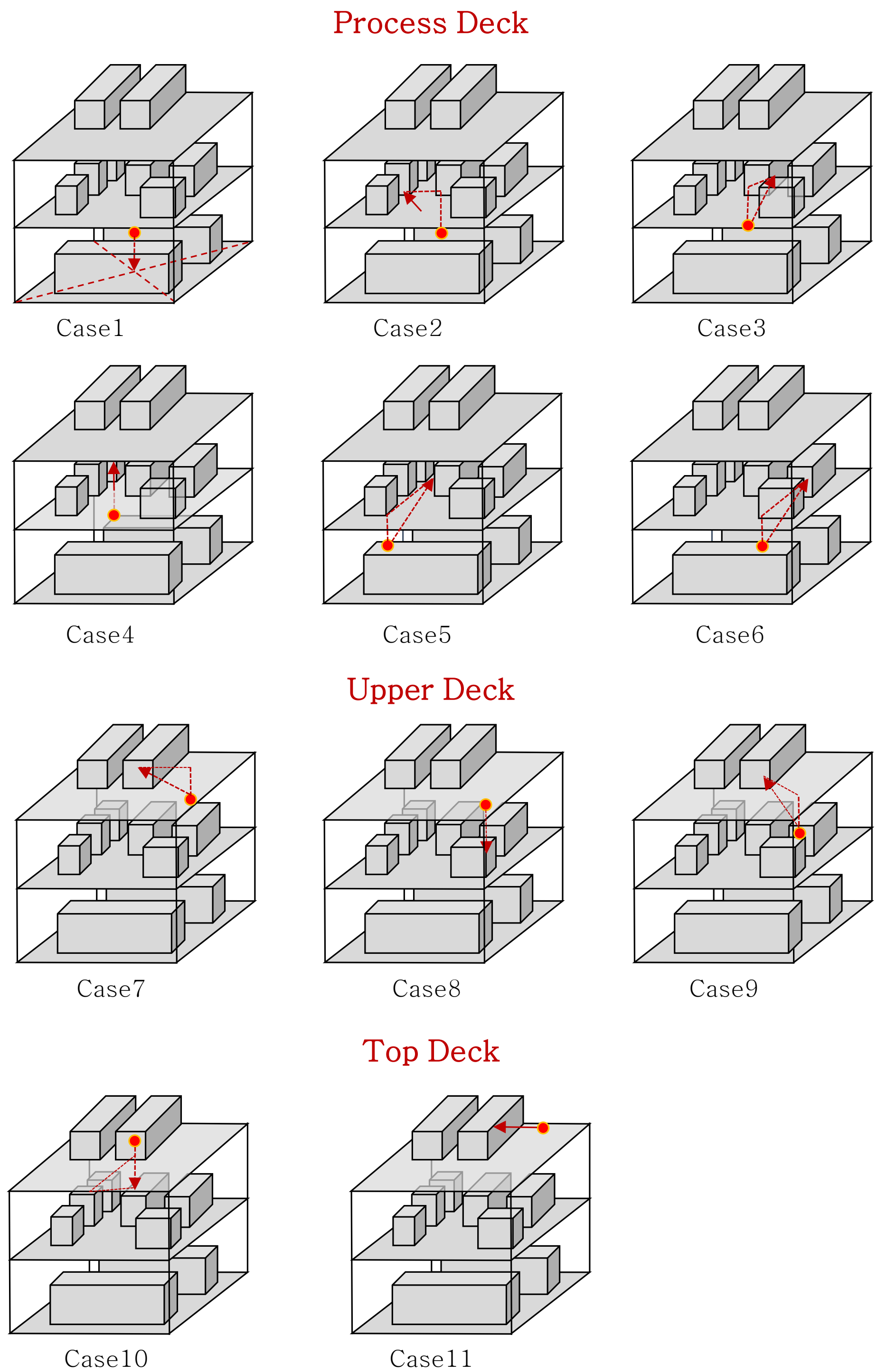
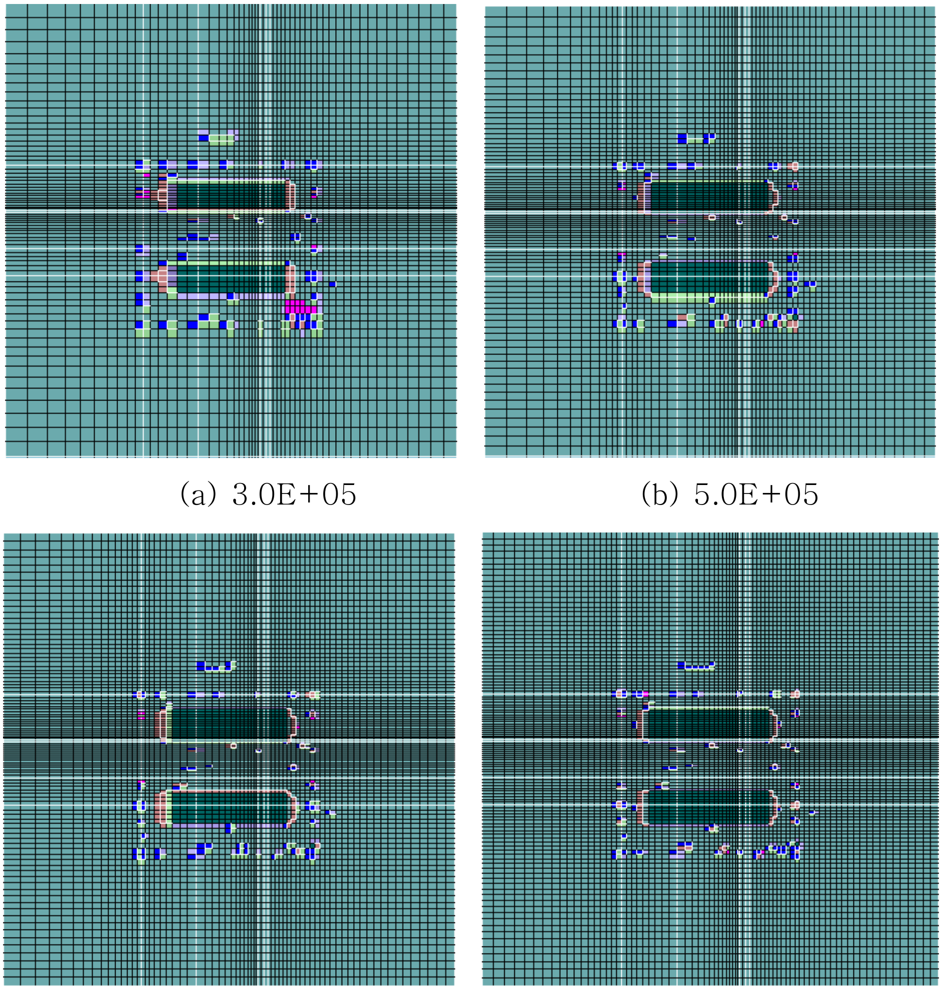


Fig. 26 Total cases considered in the example

5.2. Determination of Grid for Fire Simulation

In order to determine a proper number of grid for the identified fire scenario, 4 cases of fire simulation with different number of grid are carried out in the example. Following figure shows the 4 different cases with different number of grid.



(a) 3.0E+05

(b) 5.0E+05

(c) 7.0E+05

(d) 1.2E+06

Fig. 27 4 cases of considered grid number

The scenario used for grid testing is the large fire of case7 presented in Fig. 26, and the 4 types of fire simulation with different number of grid are continued until steady state. Through the comparison of heat flux distributions on x, y, z plane of the leak location showed in Fig 28~32, it is concluded that the proper number of grid should be 7.0E+05, because the heat flux distributions are almost unchangeable from that case. However, judging from the structural point of view, the area of interests is concentrated on the internal side of the test module, and the heat flux distributions inside the module are almost identical except for the first case with 3.0E+05 grids. Therefore, the proper number of grid applied in the example is determined as 5.0E+05.

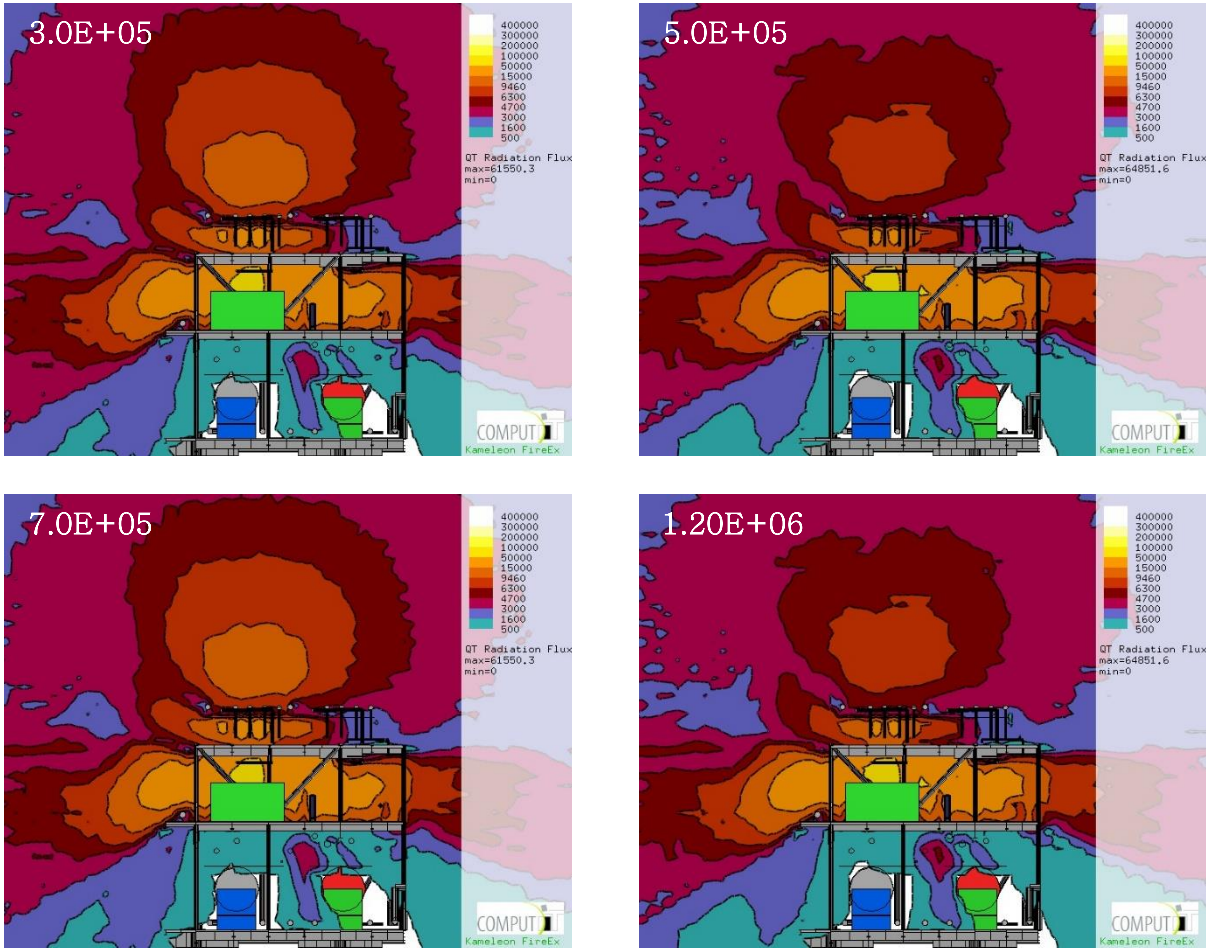


Fig. 28 Comparison of simulation results for 4 different number of grid, x plane

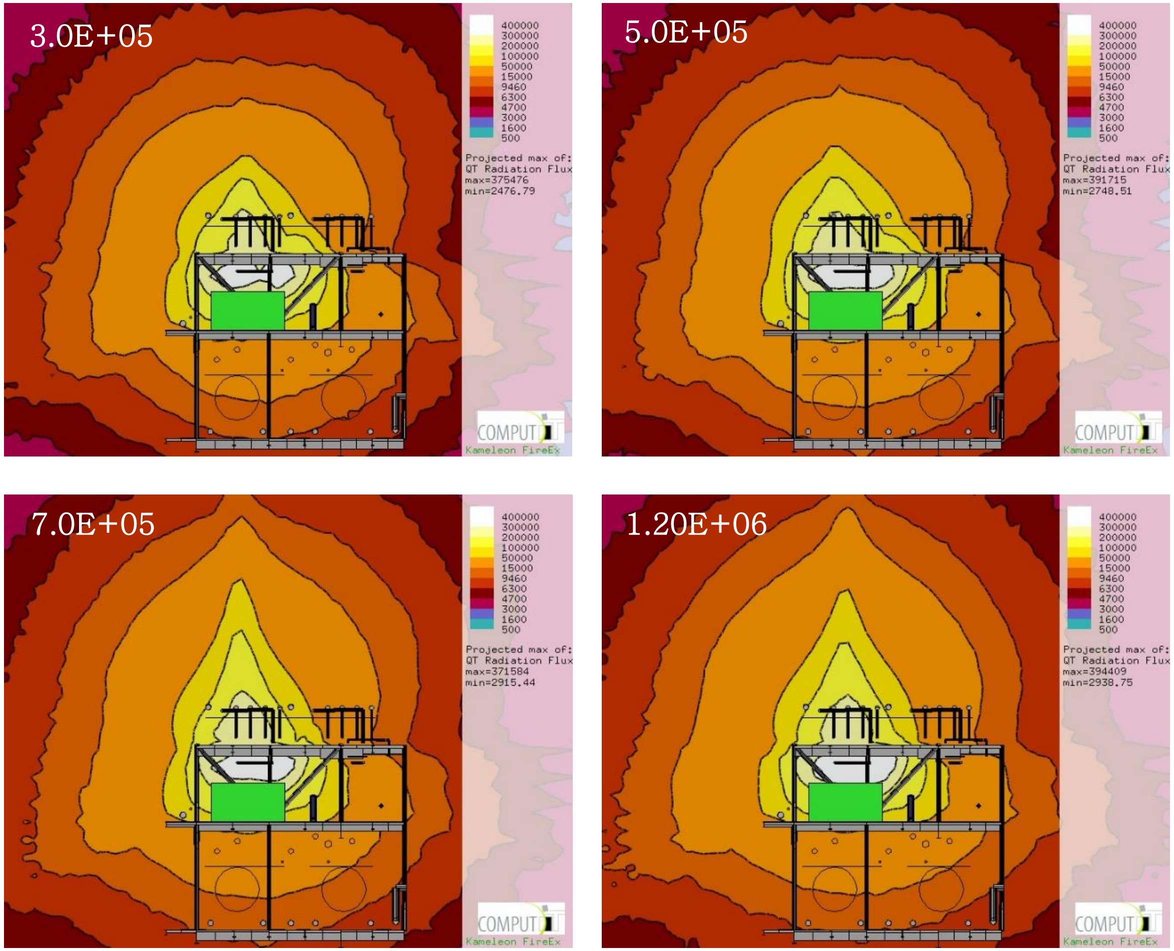


Fig. 29 Comparison of simulation results for 4 different number of grid, x projection

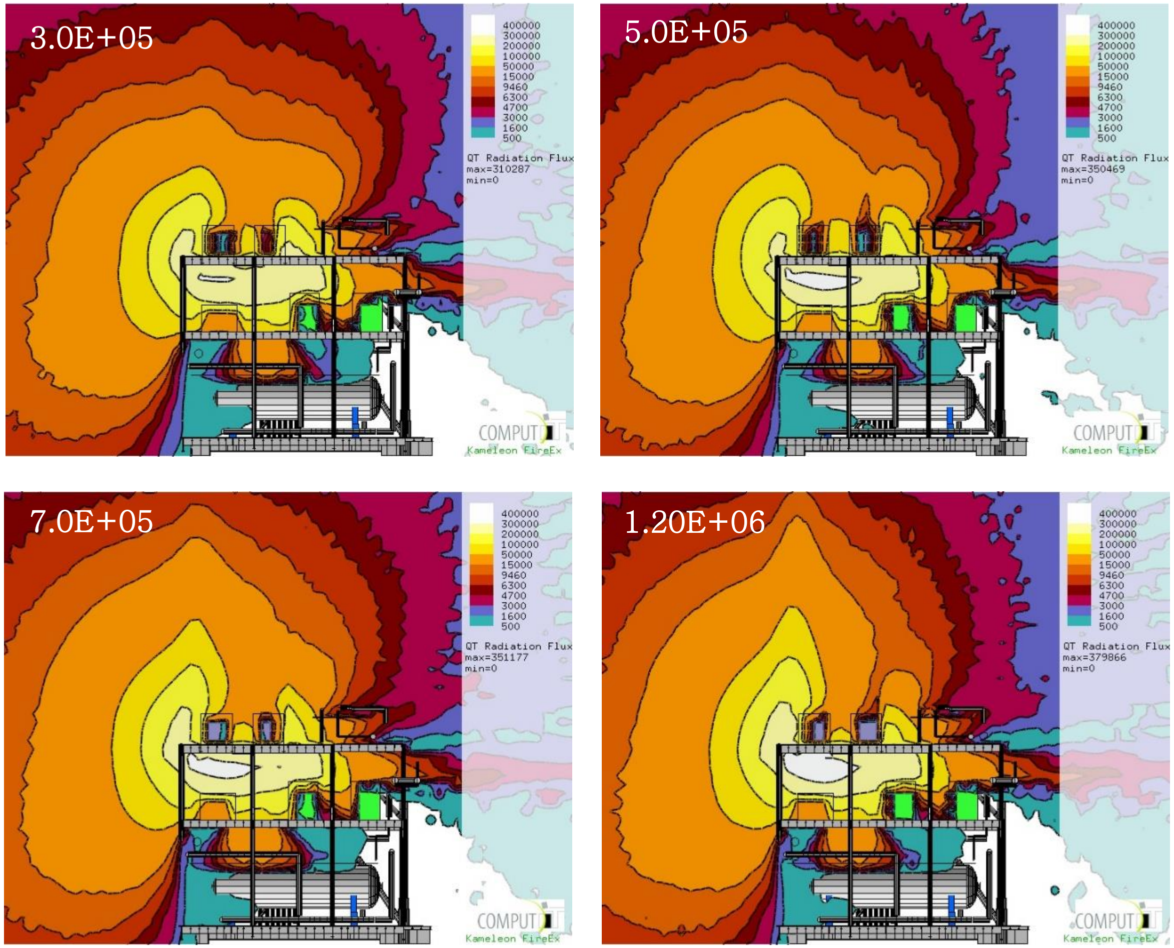


Fig. 30 Comparison of simulation results for 4 different number of grid, y plane

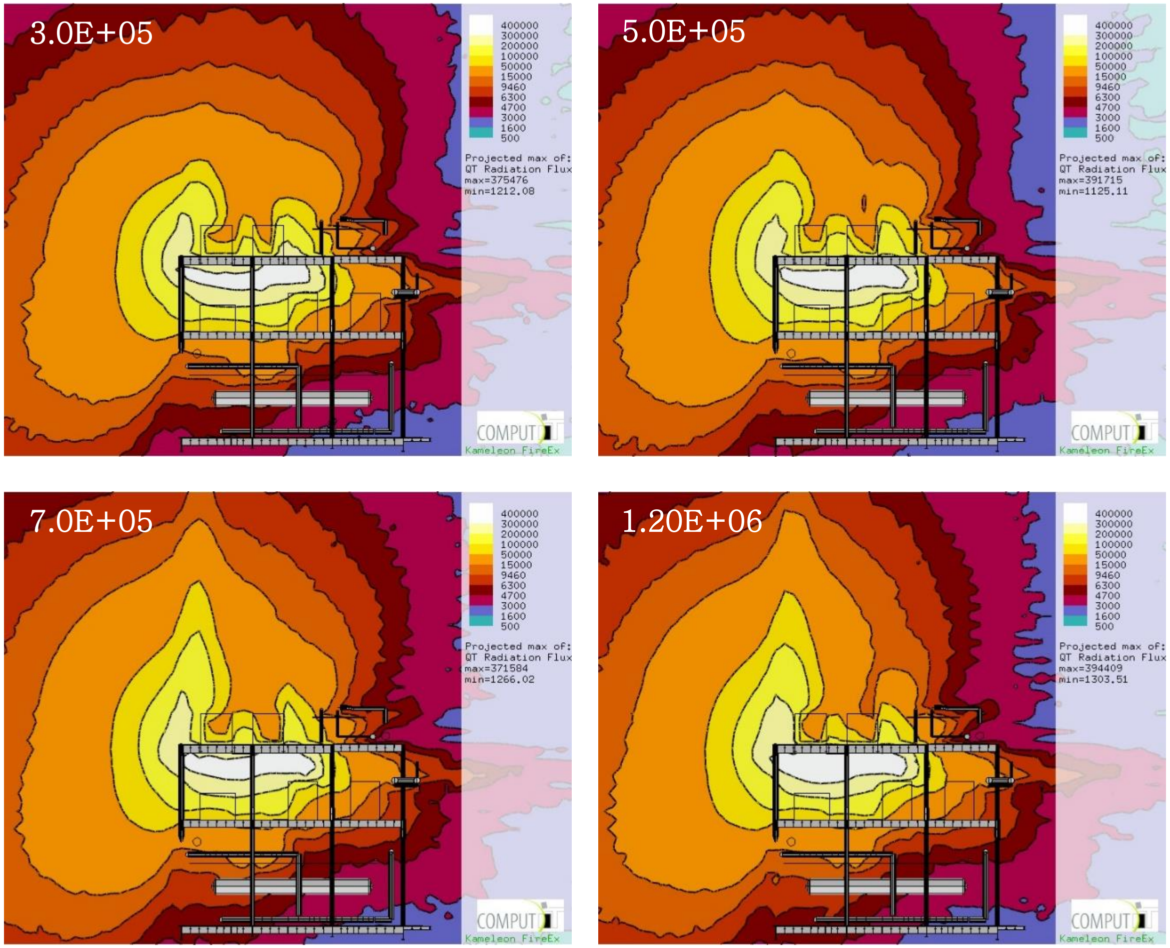


Fig. 31 Comparison of simulation results for 4 different number of grid, y projection

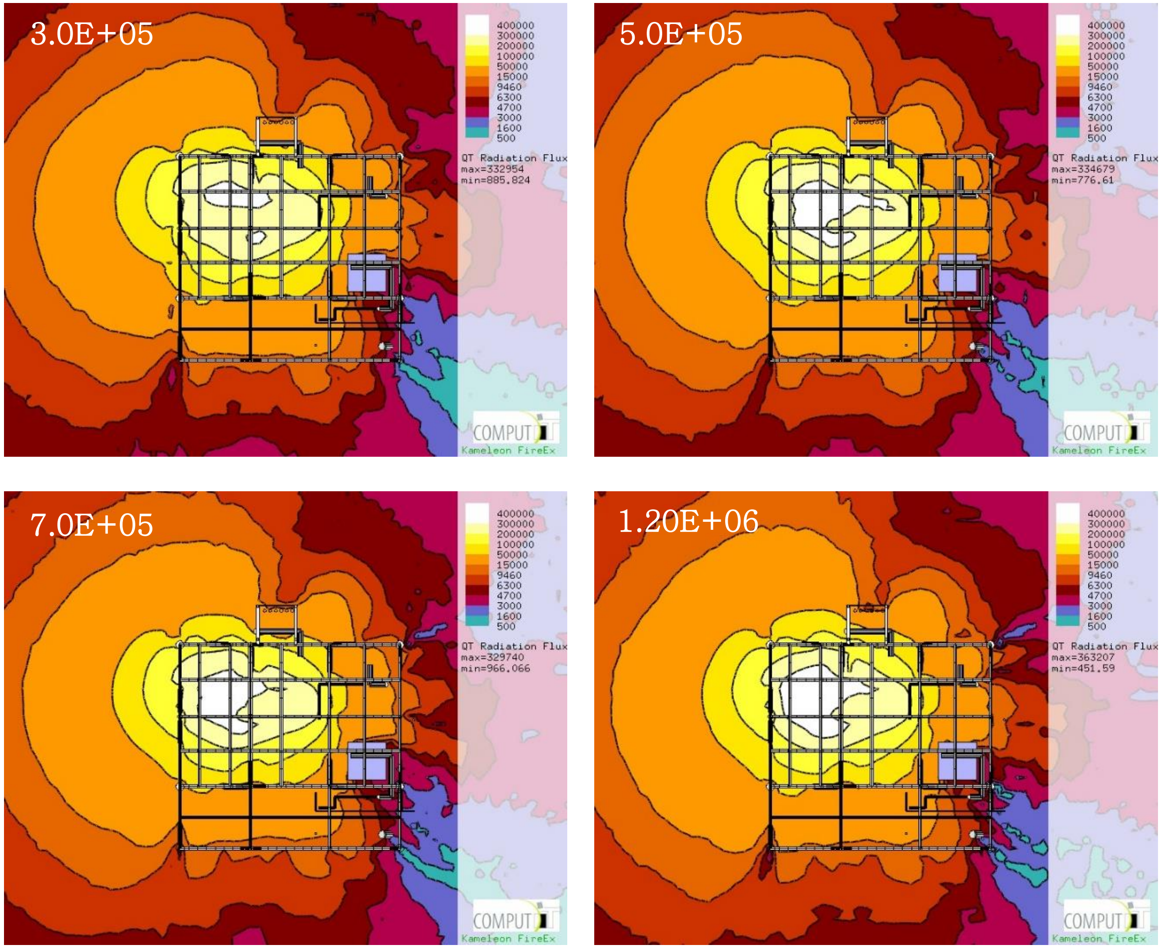


Fig. 32 Comparison of simulation results for 4 different number of grid, *z* plane

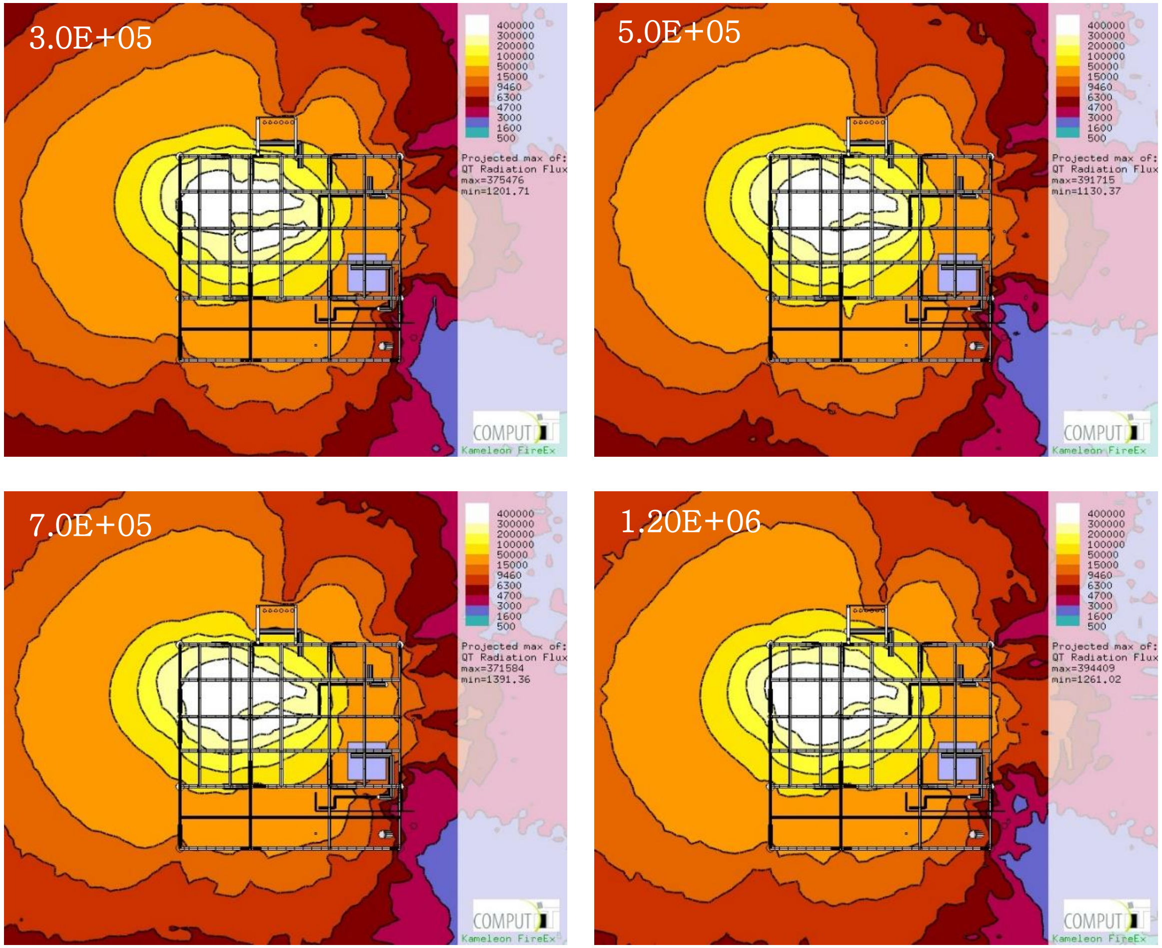
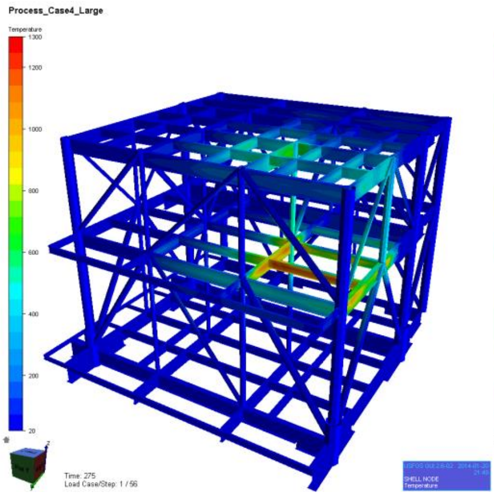


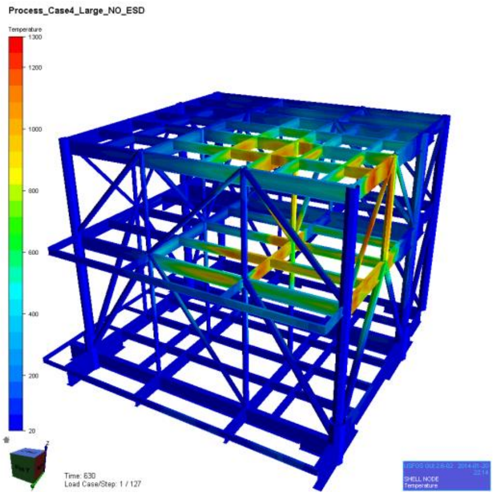
Fig. 33 Comparison of simulation results for 4 different number of grid, z projection

5.3. Structural Consequence Analysis

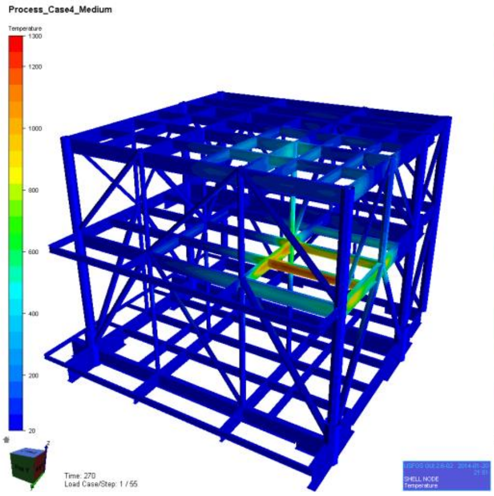
In the example totally 11 cases are considered for calculating cumulative failure frequency, and case 4 is representatively presented in the following figures.



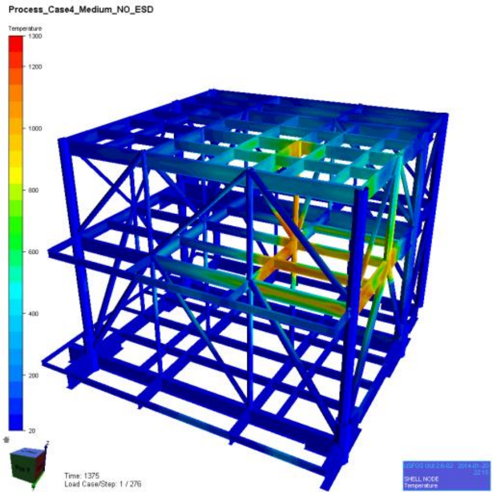
Large, successful ESD & EDP



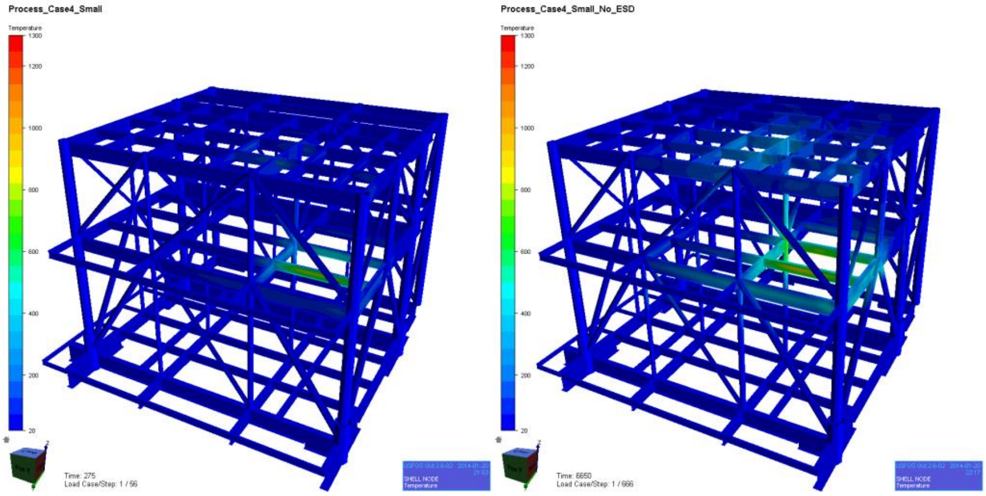
Large, unsuccessful ESD &EDP



Medium, successful ESD & EDP

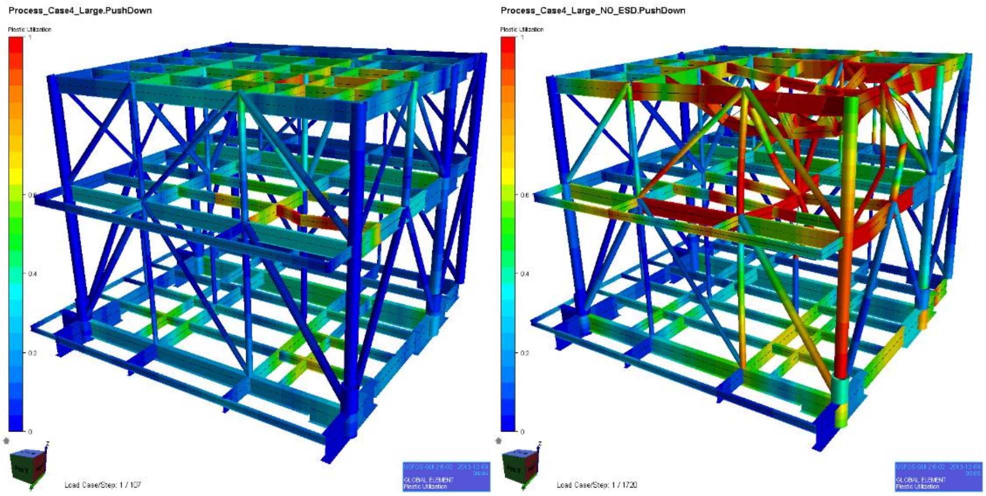


Medium, unsuccessful ESD & EDP

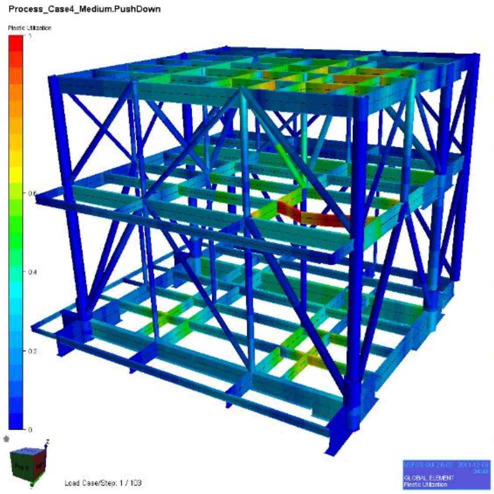


Small, successful ESD & EDP　　Small, unsuccessful ESD & EDP

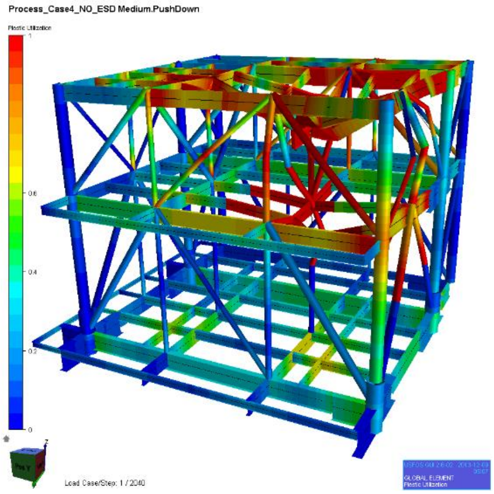
Fig. 34 Results of heat transfer analysis for Case 4



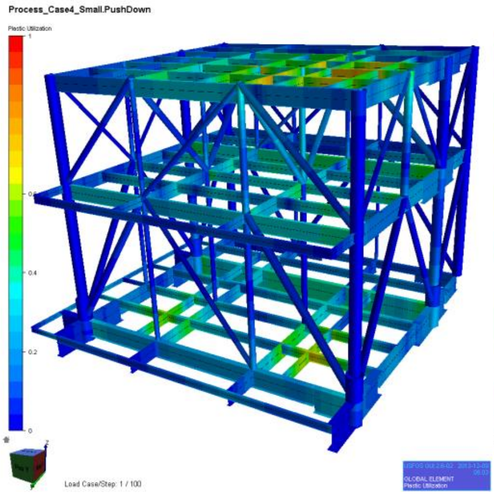
Large, successful ESD & EDP　　Large, unsuccessful ESD &EDP



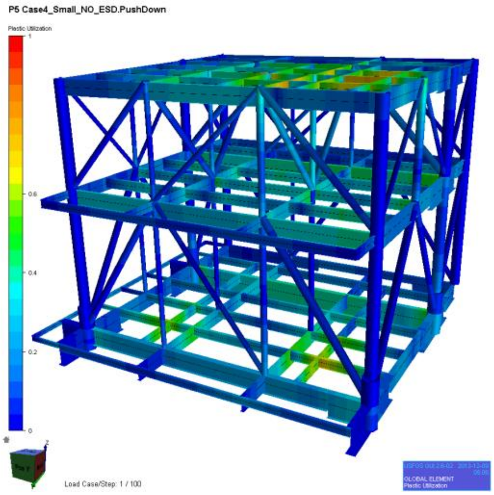
Medium, successful ESD & EDP



Medium, unsuccessful ESD & EDP



Small, successful ESD & EDP



Small, unsuccessful ESD & EDP

Fig. 35 Results of structural analysis for Case 4

According to the results of heat transfer analysis and structural analysis, it is obviously concluded that ESD, EDP system has a significant effect on the fire consequence and moreover most of small fires in the example hardly cause considerable failure of the test structure.

Furthermore, through a detail observation of other cases, it is also not difficult to find that structural parts which do not locally bear the equipment load are hardly to fail even if they are exposed to a high temperature load.

5.4. Calculation of Cumulative Failure Frequency

In the example, cumulative failure frequency of test module is calculated by using the formulae presented in section 4.5.2, and it is considered respectively by applying the two different structural failure criteria mentioned in section 4.5.1. The total number of elements for the test USFOS structure model is 379, and the results of cumulative failure frequency for each element is plotted in figure 29~30. X axis is the number of element and Y axis is the cumulative frequency.

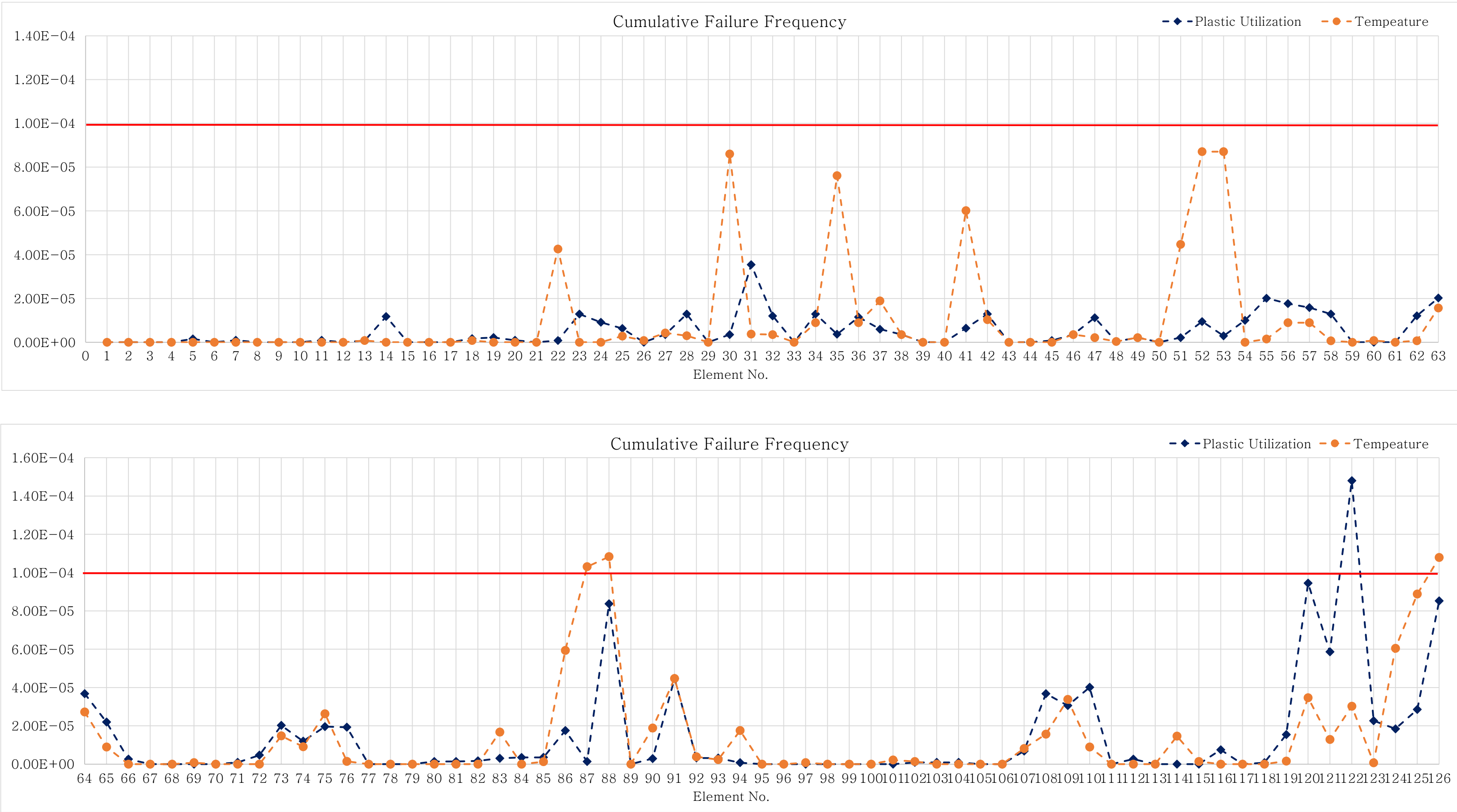
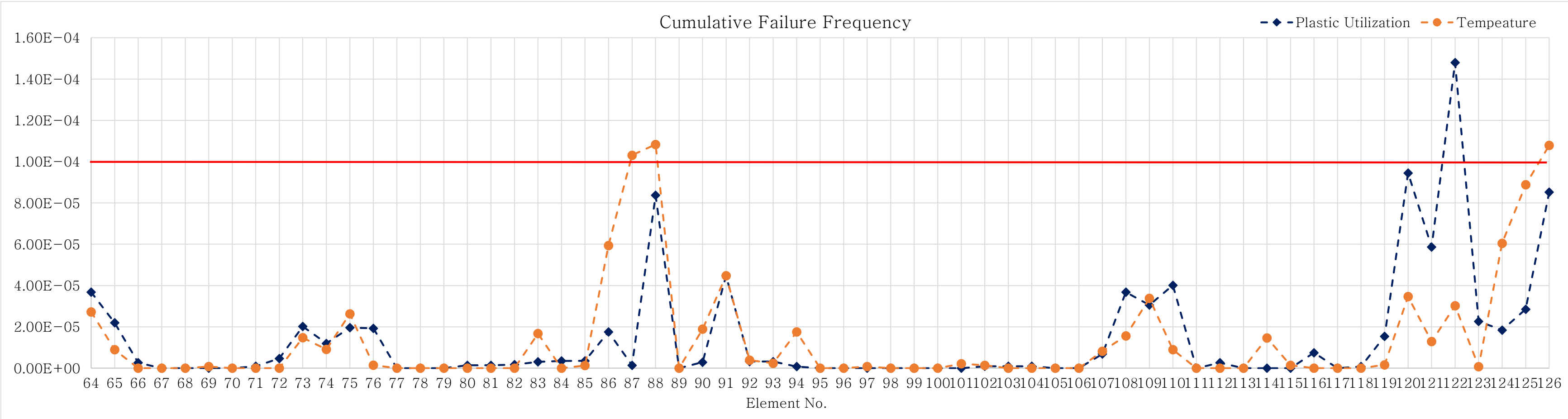


Fig. 36 Cumulative failure frequency of test module (1)



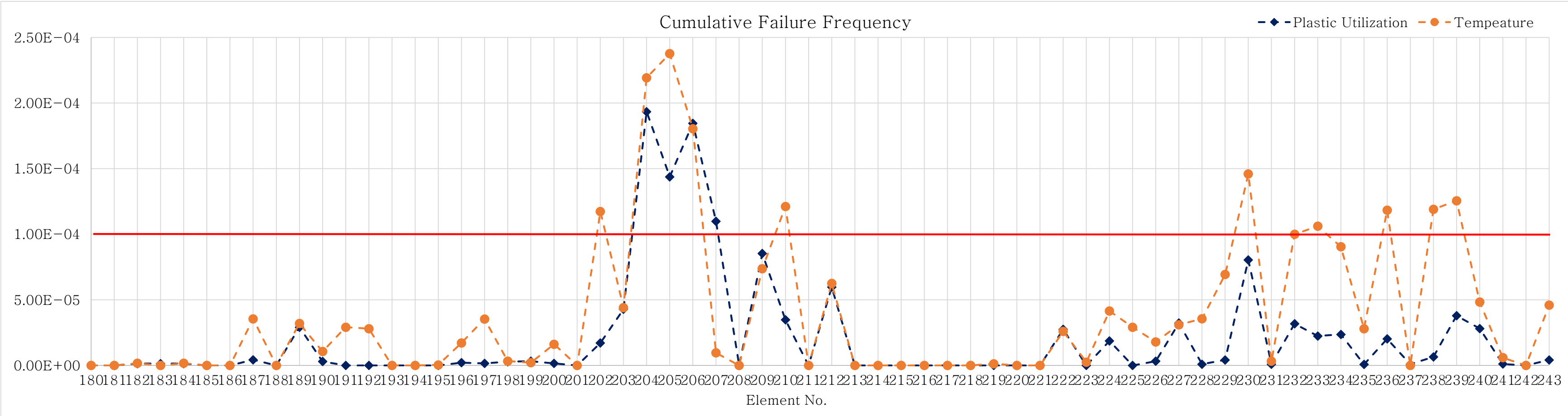
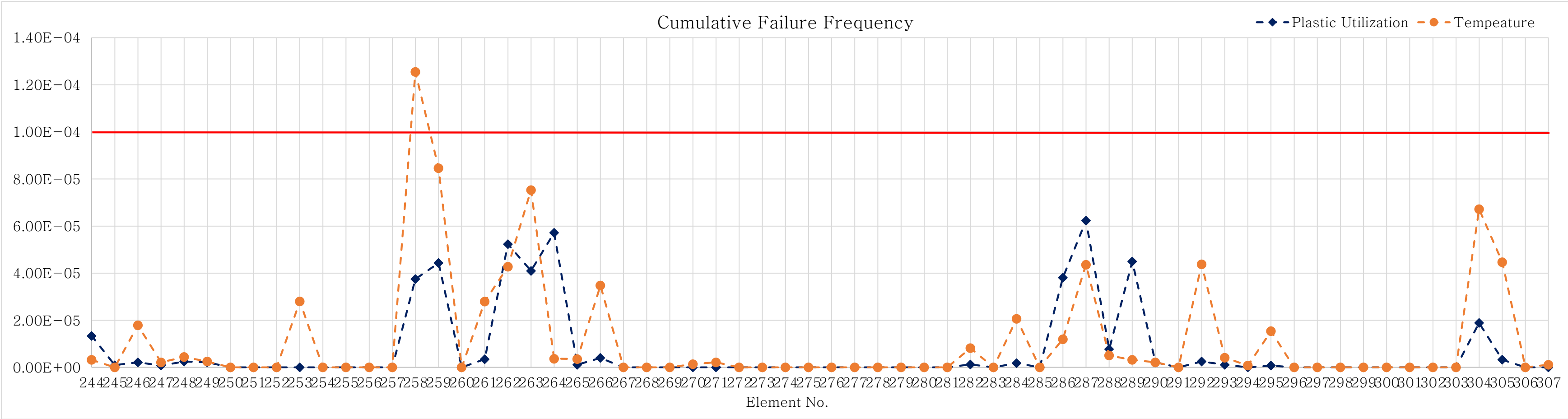


Fig. 37 Cumulative failure frequency of test module (2)



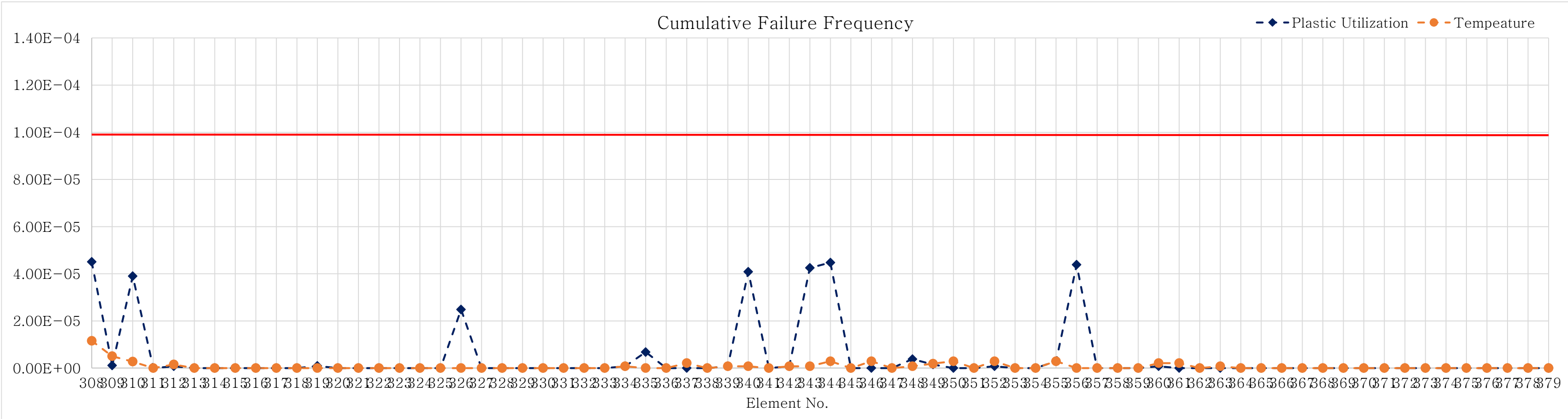
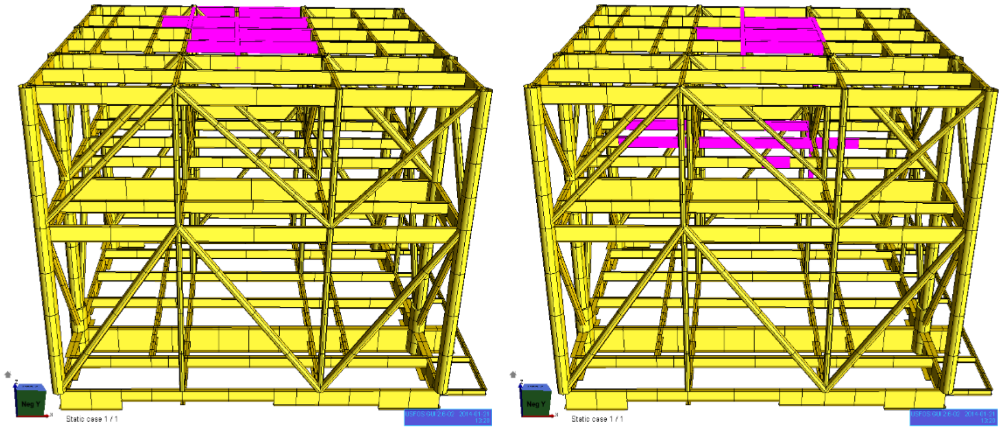


Fig. 38 Cumulative failure frequency of test module (3)

5.5. Determination of PFP Application area

In order to find the failed element that needs PFP protection, a risk criterion i.e. 1.0E−04 is applied to the graphs of cumulative failure frequency plotted in the previous section. The highlighted parts in the Fig. 38 are the identified failed elements.



(a) Structural analysis (b) Heat transfer analysis

Fig. 39 Failed structural elements

Through an observation of the failed element, following conclusions can be drawn.

- **For the failed elements of top deck:**
  - They are both identified as the failed elements through heat transfer analysis and structural analysis because

they are simultaneously subjected to high temperature and equipment weights.

- **For the failed elements of upper deck:**
  - They are identified as the failed elements through heat transfer analysis because the temperature is higher than 450 ℃.
  - Whereas, they are identified to be safe through structural analysis because the imposed equipment weights is relatively smaller than the ones on the top deck.

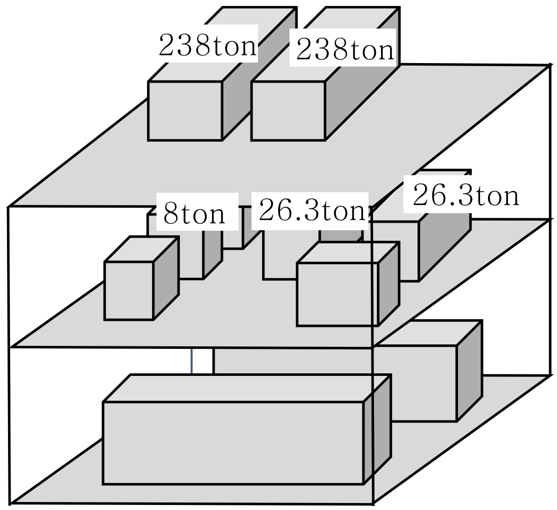


Fig. 40 Equipment load of test module

6. Conclusion

In the former FRA procedures the structural thermal consequence analysis is hardly to be accomplished, because those determined design loads are commonly just certain single physical variable, which are difficult to be applied for structure analysis. This indicates that the connection between determined design load and structure analysis always becomes a big problem in the former FRAs. To solve this, a new FRA procedure is proposed in this thesis. The most worthy point to be mentioned in the new procedure is including the result of structural response analysis at the stage of frequency analysis, and the specific method for this is calculating the cumulative failure frequency of structural element. Compared to the traditional exccedance curve, using cumulative failure frequency is much easier and more intuitively for determining the PFP application area, and this is proved by the example in this thesis.

In order to explain the new FRA procedure in more detail, an example is demonstrated with a test separation module. Through the observation of the example, it is summarized that that structural parts which do not locally bear the equipment load are hardly to fail even if they are exposed to a high temperature load. Consequently, this indicates that the structural analysis is a necessary part for evaluating the fire risk or determining the proper application area of PFP.

However, there are still a lot of uncertainties for identifying the fire scenarios by present. Especially for the part of determining the leak location and direction. Not only in the existing FRAs but also in the new one proposed in this thesis, there are too much subjective judgments involved in leak location and direction. Hence, as a future work, further studies will be focused on the leak location and direction to find more reliable and rational probabilistic models to depict their random characteristic.

Reference

[1] Andreas Falck, DNV, (2011). Leak Frequency Modeling for Offshore QRA based on the Hydrocarbon Released Database”, FABIG ISSUE 57, pp.9~18.

[2] Cox, Lees, Ang, (1990). Classification of Hazardous Locations, Institute of Chemical Engineers.

[3] EN 1993-1-2, (2005). Eurocode 3 Design of steel structures - Part 1-2: General Rules - Structural fire design.

[4] FAHTS, (2011). User’s manual for FAHTS, USFOS A/S, Norway.

[5] Hydro Carbon Release Database, (2005). HSE, http://www.hse.gov.uk/hcr3

[6] Jan Reier Huse, Ulf Danielsen, Joar Dalheim, Scandpower AS, SPE, (2011). Integrated Analysis of Fire Exposed Structures Introducing Probabilistic Analysis into Fire Modeling and Structural Analysis, Society of Petroleum Engineers.

[7] KFX, (2010). User’s manual for Kameleon FireEx (2010). Computational Industry Technologies A/S, Stavanger, Norway.

[8] NORSOK, (2001) Risk and emergency preparedness analysis, NORSOK Standard Z-013, Oslo, Norway.

[9] OGP, (2010). Process release frequencies, Risk Assessment data directory, Report No.434-1.

[10] Sávio Vianna, Asmund Huser, (2010). Fire CFD Modelling Applied to Offshore Design, Det Norske Veritas.

[11] SCI, (2009). Probabilistic Assessment of Fire loads and Structural Response, FABIG Technical Note 11.

[12] Total, (2008). Technological Risk Assessment Methodology, GSEP SAF 041.

[13] USFOS, (2012). User’s manual for USFOS, USFOS A/S, Norway.

[14] Viken Chinien, Asmund Huser, (2013). Adoption of risk based assessment method for Fires and Explosions in Design, FABIG ISSUE 62, pp. 24~30.

[15] 박정효. 해양플랜트 Topside 화재 CFD 시뮬레이션에 관한 연구. 2011. 부산대학교 석사학위논문.

[16] 유권철. 해양플랜트 Topside 가스폭발 위험도 평가에 관한 연구 – 가스폭발사고 시나리오 선정. 2010. 부산대학교 석사학위논문

초록

FPSO 상부구조에 대한 확률론적 화재 위험도 해석 및 구조 안전성에 관한 연구

많은 해양 플랜트는 가연성 오일 & 가스 정제 프로세스를 가지고 있기 때문에 탄화수소 화재 사고가 발생할 가능성이 크다. 화재 사고는 전체 해양플랜트 위험도에서 큰 비중을 차지하고 있다. 그렇지만 기존의 실제 프로젝트에 많이 적용되었던 화재위험도 해석 방법들은 여전히 해양플랜트 화재 사고 위험도를 평가하는데 있어서 많은 부족한 점을 가지고 있다. 이러한 이유 때문에 본 논문에서는 새로운 화재 위험도 해석 프로시저를 제안하여 기존 방법들의 문제점들을 극복하고자 한다.

새로 제안한 화재위험도 해석 프로시저에서는 우선 화재 시나리오 구성에 필요한 변수를 적절한 확률모델, historical database, 프로세스 P&ID, PFD 등 다양한 정보를 이용하여 신중히 고려하였고 3d CFD 기반의 수치 화재 시뮬레이션을 적용하여 각 구성된 시나리오의 화재 현상을 해석하였다. 그리고 snapshot 방법을 적용하여 시간에 따라 변화하는 화재의 동적인 특성을 수치시뮬레이션에 효율적으로 반영하였고 화재에 노출되어 있는 FPSO 상부구조의 응답을 평가하기 위해서 열 전달 및 비선형 구조해석을 새로 제안한 프로시저에

포함시켰다.

기존의 화재 위험도 해석은 화재시뮬레이션 결과에 초점을 두고 exceedance 곡선을 이용하여 확률론적으로 DAL 값을 결정하였다. DAL 값은 흔히 FPSO 상부구조나 장비의 설계에 반영 된다. 하지만 exceedance 곡선을 통하여 얻은 DAL 값은 흔히 화염의 길이, heat dose, heat flux contour 등 단일 물리 량으로 표현되었기 때문에 실제 구조해석에 적용하기에는 많이 부족하다. 이를 해결하기 위하여 본 논문에서는 각 시나리오의 구조해석 결과에 초점을 두고 exceedance 곡선 대신에 새로 제안한 구조의 누적 파괴 빈도를 이용하여 화재에 노출되어 파괴될 가능성이 높을 구조 부재를 직접적으로 찾아냈다.

보편적으로 해양 플랜트에서 가장 많이 사용되는 있는 화재 위험도 경감 방법은 PFP를 구조 또는 장비 표면에 부착 하는 것이다. 하지만 PFP는 고가의 제품이기 때문에 해양플랜트의 많은 부분에 적용하게 되면 자체의 안전성은 크게 향상 시킬 수 있으나 반면에 경제적으로 엄청난 비용을 부담해야 된다. 그 이유로 PFP의 적용 면적을 최적화 하는 부분은 실제 해양 프로젝트에서 아주 중요한 문제로 간주되고 있다. 그러한 의미에서 본 논문에서 제시한 화재위험도 해석 프로시저는 구조 관점에서 정립된 방법이고 특히 구조의 누적 파괴 빈도를 기반으로 파괴될 가능성이 큰 구조 부재를 판단하기 때문에 PFP 결정을 하는데 있어서 아주 유용하게 이용될 수 있다.

본 논문의 앞 부분에서는 새로 제안한 화재 위험도 프로시저에 대하여 상세히 소개하고 마지막 부분에서는 실제 FPSO separation module을 테스트 모델로 선택하여 하나의 예제를 보여 주었다.

주요어: QRA(Quantitative Risk Assessment), FRA(Fire Risk Analysis), PFP(Passive Fire Protection), CFD, Snapshot

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공학석사 학위논문

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2014 년 02 월

서울대학교 대학원

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2014 년 2 월

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JIN YANLIN의 공학석사 학위논문을 인준함

2014 년 2 월

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Abstract

Study on a Probabilistic Fire Risk Analysis and Structural Safety Assessment of FPSO Topside Module

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Many offshore platforms are usually exposed to the flammable oil & gas circumstances; hence hydrocarbon fire is a big threat to the offshore platforms. Fire accident on the offshore platform occupies a major part of the total risks. Nevertheless, former procedures of fire

risk analysis used in the industry are still not intact enough to evaluate the risks related to fire accident. For this reason a new procedure of fire risk analysis is established in this paper to overcome the deficiencies in the former FRAs.

In the new FRA procedure, the key parameters used for constructing fire scenarios are carefully considered and discussed for fear of the too much conservative judgment. Some of the parameters are considered in a probabilistic way or by using historical database and even sometimes based on the information of P&ID and PFD. CFD fire simulation is carried out based on the identified representative fire scenarios. In the fire simulation, the dynamic effect of hydro carbon fire determined by the inventory condition is also properly reflected by applying an effective method called 'snapshot'. Furthermore, for investigating the structural response under the fire, heat transfer analysis and non-linear structural analysis are both included in the new FRA procedure.

In the former FRAs, a concept of exceedance curve with certain physical variable is generally used in the frequency analysis for combining the results of fire simulation and fire frequency calculation. The purpose of using exceedance curve is for deciding a DAL, which is used for structure design against the fire accident or determination of proper PFP application area. Whereas, in the new FRA procedure, a new concept of structural cumulative failure frequency is presented to take place of the conventional exceedance curve. The purpose of using cumulative failure frequency in the new FRA can be summarized as two aspects. One is to solve the connection problem between the determined design load and structure analysis existed in the former FRAs, and other one is to have the determination of PFP application area become more intuitively and precisely.

Generally, in the offshore platform PFP (Passive Fire Protection) is the most common and useful measure to reduce the failure of offshore structure under the hydro carbon fires. However, wide use of the PFP leads to a considerable increase of total project cost and this indicates that minimizing or optimizing the application areas is quite important. In that sense, cumulative failure frequency presented in this paper can be a quite useful tool to determine the proper PFP application areas for the structures. Furthermore, in order to demonstrate more detail of the new FRA procedure, an example with FPSO separation module is presented at last.

Keywords : QRA(Quantitative Risk Assessment), FRA(Fire Risk Analysis), PFP(Passive Fire Protection), CFD, Snapshot

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Contents

List of Figures

List of Tables

NOMENCLATURE

DAL	Design accidental load
ESD	Emergency shutdown
EDP	Emergency depressurization
FRA	Fire risk analysis
FAHTS	Fire and heat transfer simulator
HC	Hydro carbon
HSE	Health and Safety Executive
HCRD	Hydro carbon release database
KFX	Kameleon FireEx
OGP	Oil & Gas producer
PFP	Passive fire protection
PFD	Process flow diagram
QRA	Quantitative risk assessment
SDV	Shutdown valve

1. Introduction

1.1. Research Background and Objective

Facing with the rapid development of society and industry, energy consumption and requirement have been increasingly grown in the last few decades. In the past, the main source of human fuel comes from the crude oil buried underground but now it has been changed. The increasing energy requirement forces the resource exploitation activity to expand to the sea floor, driving the whole energy industry into a new era. The development of drilling & subsea techniques provides a significant possibility of exploiting the crude oil & gas buried under the sea floor, and also many different shapes of offshore platforms are designed to provide a stage to ensure the availability of drilling & exploitation activity for deeper and deeper water.

However, because most of the offshore platforms are exposed to the flammable oil & gas circumstance, hydrocarbon fire accident is a big threat to the offshore platform. Typically, there are 3 types of offshore hydrocarbon fire, respectively jet fire, pool and BLEVE (Boiling liquid expanding vapor explosion). All of these fires could possibly weaken the strength of offshore structures or safety equipment and result in a considerable disaster.

Fig. 1 Piper Alpha accident

One of the typical offshore platform fire & explosion accidents in the history is the well-known Piper Alpha disaster in 6^{th} June, 1988. The disaster was begun with an error of maintenance routine procedure. During the work shift, the primary propane condensate pump was failed, but none of the shifted workers were aware that a vital part of the equipment had been removed and decided to start the backup pump. Gas products escaped from the hole left by the valve at a high pressure and ignited. Afterward, the fire spread most of the platform, destroyed some oil lines and a large quantity of stored oil burned out of control. The whole accident took place only in 22 minute, and caused the loss of 167 crewmen and $ 3400 million.

Fig. 2 Deep Water Horizon accident

Another typical accident is the Deepwater Horizon disaster occurred in 20th April, 2010. The accident was caused by a HC blowout from the well which resulted in an explosion and fire on the rig later. 11 people lost their lives during the accident, and the whole rig sank after the 36 hours of struggling. Moreover, during the accident the whole well control system (including BOP) was failed, and leakage from the well continued for 87days even though several interventions were tried to stop the situation. Nevertheless, the considerable amount oil spill still left a giant damage to the surrounding environment in the end.

As above two accidents reflected, explosion & fire accident is quite deathful to an offshore platform even though it has a very little frequency of occurring; hence the risk management should be carried out to guarantee the survival of offshore plant as far as possible from those destructive accidents.

QRA (Quantitative risk assessment) is the most advanced method of managing all types of possible accidents on the offshore platform, and the main purpose of QRA is evaluating the quantified risk which is defined as the product of consequence and frequency. Quantified risk is usually used for determination of the prevention and mitigation measures against the accidents. QRA for an offshore plant is consisted of many sub-parts according to different types of risk, and FRA (fire risk analysis) is one of the sub-parts for evaluating the risk related to fire accident.

However, existing methods of fire risk analysis used in the industry are lack of standard procedure, therefore those FRAs appeared in the past offshore projects were not unified. Practical details associated with the methodologies involved in the former FRA procedures are quite diverse and ambiguous because they were independently carried out by different engineering companies. Furthermore, according to the different levels of accuracy or interesting targets, the physical variable used in the procedure for calculating the DAL is different (e.g. flame size, heat dose, heat flux etc.), and this could probably influence the methodology of FRA.

Facing with above problems of former FRAs, a new scenario based probabilistic FRA procedure is established in this thesis. The purpose of the new FRA procedure can be sorted out as two aspects. One is regulating a general procedure to reduce the variances and uncertainties in the former FRAs, and the other one is constructing an unprecedented FRA procedure, which is focusing on the connection problem between fire simulation and structural consequence analysis to identify the failed structure members that need certain protection. In the former FRA procedures, the analyses are normally ended up with calculating DAL (design accidental load), and no more detail procedure is described for how to use the determined DAL to perform the structural consequence analysis. This is because the determined DAL is usually expressed by certain physical variable, which is quite difficult to be used in structural consequence analysis. Therefore in the former FRA studies, the part of structural consequence analysis is always either omitted or considered with an uncertain procedure. To solve this, a lot of efforts are paid in this thesis to think about the way how to probabilistically reflect the result of structural consequence analysis in the FRA studies, and the answer is the cumulative structural failure frequency. By using the cumulative structural failure frequency, structural response under the fire can be easily connected to the frequency analysis, which makes possible to probabilistically identify venerable parts of topside structure and optimize the area of PFP application or deluge system.

1.2. Research Status

FRA (Fire risk analysis) is defined as a course of study, which determines the threats of potential fire scenario to the offshore plant and its associated facilities through proper number of fire simulations as well as structural consequence analysis if needed. The results and finding of FRA will be used as input to an overall quantitative risk assessment (QRA). The specific objectives fire risk analysis can be summarized as followings. First, identify a series of representative fire scenarios that can be enough to stand for the potential fire accidents on the offshore plant. Second, quantify the identified scenarios with certain physical values (e.g. flame size, heat dose, heat flux etc.), which are used for calculating DAL (design accidental load). Third, identify the vulnerable targets to the fire scenarios and evaluate their consequence under the fires. Forth, identify the potential escalation of each fire accident and the possible damages to the asset, and lastly determine the possible requirement for additional risk reduction measures to help prevent and/or mitigate the effects of the identified fire scenarios.

Typically, fire accidents on the offshore plant is quite deathful even though they happen rarely, so directly using the fire simulation results to assess the risks is seemed to be very conservative. To avoid this, commonly probabilistic methodology is involved in the FRAs. Generally, the fire scenarios identified in the FRA are consisted of several parameters, and most of the parameters are considered in a probabilistic approach for calculating the fire scenario frequency as well as DAL. However, some of the parameters are naturally quite difficult to treat in a probabilistic way; hence for these parameters, simple assumptions or expert's judgment were more plausible in the former FRAs. Also, as mentioned in the previous section, the physical variable concerned about in the FRA study influences its methodology. The purpose of using certain physical variable is for quantifying the impact of identified fire scenarios in the FRA. Fire simulation result is usually used as input for the overall QRA, thus it must be reflected by some quantified variables to measure its damages or impacts. Typically, there are several types of quantified physical variables were mainly selected in the former FRAs, for example, flame size, heat dose, heat flux contour, temperature etc, and among those physical variable, flame size and heat dose are typically to be used. When using the flame size, the accuracy level of FRA is just limited to roughly judge the failure of critical targets with flame size, and no further detailed analysis about fire simulation and structural consequence is included. The critical target is defined as some important parts of offshore plants whose failure probably can cause a significant loss (e.g. Module supports, ESDVs, Crane Pedestal, Flare KO drums etc.). Conversely, when using the heat dose, the accuracy level of FRA is much higher since detailed fire simulation is involved to calculate the DAL. The detail of both methods will be accounted particularly in this paper.

2. Generic Outline of Fire Risk Analysis

Fire risk analysis is a sub-part of QRA (Quantitative risk assessment), which mainly evaluates the fire related risks on the offshore platform. The generic outline of former fire risk analysis and the new proposed one both can be consisted of 3 phases, each of them are presented in Fig. 3. In the outline only key steps are sorted out; hence it can be regarded as a foundation and the specific methodologies used in each FRA are all started from the outline.

2.1. Phase 1

Phase 1 is a preparation stage for the following fire simulation. Identically, for both generic outlines, the phase 1 is made up with two parts, one is fire scenario identification and the other one is frequency calculation.

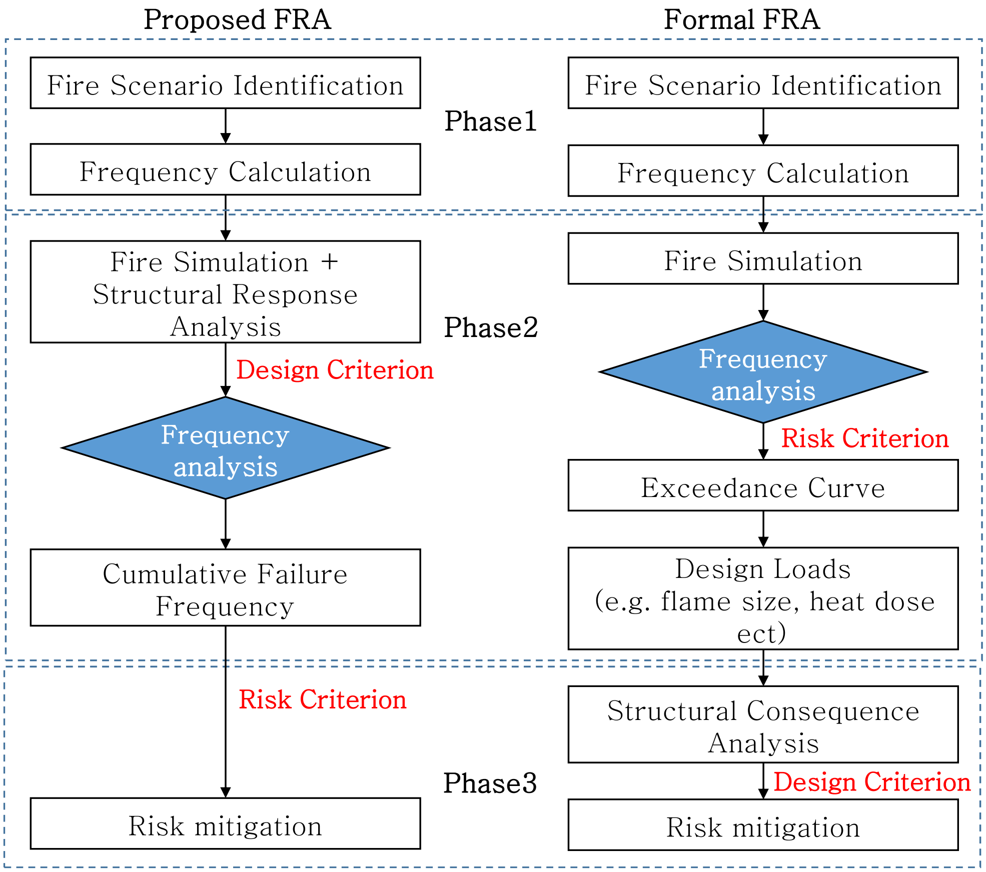


Fig. 3 Generic outline of fire risk analysis

2.1.1. Fire Scenario Identification

Typically, several fire control parameters are considered during the scenario identification, and they are summarized below:

- Leak rate
- Leak duration
- Leak direction
- Leak location
- Leak frequency
- Ignition probability

Among these parameters, leak rate, duration, frequency, ignition probability are predictable by various source of data, whereas, leak location and direction is not easy to determine, because they are quite random variables. For this reasons, usually conservative assumption or expert's judgment is the most practical ways to consider the two parameters. Furthermore, in order to identify the scenarios more efficiently, usually the whole process is divided into several isolatable segments, and each segment should be bounded by SDV (shutdown valve) or ESDV (Emergency shutdown valve). For FPSO, each module in the process area is isolated by SDV or ESDV, thus each module can become an isolatable segment.

2.1.2. Leak frequency

Hydrocarbon leaks from process equipment make a significant contribution to the risks of offshore plants. When risk management options are determined using QRA, the frequency of HC leaks is an input to the study and it will have a major influence on the estimated risk. Leak frequency in FPSO process area is usually calculated based on historical leak database (e.g. HCRD by HSE). Following figure is showing the generic HSE release statics from 1996 to 2013. The data is plotted based on 3 levels respectively, minor, significant and major. More detail about the leak frequency calculation is instructed in chapter 4.

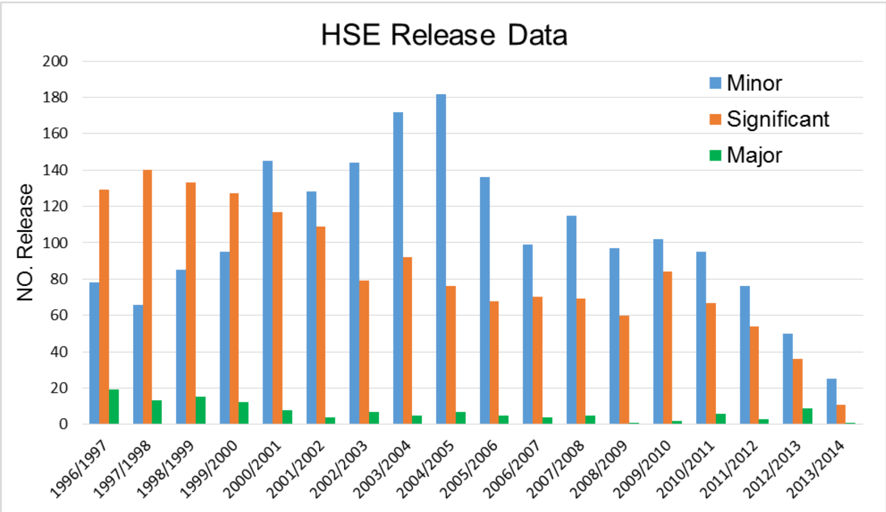


Fig. 4 HSE hydro carbon leak data (1996−2013)

Table 1 Three levels of HSE leakage

	Leak rate	Duration
Major	>1kg/s	> 5min
Significant	0.1~1kg/s	2~5min
Minor	0.1kg/s<	2 min <

2.2. Phase 2

Phase 2 is made up with two key parts, one is fire simulation and the other one is frequency analysis. Usually the structural consequence analysis is placed after the step of frequency analysis, and this sequence was normally used in the former FRAs (Right one in the Fig. 3). However, in the new proposed method, the step of structural analysis changes to be placed before the step of frequency analysis (Left one in the Fig. 3). Determination of design load in the former FRAs is based on an exceedance curve with certain physical variable. The purpose of using the variable is for quantifying the impact of identified fire scenarios. Fire simulation results in the FRA are usually used as input for the overall QRA, and this indicates that they must be reflected by some quantified variables to measure their damages or impacts. Typical quantified variables used in the existing FRAs are respectively flame size, heat dose, heat flux contour etc. Commonly, the quantified variables are quite useful during frequency analysis to extract the design load of fire accident. However, since the extracted design load is usually expressed by a single variable; hence using such design load to analyze the structural response is quite difficult. This is the reason why most of the former FRAs are stopped at the step of determining design load, and cannot provide no more specific details about how to use the design load to perform the structural consequence analysis. Facing with above problems, in the new proposed FRA, structural consequence analysis is added before frequency analysis by using a full of fire simulation results, and the cumulative failure frequency is developed to take place of conventional exceedance curve aiming at a probabilistic evaluation of structural safety.

2.3. Phase 3

Phase 3 is mainly focusing on the risk mitigation measure according to the results of several previous analyses. Typically, there are two types of effective risk measures for offshore structures, one is passive fire protection and the other one is deluge systems. In this thesis, the new procedure is mainly customized for determining the proper PFP application area, but the simulation results still can be used for other QRA studies.

3. Former Fire Risk Analysis

There are typically two main physical variables were usually used in the former FRAs. One is flame size and the other one is heat dose. When using the flame size, the level of FRA is just limited to roughly judge the failure of critical targets, and no further detailed analysis about fire simulation and structural response is included. Conversely, when using the heat dose, the level of FRA is much higher, and detailed fire simulation is involved to calculate the design fire load.

3.1. FRA with Flame Size

Using flame size in the FRA is a simplified method that usually carried in early stage of offshore structure design. It is used for roughly judging the impairment of identified critical target, PFP range as well as sub−deluge zone. The critical target is defined as some important parts of offshore plants whose failure probably can cause a significant loss (e.g. Module supports, ESDVs, Crane Pedestal, Flare KO drums etc.).

Fig. 5 is the detail flowchart of FRA procedure using flame size.

First of all, based on P&ID, PFD drawings divide the process of objective FPSO into several isolatable segments, and in the each segment identify the main inventory according to operation conditions as well as contained hydrocarbon component.

Then, generate representative fire scenarios for carrying out the fire simulations. Leak location position is usually assumed as the center of the module. Fire frequency is calculated through multiplying the leak frequency by ignition probability. Fire simulation is only carried out by 2D simple fire simulation tool e.g. Phast, and the actual CAD data of objective process module is not reflected in the simulation.

After that, flame size exceedance curve is calculated using the results of simulation, and design flame size is determined according to the exceedance curve. At last, failure of critical target is judged by using the design flame size. In other words, draw a circle using the design flame size at each time interval and check if the interested critical target locates in the circle. Following is an example of the procedure.

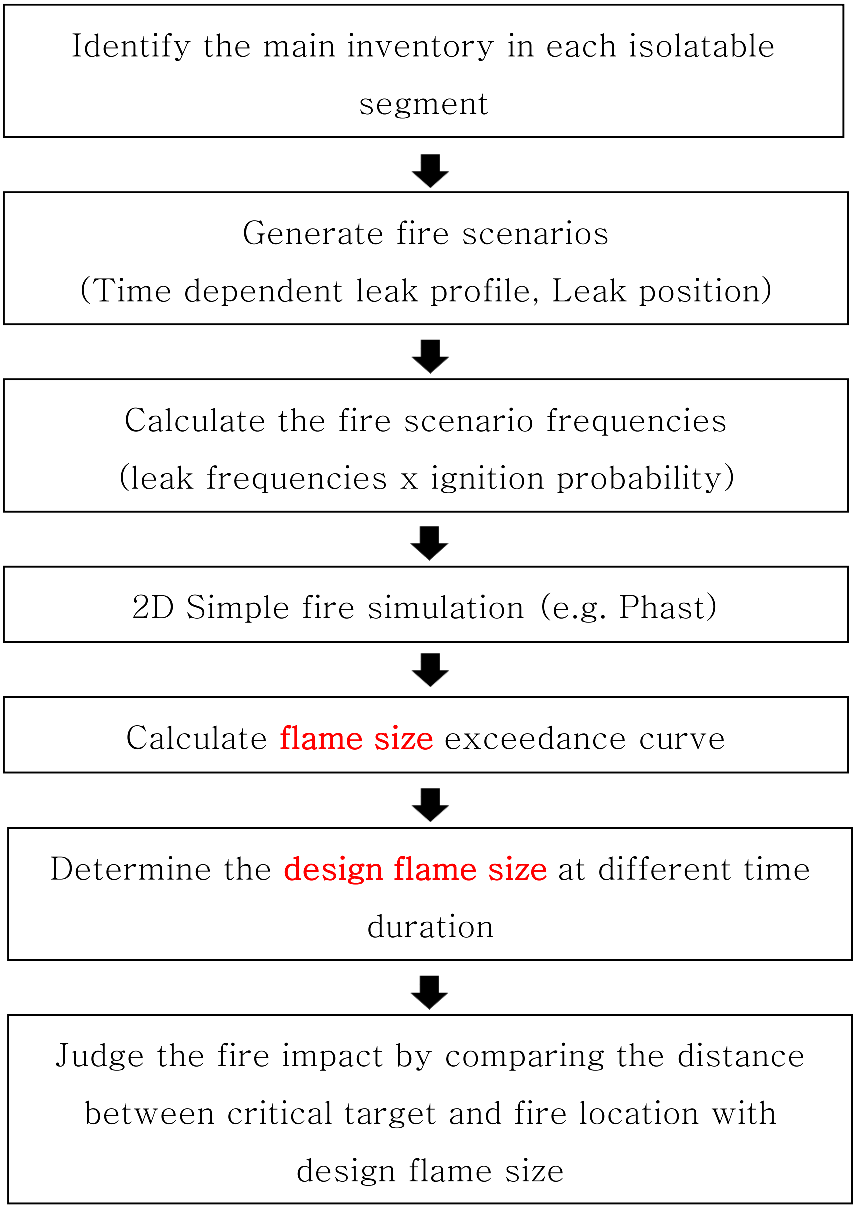


Fig. 5 FRA Diagram using flame size

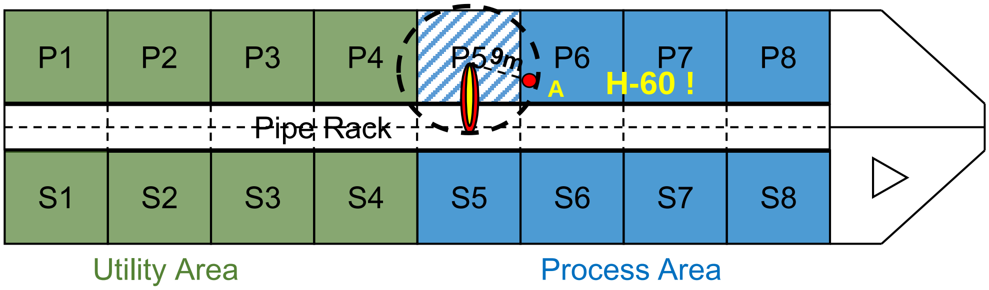


Fig. 6 Example of FPSO module layout

Fig. 6 is module layout of FPSO used in the example. The objective module is P5, and the identified segments, scenarios, fire simulation results are listed in the Table 3. In this example the flame size exceedance curve is calculated for 5 different time durations, and two of them are presented in the Fig. 7. When the risk criterion (e.g. 1.0E−04) is applied to each exceedance curve, then the design flame size is determined as showed in Table 4. Table 2 is showing the required time of critical target A becomes failed when it is continuously exposed to the fire. The distance between A and center of P5 is 9m, and this is much bigger than the magnitude of design flame size for the first 5 min. This indicates that the critical target A is probably to be failed if it does not get any protection. Subsequently, another design flame size is selected to determine the rate of PFP. In the example, before 60 min the design flame size is entirely bigger than the distance between A and module center, and this illustrates that the PFP required for A should sustain its protection at least for 60min. Consequently, the minimum rate of PFP for critical target A is determined as H60.

Table 2 Failure time of critical target A

Time to failure (min)	5
Flame size (m)	23

Table 3 2D fire simulation results of identified segments

Segment	Flame Length	Frequency	ESD/No EDP					ESD/EDP				
			5min	10min	30min	60min	120min	5min	10min	30min	60min	120min
MA2 (Oilgocene production manifold)	S	2.30E-05	12	12	12	12	12	12	11	8.8	5.2	5.1
	M	6.10E-06	37	36	34	6	0	36	34	29	22	6
	L	7.00E-06	2	0	0	0	0	2	0	0	0	0
	Full	7.90E-06	2	0	0	0	0	2	0	0	0	0
SAG (O9 MP separator gas)	S	8.50E-05	4.1	4.1	4.1	4	3.8	3.6	3	2	0	0
	M	3.40E-05	13	12	9.9	7.3	3.7	11	9	3	2	0
	L	4.80E-05	22	2	0	0	0	20	2	0	0	0
	Full	8.60E-05	2	0	0	0	0	2	0	0	0	0
SAL (O9 MP separator liquid)	S	2.30E-04	12	12	12	12	12	12	12	9.8	6.5	6.5
	M	3.70E-05	31	30	30	29	27	29	26	18	8.1	7.8
	L	1.50E-05	75	0	0	0	0	72	0	0	0	0
	Full	1.20E-05	0	0	0	0	0	0	0	0	0	0
CDG (Piping from MP separator to MP compression)	S	1.70E-05	3.6	3.1	2	0	0	3	2	2	0	0
	M	6.20E-06	2	0	0	0	0	2	0	0	0	0
	L	6.60E-06	2	0	0	0	0	2	0	0	0	0
	Full	3.00E-05	2	0	0	0	0	2	0	0	0	0
SBL (Piping to crude oil inlet manifold)	S	2.00E-04	11	10	9.2	8.4	7.6	0	0	0	0	0
	M	4.30E-05	14	10	7.8	7.8	1	0	0	0	0	0
	L	1.60E-05	0	0	0	0	0	0	0	0	0	0
	Full	2.00E-05	0	0	0	0	0	0	0	0	0	0
MCG (UM gas production manifold)	S	1.20E-04	3.4	3.4	3.2	2.9	2.4	3.3	3.2	2.5	2	0
	M	4.80E-05	8.7	6.8	2	0	0	8.4	6.3	2	0	0
	L	7.30E-05	2	0	0	0	0	2	0	0	0	0
	Full	1.50E-04	2	0	0	0	0	2	0	0	0	0

Table 4 Design flame size for each time duration with successful ESD/EDP

Time (min)	5	10	30	60	120
Flame size (m)	23	20	16	7.8	7.5

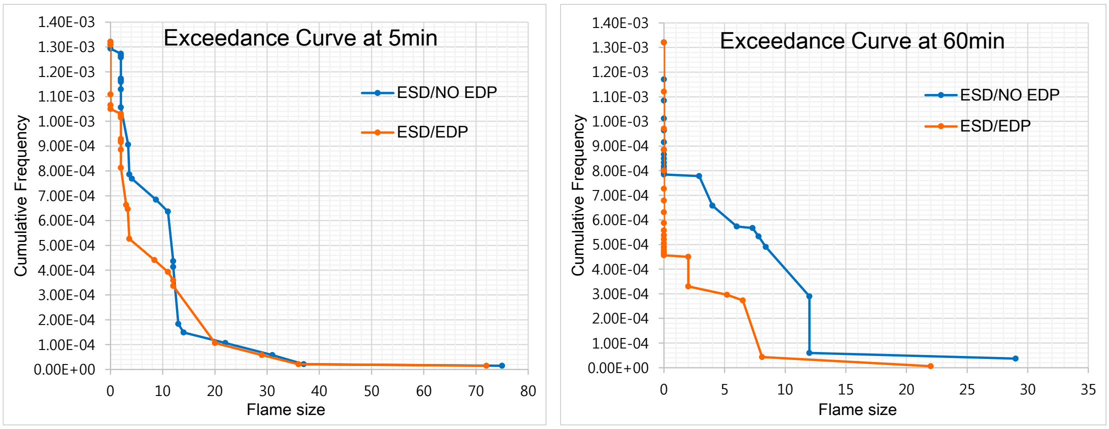


Fig. 7 Exceedance curve of flame size

The most critical problem in the flame size method is using 2D simple fire simulation. In actual conditions, most of jet fires occur inside of process module are hindered by surrounding structures or facilities, and this type of fire is named as impinged fire. However, in 2D fire simulation, CAD data is not considered, and this indicates that 2D simple fire simulation cannot precisely reflect the result of fire but roughly predict the magnitude of flame size.

Furthermore, even if 3D fire simulation is added to replace the 2D fire simulation, the flame size method still cannot be reasonable. Because when the 3D CAD data is considered, the size of flame cannot keep identical in all direction due to the different magnitudes of geometry congestion. This indicates that the circle showed in Fig. 6 is not possible to mapping on the module lay out any more. In summary, the FRA using flame size is a simple but rough method which is only limited to the initial design stage, and if additional structural response is required to investigate, other advance FRA method is much more suitable.

3.2. FRA with Heat Dose

Method of using heat dose is detailed sorted out in FABIG Technical Note 11 which is fitted for probabilistically checking the structural consequence. In this method, another physical variable named heat dose is used for calculating the exceedance curve. Heat dose is defined as the time integral of heat flux. Figure 8 shows the detail flowchart of FRA procedure by using heat dose.

Identify the main inventory in each isolatable segment

↓

Generate fire scenarios
(Time dependent leak profile, Leak position, Direction)

↓

Calculate the fire scenario frequencies
(leak frequencies x ignition probability)

↓

1st 3D fire simulation (e.g KFX)

↓

Calculate the heat dose for each scenario

↓

Calculate the heat dose exceedance curve

↓

Determine the design heat dose value /or fire scenario

↓

2nd 3D fire simulation with design fire scenario

↓

Structure consequence analysis

↓

Determine risk mitigation measures

Fig. 8 FRA diagram using heat dose

In the flowchart the first three steps are almost identical to the ones in the previous procedure. The only difference is that leak direction is more intentionally considered in this method and moreover 3D fire simulation is applied to improve its accuracy. Several specific points are picked up for calculating the heat dose, and design heat dose or corresponding fire scenario is determined through the exceedance curve. Then, structural consequence analysis is carried out using the design fire scenario, and risk mitigation measures are determined based on the results of structural response analysis at last. Following is an example of the procedure using heat dose variable.

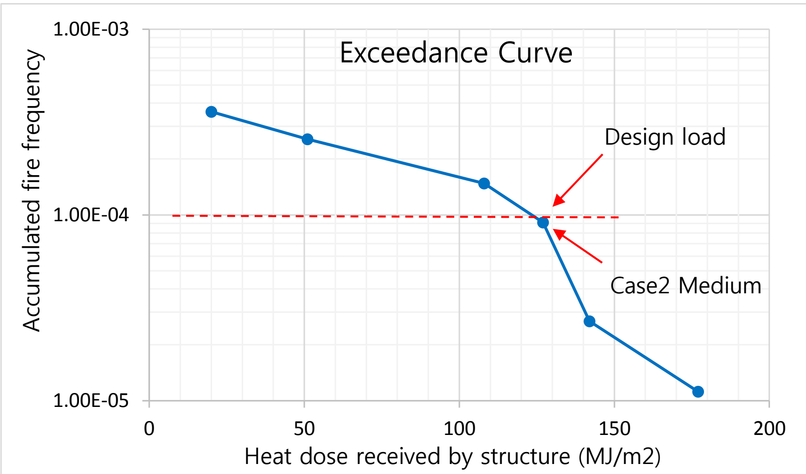


Fig. 9 Exceedance curve of heat dose

Table 5 Inventory data for each segment

Segment	Case name	Leak Medium	Inventory of gas in segment (kg)
Case1	LP stage	gas	558
Case2	HP stage	gas	1342

Table 6 Results of heat dose calculation with identified fire scenarios

Segment	Size	Heat dose (MJ/m^2)	Fire frequency
Case1	Large	20	1.04.E-04
	Medium	108	5.71.E-05
	Small	142	1.56.E-05
Case2	Large	51	1.07.E-04
	Medium	127	6.44.E-05
	Small	177	1.12.E-05

Table 5 & 6 illustrates the information of identified segment, especially Table 6 lists the fire scenarios considered in the example as well as their heat dose calculated by using the 3D fire simulation result.

In the example, heat dose is calculated by integrating the heat flux history at all grid points, and the maximum integral is subsequently selected as the one for plotting exceedance curve. Deservedly, the point that has the maximum heat dose usually locates at the center of flame, and this indicates that only the hottest point inside the flame is reflected in the design load.

Then, through the exceedance curve showed in Fig. 9 a design load is determined, however, as previously mentioned the design load is only expressed by the heat dose and it is difficult to analyze structural consequence with it. Therefore, instead of using the heat dose, corresponding fire scenario is selected for the structural analysis. When using a fire scenario as the design load, the actual input for structural analysis is an entire 3D heat flux distribution obtained from the fire simulation. In the example the design scenario is medium fire size of case2 whose magnitude of heat dose is 127 MJ/m^2.

Furthermore, two times of fire simulation are involved in the flowchart of Fig. 8, and following two pictures explain how the fire simulations are different from each other. In the first time of fire simulation, the leak direction is simply determined with several orthogonal vectors starts from the center of module, and its purpose is only for calculating heat dose to quantify the result of fire simulation for each scenario. However, in the second time, the determined design fire scenario is not directly put into the simulation, instead, they are redefined to have the scenario cause the worst condition to the module. The right picture in Fig. 10 shows the worst combination of leak direction and location which brings significant damage about the module. Obviously, it is concluded that the determined design fire scenario almost become useless in the second fire simulation except for reflecting the information of leak rate and duration.

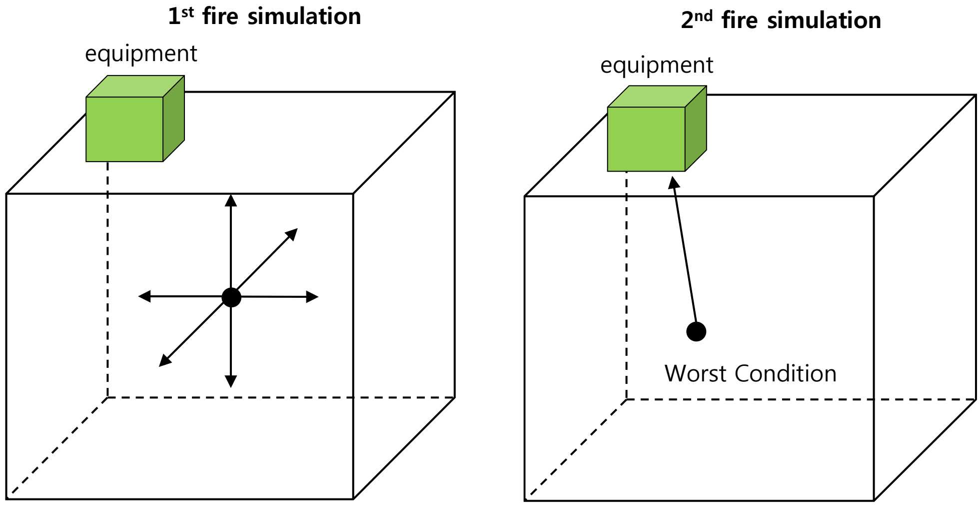


Fig. 10 Two times of fire simulation

In summary, compared with the FRA using flame size, method of using heat dose is much more progressive since it uses the 3D fire simulation. However, the way to decide the heat dose for each scenario is still too weak to properly reflect the whole domain of fire accident. Also, during heat dose calculation as well as structural analysis, the inconsistent consideration of leak direction and location not only leads to two times of fire simulation but also breaks the original intention of using heat dose.

4. Proposed FRA Procedure

Following Fig. 11 shows the details of new FRA procedure proposed in this thesis. The whole procedure is composed of 7 steps, and each of them will be discussed in the following sections. Also, some important methods or key consideration are noted under the box of each step.

4.1. Fire Scenario Identification

Different from previous FRAs, leak location is particularly considered in the new procedure through analyzing the PFD, P&ID diagram. Normally, the most probable leak position in FPSO process comprises the flange, valve and pipe connection, however, the number of these components in a process module is significant, and when all of them are considered together with leak direction, the work of fire scenario identification seems impossible to be accomplished. To solve this problem, an approximation method is applied in the new procedure to efficiently determine the leak location. Following three figures are the equipment layout drawings of the test separation module introduced in chapter 5.

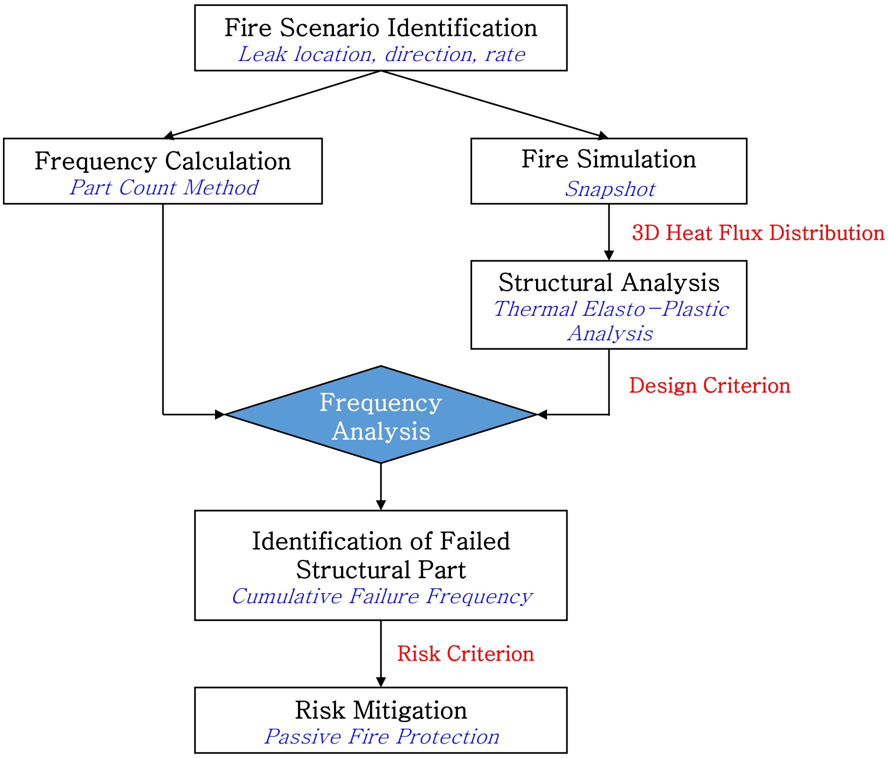
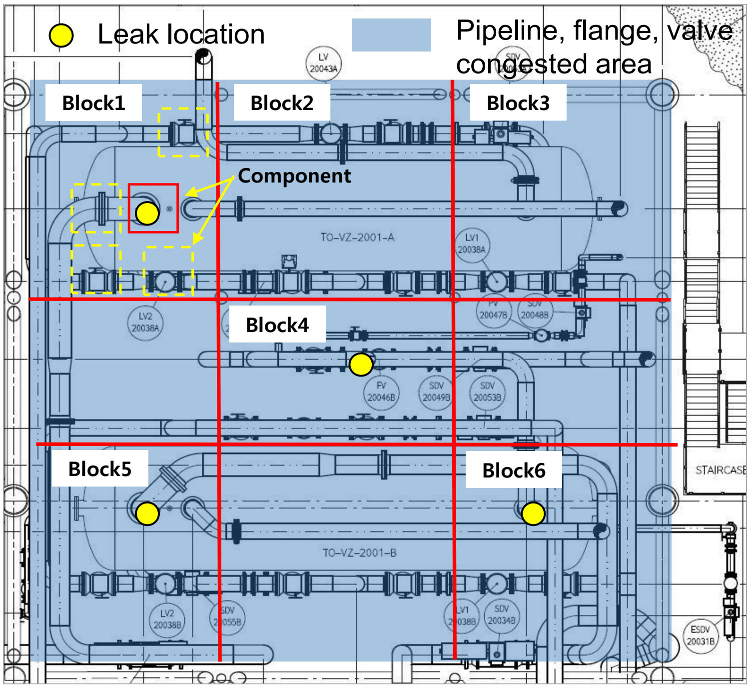
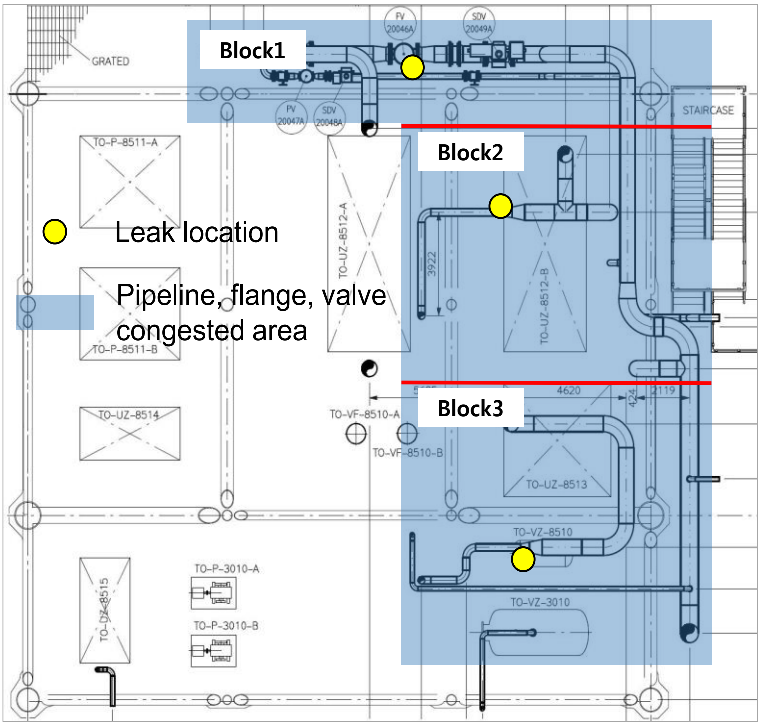


Fig. 11 Diagram of new FRA procedure

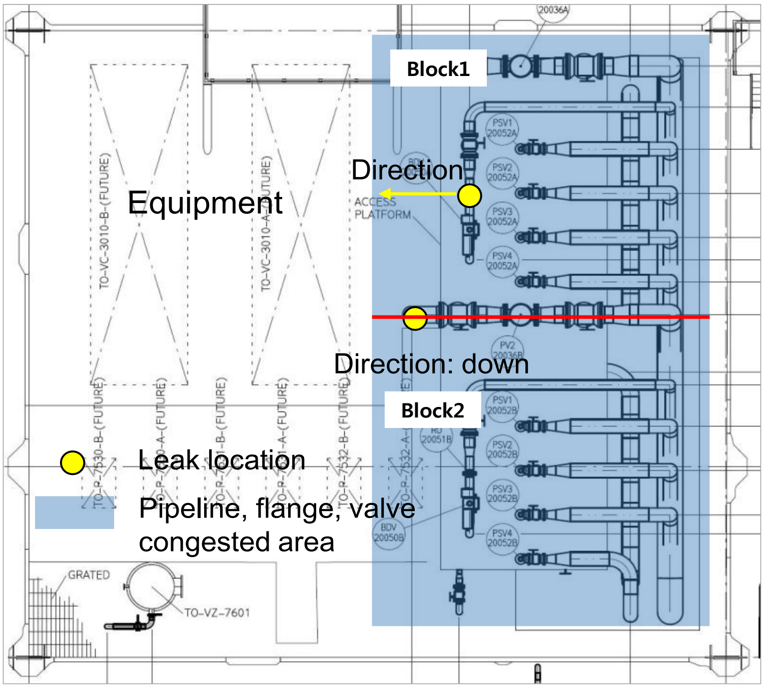
The first step of determining leak location in the new FRA procedure is identifying the pipeline, flange, and valve congested area. In the following figures, the shading area represents the congested area. Then, divide the congested area into several blocks according to its shape. There are several types of component in each block, and among them leak location is selected as the one which is not only close to the center of block but also itself connected to the identified main inventory.



(a) Process Deck



(b) Upper Deck



(c) Top Deck

Fig. 12 Equipment layout of test module

For example, in the figure (a) there are 5 components identified with dash line in block 1, and among them, the one outlined with full line is selected as the leak location since it simultaneously satisfies the two requirements mentioned above.

Furthermore, in the new procedure, leak location is determined together with leak direction. Similar to the previous FRA procedure using heat dose, leak direction is only considered with the vulnerable parts of structure. This is the reason why there is not any leak location identified in block 3 of process deck.

Leak direction has a quite random characteristic; therefore it is impossible to consider all kinds of the directions at each identified leak location. However, the original purpose of FRA is to evaluate the threats of fire accidents to the structure or associated facilities, and this indicates that the identified leak directions should at least comprise the cases that hydro carbon leaks directly towards the vulnerable parts of the structures. In this thesis, vulnerable parts of structure is defined as the ones who locally bear the weights of process equipment, and the leak direction is only considered with them. Although the approach seems to be very conservative, at least it guarantees the safety of structure since it takes all of the vulnerable parts into consideration.

Leak rate is a time dependent parameter, which controls the dynamic effect of fire accident. Following Fig. 13 is the considered leak rate profile for the test module in chapter 5. The actual fire on the FPSO topside usually has a time dependent leak rate, which decays over the time, and it is commonly named as the dynamic fire (Sávio Vianna, Asmund Huser, 2010). The dynamic effect of actual fire must be considered since it influences the accuracy of fire simulation. However, if the whole duration of actual dynamic (transient) fire is considered, the time required for simulation is too much. As a result, an effective method called snapshot is used in the new procedure for purpose of reducing the required simulation time. Fire simulation with snapshot is concretely accounted in section 4.3.2.

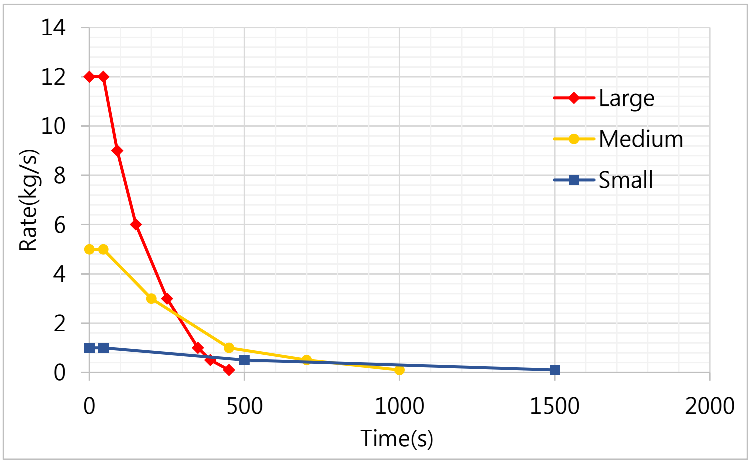


Fig. 13 Time dependent leak rate

4.2. Frequency Calculation

4.2.1. Historical Leak Frequency Data

As mentioned in the previous section, leak frequency is usually calculated based on the historical database. HCRD by HSE has become a standard source of leak frequencies for offshore QRA studies. The data allows 78 separate types and sizes of process equipment to be distinguished. However, for certain types and sizes of process equipment, there is relatively little leak experience, and the statistical differences of leak frequency between them are also too small to be used for distinguishing them. Such deficiencies may probably lead to conservative assessment of risk. To avoid this, modification of the HSE database is a common practice. Usually, different analysts use different approaches and assumptions in modifying the data, but these different types of modification can lead to the frequencies used by analysts being inconsistent despite being based on the same HCRD dataset (Andreas Falck, 2011). Therefore, standardizing the approach of modifying the HCRD is an urgent need.

DNV developed a methodology (Andreas Falck, 2011) for obtaining leak frequencies from HCRD. The methodology consists of the following three steps:

- **Grouping data for different types and sizes of equipment**, where there is insufficient experience to show significant differences between them.
- **Fitting analytical frequency functions to the data**, in order to obtain a smooth variation of leak frequency with equipment and hole size.

- **Splitting the leak frequencies into the different leak scenarios**, in order to promote compatibility with different approaches to outflow modelling in the QRA.

Following table 7 shows the HCRD leak statistics from 1992 to 2006. There are two different equipment types mentioned in the table, one is DNV equipment type and the other one is HCRD equipment type. Since some of the equipment types and sizes in HCRD have little leak experience; hence they have been merged into one type and this process results in the DNV equipment type.

Table 7 Leak statics for HCRD 1992-2006

	DNV EQUIPMENT TYPE	HCRD EQUIPMENT TYPE	All leaks	Leaks excluding < 1 mm	Exposure
1	Steel process pipes	Piping, steel (3 sizes)	700	646	5,958,814 pipe metre years
2	Flanges joints	Flanges (3 sizes)	327	298	3,368,520 flange joint years
3	Manual valves	Valve, manual (10 types & sizes)	175	154	1,498,038 valve years
4	Actuated valves	Valve, actuated, non-P/L (18 types & sizes)	264	221	329,562 valve years
5	Instrument connections	Instruments (including connecting tubing)	528	442	749,786 instrument years
6	Process (pressure) vessels	Pressure vessel (14 types)	42	37	17,494 vessel years
7	Pumps: Centrifugal	Pumps, centrifugal (2 seal types)	126	110	14,564 pump years
8	Pumps: Reciprocating	Pumps, reciprocating (2 seal types)	21	19	2,652 pump years
9	Compressors: Centrifugal	Compressors, centrifugal	40	33	3,110 compressor years
10	Compressors: Reciprocating	Compressors, reciprocating	43	36	507 compressor years
11	Heat exchangers: Shell & Tube, shell side	Heat exchangers, HC in shell	18	14	3,398 exchanger years
12	Heat exchangers: Shell & Tube, tube side	Heat exchangers, HC in tube	26	21	6,165 exchanger years
13	Heat exchangers: Plate	Heat exchangers, plate	31	30	2,865 exchanger years
14	Heat exchangers: Aircooled	Fin fan coolers	5	2	1,069 exchanger years
15	Filters	Filters	48	47	12,495 filter years
16	Pig traps	Pig launchers & pig receivers (4sizes)	29	28	3,994 pig trap years

Following equation is the analytical function used in DNV methodology, which represents the variation of leak frequency depended on leak hole size, equipment type and diameter.

$$F(d) = C(1 + aD^n)d^m + F_{rup}$$, Andreas Falck(2011)

F(d)	= Frequency per year of leaks exceeding size d (mm)
D	= Equipment diameter
D	= Hole size
F_{rup}	= Rupture frequency per year
C,a,m,n	= Constants specific to the equipment type and leak scenario

Hence the frequency of holes within any range from d_1 to d_2 is:

$$F(d_1) = C(1 + aD^n)(d_1{}^m - d_2{}^m)$$, Andreas Falck (2011):

In this thesis leak frequency is referred to an open source released by the Oil & Gas Produce. OGP is a third party who modifies the original HSE's HCRD by using the DNV methodology and releases an open source of leak frequency database in a general tabulated form showed in table 8. Table 8 is an example of the leak frequency data for steel process pipe in the OGP leak frequency source.

Table 8 Example of OGP leak frequency data – steel pipe

Equipment Type: (1) Steel process pipes

Definition:

Offshore: Includes pipes located on topsides (between well and riser) and subsea (between well and pipeline).
Onshore: Includes pipes within process units, but not inter-unit pipes or cross-country pipelines.
The scope includes welds but excludes all valves, flanges, and instruments.

(a) All piping release frequencies (per metre year) by pipe diameter

HOLE DIA RANGE (mm)	2" DIA (50 mm)	6" DIA (150 mm)	12" DIA (300 mm)	18" DIA (450 mm)	24" DIA (600 mm)	36" DIA (900 mm)
1 to 3	9.0E-05	4.1E-05	3.7E-05	3.6E-05	3.6E-05	3.6E-05
3 to 10	3.8E-05	1.7E-05	1.6E-05	1.5E-05	1.5E-05	1.5E-05
10 to 50	2.7E-05	7.4E-06	6.7E-06	6.5E-06	6.5E-06	6.5E-06
50 to 150	0.0E+00	7.6E-06	1.4E-06	1.4E-06	1.4E-06	1.4E-06
>150	0.0E+00	0.0E+00	5.9E-06	5.9E-06	5.9E-06	5.9E-06
TOTAL	1.5E-04	7.4E-05	6.7E-05	6.5E-05	6.5E-05	6.5E-05

(b) Full piping release frequencies (per metre year) by pipe diameter

HOLE DIA RANGE (mm)	2" DIA (50 mm)	6" DIA (150 mm)	12" DIA (300 mm)	18" DIA (450 mm)	24" DIA (600 mm)	36" DIA (900 mm)
1 to 3	5.5E-05	2.6E-05	2.3E-05	2.3E-05	2.3E-05	2.3E-05
3 to 10	1.8E-05	8.5E-06	7.6E-06	7.5E-06	7.4E-06	7.4E-06
10 to 50	7.0E-06	2.7E-06	2.4E-06	2.4E-06	2.4E-06	2.3E-06
50 to 150	0.0E+00	6.0E-07	3.7E-07	3.6E-07	3.6E-07	3.6E-07
>150	0.0E+00	0.0E+00	1.7E-07	1.7E-07	1.6E-07	1.6E-07
TOTAL	8.0E-05	3.8E-05	3.4E-05	3.3E-05	3.3E-05	3.3E-05

(c) Limited piping release frequencies (per metre year) by pipe diameter

HOLE DIA RANGE (mm)	2" DIA (50 mm)	6" DIA (150 mm)	12" DIA (300 mm)	18" DIA (450 mm)	24" DIA (600 mm)	36" DIA (900 mm)
1 to 3	3.1E-05	9.9E-06	8.1E-06	7.8E-06	7.7E-06	7.6E-06
3 to 10	1.5E-05	4.9E-06	4.0E-06	3.8E-06	3.8E-06	3.7E-06
10 to 50	1.3E-05	2.5E-06	2.0E-06	1.9E-06	1.9E-06	1.9E-06
50 to 150	0.0E+00	3.2E-06	5.2E-07	5.0E-07	4.9E-07	4.9E-07
>150	0.0E+00	0.0E+00	2.4E-06	2.4E-06	2.4E-06	2.4E-06
TOTAL	5.9E-05	2.0E-05	1.7E-05	1.6E-05	1.6E-05	1.6E-05

(d) Zero pressure piping release frequencies (per metre year) by pipe diameter

HOLE DIA RANGE (mm)	2" DIA (50 mm)	6" DIA (150 mm)	12" DIA (300 mm)	18" DIA (450 mm)	24" DIA (600 mm)	36" DIA (900 mm)
1 to 3	3.7E-06	3.2E-06	3.1E-06	3.1E-06	3.1E-06	3.1E-06
3 to 10	2.7E-06	2.3E-06	2.3E-06	2.3E-06	2.3E-06	2.3E-06
10 to 50	6.0E-06	1.9E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06
50 to 150	0.0E+00	3.4E-06	7.7E-07	7.6E-07	7.6E-07	7.6E-07
>150	0.0E+00	0.0E+00	2.6E-06	2.6E-06	2.6E-06	2.6E-06
TOTAL	1.24E-05	1.07E-05	1.06E-05	1.05E-05	1.05E-05	1.05E-05

4.2.2. Leak Frequency Calculation

Leak frequency in FPSO process area is usually calculated based on historical leak database, and one of the common calculation method is called part count. Part count method is generally based on counting the number of equipment that have the possibility of HC leaks in the oil & gas process. A simple example of part count method is presented in the following with a segment showed in the Fig. 14.

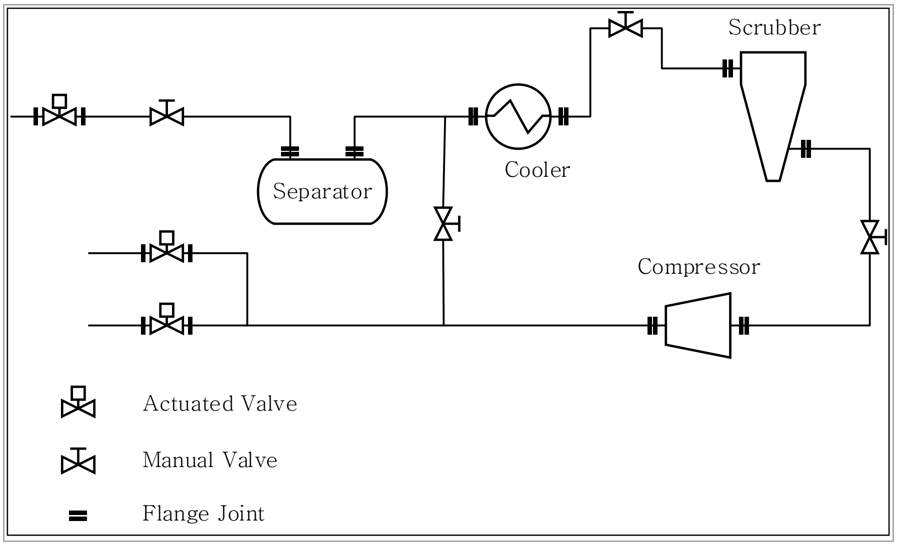


Fig. 14 Sample of process segment

In the Table 9, the quantity of each equipment type is counted according to the diagram of sample segment, and the total frequency is calculated through multiplying it by the frequency per equipment obtained from leak frequency database.

Table 9 Example of part count method

Equipment	Quantity	Equipment size	Frequency per equipement year[1)]	Total
Process vessel	1.5	6"	1.70E−04	2.55E−04
Compressor	1	6"	1.10E−04	1.10E−04
Heat Exchanger	1	6"	1.20E−04	1.20E−04
Flange joint	9.5	6"	1.10E−04	1.05E−03
Actuated Valve	1.5	6"	6.20E−04	9.30E−04
Manual Valve	4	6"	1.30E−04	5.20E−04
Pipe	20	6"	7.40E−05	1.48E−03
Total				4.46E−03
1) Frquency per equipment is referred to OGP data				

When counting the number of equipment, there are some matters need to be taken carefully.

- The segment is bounded by actuated valves, thus only half of these valves should be counted.
- Only half of the separator should be counted since its bottom is not connected to the pipe.
- Flange in the figure is considered as a joint which comprises two flange faces. Also similar with the actuated valve, only one side of flange joint should be counted.

Leak frequency of the test separation module is calculated in a similar way and the results are presented in chapter 5.

4.2.3. Fire Frequency Calculation

Fire frequency of each identified scenario is calculated by using the original leak frequency and several probabilities of fire control parameters. Following is the general formulations used in this thesis for fire frequency calculation.

$$F_{fire,i} = \frac{F_{leak}}{n} \cdot P_{ign} \cdot P_{ESD} \ , \quad \text{for failed ESD \& EDP}$$

$$F_{fire,i} = \frac{F_{leak}}{n} \cdot P_{ign} \cdot (1 - P_{ESD}) \ , \quad \text{for successful ESD \& EDP}$$

$F_{fire,i}$ = Fire frequency of scenario i

F_{leak} = Total leak frequency of certain hole size for each segment

P_{ign} = Ignition probability

P_{ESD} = Failure probability of ESD & EDP

n = Total number of leak location in each segment

ESD = Emergency shutdown

EDP = Emergency depressurization

During the calculation of leak frequency for example module, three sizes of leakage are considered for each type of equipment, and leak frequency is separately calculated for each deck by using the part count method. Furthermore, the total leak frequency of each deck is split for each leak location according to the number of it considered in section 4.1. In the actual condition, the leak frequency of each leak location may be variable, but for simplicity in the example it is given equally by dividing the total leak frequency of each deck with its number of leak location n.

Ignition probability used in this thesis is developed by Cox, Lee & Ang. The ignition model is dependent on leak rate, and it is plotted in Fig. 15

$$P_{ign} = 0.0158 \cdot R^{0.6415} \quad \text{Cox et al. (1990)}$$

P_{ign} = Ignition probability

R = Leak rate

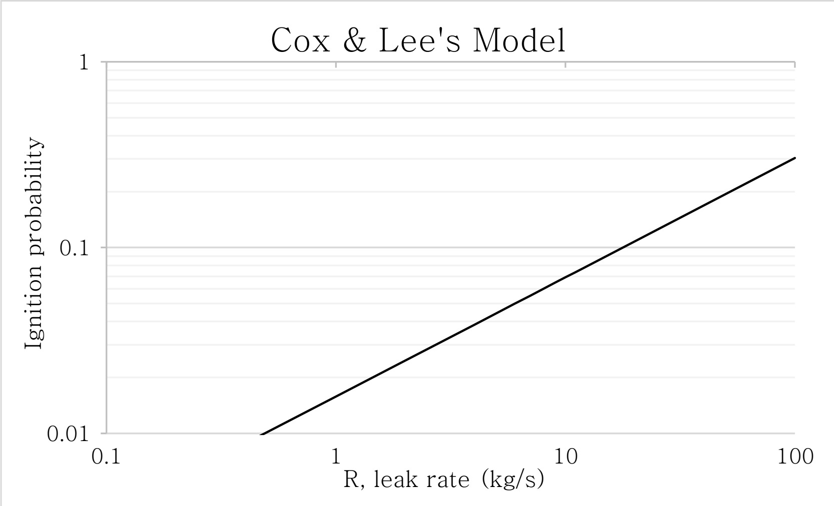


Fig. 15 Ignition model of Cox, Lee & Ang

4.3. Fire Simulation

4.3.1. Radiation Calculation

In thesis, fire simulation is carried out by using the KFX (Kameleaon FireEx) program. When a fire accident occurs, the surrounding gas mixture composed of CO_2, H_2O, Soot may participate in radiation heat transfer. At moderate temperatures the gas mixture heats up itself by absorbing the radiation emitted from the flame, and conversely at high temperature it also emits the radiation to surroundings at the same time. The emission and absorption characteristic of a mixture gas is usually dependent on its temperature, pressure as well as chemical composition. Furthermore, since the mixture gas belongs to fluid, its fluidity should also be simultaneously considered with the radiation process.

KFX can be called as the most advance fire simulator which is available to reflect the turbulent combustion flow using the Eddy Dissipation Concept proposed by Magnussen and Hjertager (1976), and simultaneously calculate the radiation heat flux by using Discrete Transfer Model proposed by Shah and Lockwood (1979). Following equation describes the radiation transfer along a path through an absorbing and emitting medium which is a basis of the DTM. Radiation intensity I for certain direction is defined as a rate of radiation energy emission or absorption per unit area normal to the direction and per unit solid angle of the direction. DTM is used for calculating the radiation intensity for all directions and furthermore the obtained radiation intensities are used for calculating radiation heat flux through proper mathematical integrations. In KFX radiation heat flux calculation is accomplished by using the bullet monitor. Bullet monitor is a virtual small ball spread over the whole calculation domain and its surface is discretized by proper number of solid angle for logging the entire radiation intensities. Radiation intensity and solid angle is illustrated in Fig. 16 and they are also defined by the following equations.

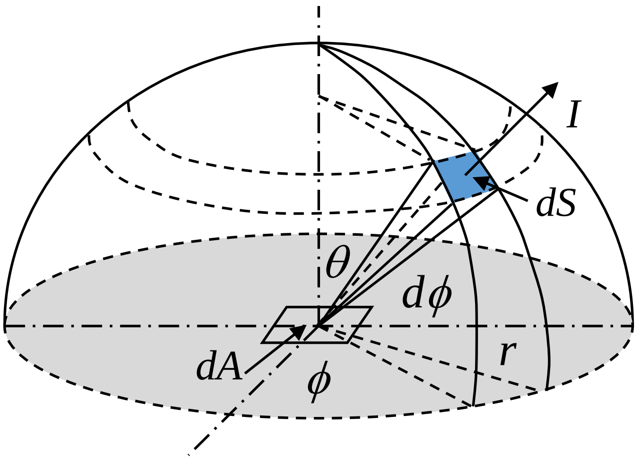


Fig. 16 Radiation intensity and solid angle

<u>Solid Angle:</u>

$$d\Omega = \frac{dS}{r^2} = \sin\theta d\theta d\varphi$$

<u>Radiation Intensity:</u>

$$I(\theta,\phi) = \frac{d\dot{Q}}{dA\cos\theta \cdot d\omega} = \frac{d\dot{Q}}{dA\cos\theta \cdot \sin\theta d\theta d\phi}$$

<u>Radioactive Transfer Equation:</u>

$$\frac{dI}{dx} = -\alpha I + \frac{\alpha\sigma T_g^4}{\pi}$$

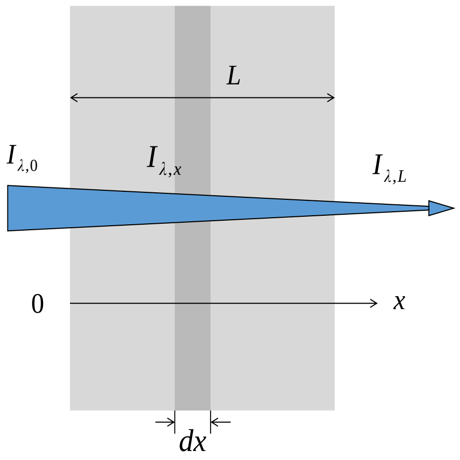


Fig. 17 Beer's law

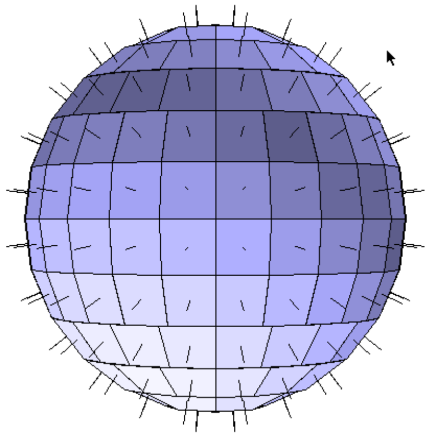


Fig. 18 Bullet monitor

Incident Radiation Heat Flux:

$$q_{in} = \int I \cdot d\Omega = \sum_{n=1}^{N} I_n \cos\theta \sin\theta \cdot d\phi \cdot d\theta$$

Ω = Solid angle

I = Radiation intensity

κ_λ = Spectral absorption coefficient

α = Absorptivity

n = Number of solid angle

T_g = Gas temperature

λ = Wave length

4.4. Snapshot

When a fire accident occurs on the FPSO, the leak rate of hydro carbon becomes smaller with time. This is because the shutdown or depressurization system installed on the process intervene the flow of hydro carbon. Therefore dynamic effect of leakage must be considered in QRA studies; otherwise it results in an over estimation of the risk. Unfortunately, since considering the dynamic effect of leakage in a CFD based fire simulation requires a significant amount of time consuming, thus it always becomes an issue in QRA studies. In order to reduce the time needed for simulating dynamic fire accidents a concept of snapshot is appeared to properly approximate the actual fires without simulating the whole fire accidents. Literally, snapshot is a moment of an actual fire accident and it is only bound with a unique leak rate. Commonly, 3 different sizes of leakage are commonly considered in FRA studies i.e. small, medium, large fire. In the new FRA procedure, several snapshots are specified simultaneously for the 3 sizes of fire scenario at each identified leak location. The specified snapshots are bundled together to construct a virtual compressed leak profile, the one which is actually reflected in the carried out fire simulations.

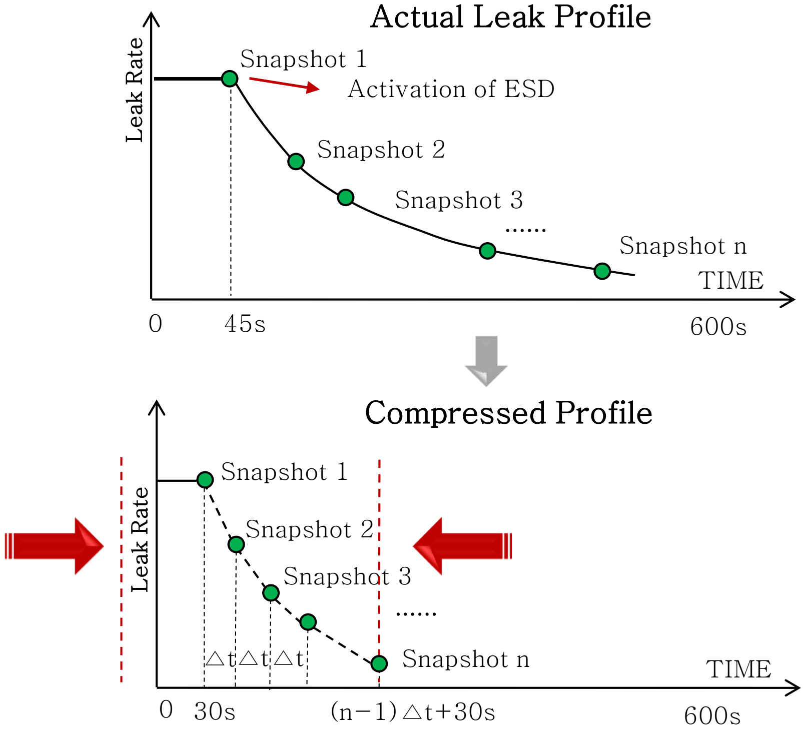


Fig. 19 Compressed virtual leak profile

Fig. 19 distinctly shows the how to construct a compressed virtual leak profile with the snapshots. In the compressed profile, the key thing is the time interval between each snapshot. This must be specified with enough time to reduce the difference of simulation results between the actual and compressed one. For instance, in the actual leakage showed in Fig. 19, the snapshot 1 stands for the moment after 45 seconds pass from the starting of leakage, and it is also an actual starting point of the ESD activation. However, in the compressed leak profile, the time interval from starting point of leakage to the activation of ESD is reduced as 30 seconds, this is because when the time is over 30 seconds the result of fire simulation almost becomes consistent until the activation of ESD. Consequently, the proper time interval from starting of leakage to snapshot 1 is determined as 30 seconds and this make the simulation save around 15 seconds at the first stage of leak within snapshot 1.

Following Fig. 20 shows a detail procedure of using snapshot for the test separation module introduced in chapter 5. In this case the snapshots are specified together by simultaneously considering the 3 different sizes of leakage, i.e. the ‘compress’ step in Fig. 20. As a result of the fire simulation, a 3D heat flux distribution is bound to each snapshot, and these heat flux distributions are later used as inputs for the structural analysis. However, before using these 3D heat flux distributions for structural analysis, the time interval between each of them must be recovered to an actual condition, i.e. the ‘Recover’ step. Most of the snapshots are repeatedly used in the 3 sizes of leakage with different time intervals since the 3D heat flux distributions of snapshot are almost identical as long as their associated leak rates are equal to each other in the 3 considered leakages. In summary, if use the snapshot, the time required for fire simulation is significantly reduced from 2950 seconds to 90 seconds in the example.

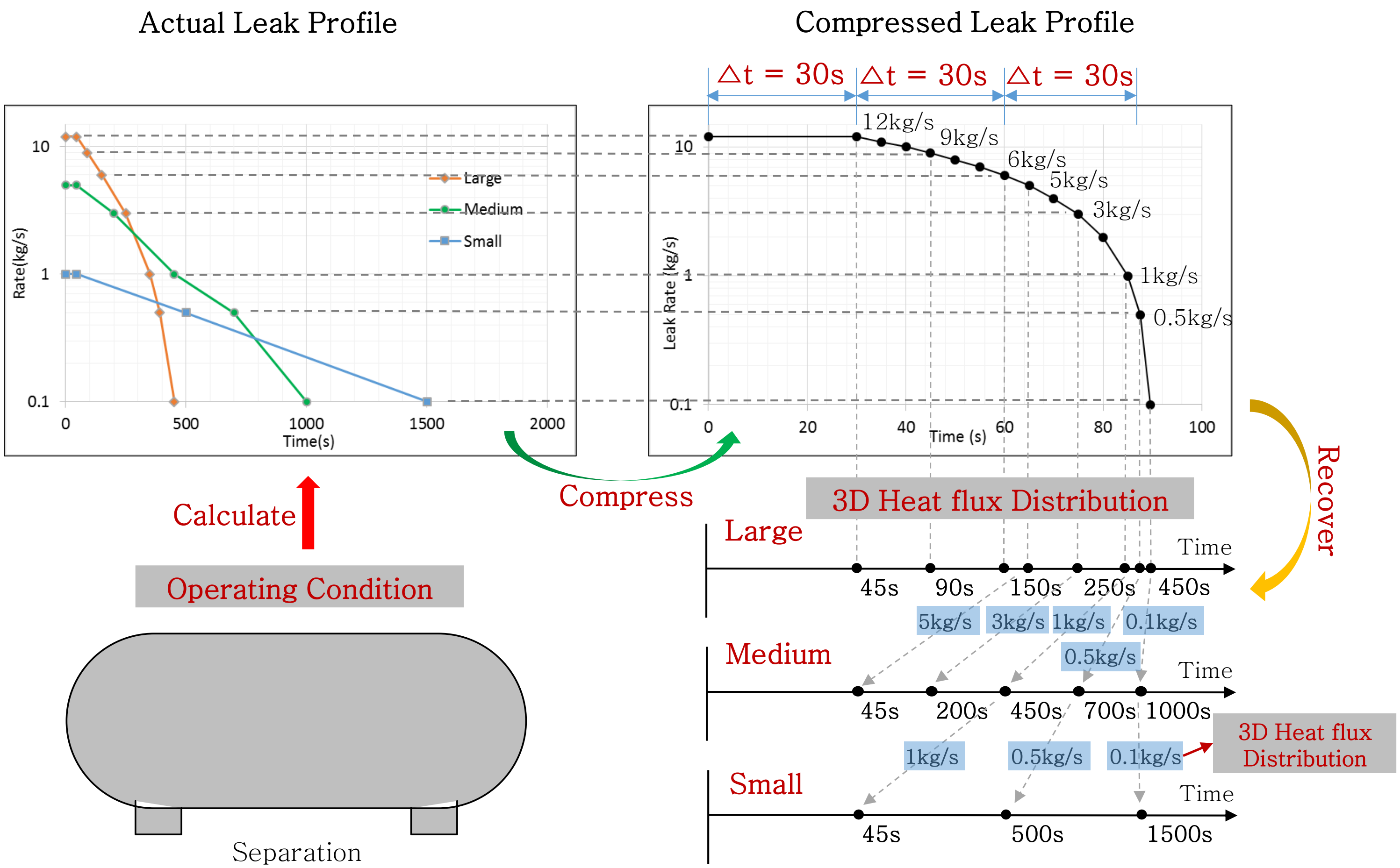


Fig. 20 Detail procedure of using snapshot

4.5. Structural Consequence Analysis

The structural response under the fire is assessed by using thermal elaso−plastic analysis. This analysis is composed of two parts, one is heat transfer analysis and other one is nonlinear structural analysis within the calculated temperature loads. In following two sections both of them are discussed respectively in detail.

4.5.1. Heat Transfer Analysis

In thesis, heat transfer analysis is carried out by using the FATHS program. FATHS is an interface face program between the KFX and USFOS which is aimed at transferring the fire loads to structure analysis. As mentioned in previous section, the compressed time of 3D heat flux distributions must be recovered before they are put into the heat transfer analysis, and the work is easily accomplished by editing the result files generated during the fire simulation. The result of heat transfer analysis is temperature distribution and it is used for the following non−linear structural analysis.

4.5.2. Non-Linear Structural Analysis

In this thesis, non−linear structural analysis is carried out by using the USFOS program. Since material property of steel is usually dependent on the temperature, the variation must be considered in the non−linear structure analysis. In that sense, the purpose of heat transfer analysis mentioned in the previous section has no other reasons than to calculate the increased structural temperature for modifying its material property. In this thesis the material property of each structural element steel is modified according to the following graph.

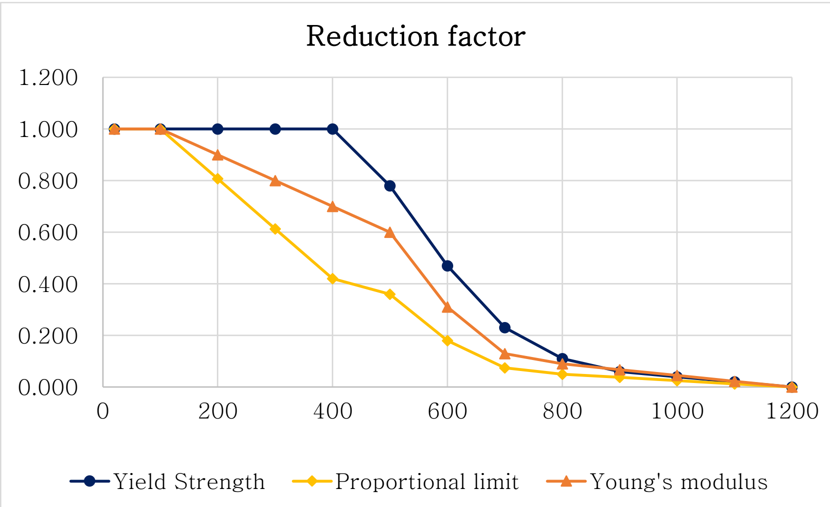


Fig. 21 Time dependent material property reduction factor

Furthermore, instead of using a normal transient structural analysis with considering the whole temperature history, a simplified static analysis is selected in the new FRA procedure. Different from other research fields, which need a high quality of structural analysis, structural analysis in general FRA studies is just aimed at globally checking and estimating the failure of structure; hence the static analysis seems is advisable enough.

In static analysis the reduced material property is specified per structural element according to its maximum temperature during the whole fire accident.

4.6. Cumulative Failure Frequency

4.6.1. Identification of Failed Element

Prior to calculate the structural cumulative failure frequency, the failed structural element must be identified for each fire scenario. Commonly, there are two different types of criteria used in FRA studies for checking the failed elements, and both of them are presented in the following figures. For simplicity, sometimes the structural response under the fire is assessed only by using the result of heat transfer analysis, and in that case the temperature criterion is used to judge the failure of element.

Temperature Distribution

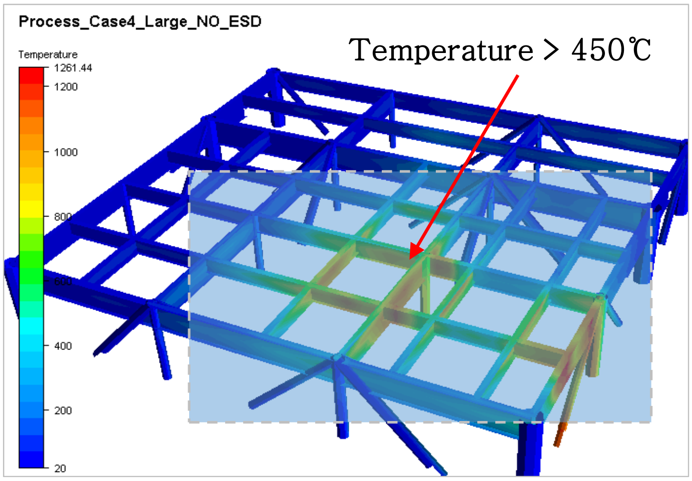


Fig. 22 Failure criterion with temperature

Plastic Utilization

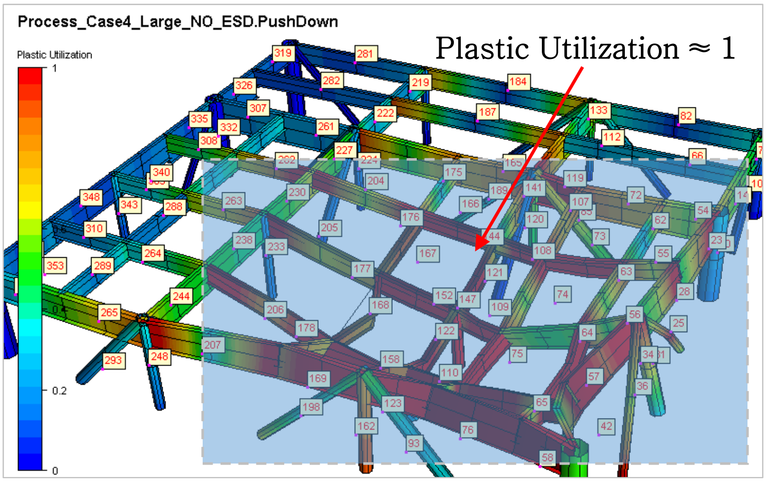


Fig. 23 Failure criterion with plastic utilization

4.6.2. Calculation of Cumulative Failure Frequency

Cumulative failure frequency of structural element is the most central part in the new prosed FRA procedure. It is generally obtained by combing the result of frequency calculation and structural response analysis. In order to distinguish the failed elements identified in the previous section from the safe ones an index I is used to quantify the element's condition. Following is the formulae used for calculating cumulative failure frequency of structure with index I

Radioactive Transfer Equation:

$$F_{failure,j} = \sum_{i=1}^{m} F_{fire,i} \cdot I_i$$

$F_{failure,j}$	= Cumulative failure frequency for element j
$F_{fire,i}$	= Fire frequency of scenario i
I_i	= Index of element j at scenario i
	$I_i=1$ for failed, $I_i=0$ for safe
i	= Scenario number

When the risk criterion is applied to the cumulative failure frequency of structural element, the element that has a high possibility of failure in the identified fire scenarios is easily found out.

5. Example of Proposed FRA

5.1. Scenario Identification and Frequency Calculation

As showed in Fig. 24, 25, a FPSO separation module is taken as the test model in this chapter for demonstrating the new FRA procedure in more detail. The test module is composed of 3 decks, and the scenario identification as well as frequency calculation is carried out by each deck. More detail about them has already discussed in chapter 4. The results of both leak frequency and fire frequency calculation are showed in Table 10 ~ 12.

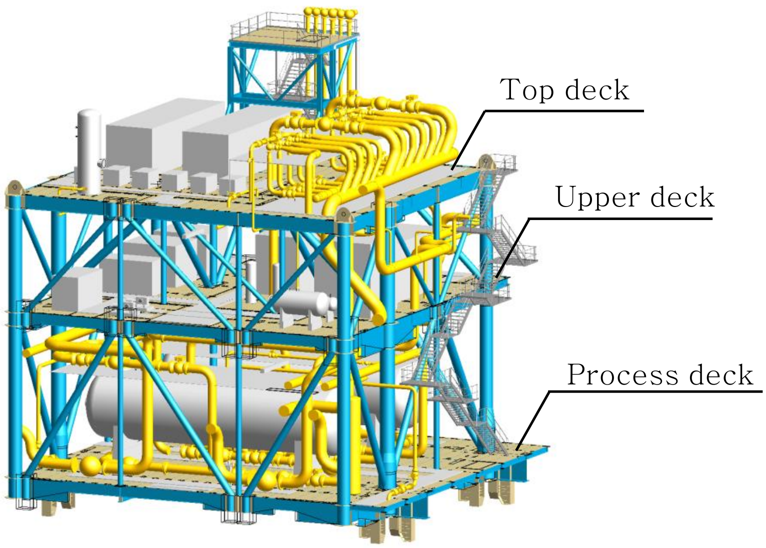


Fig. 24 Test separation module

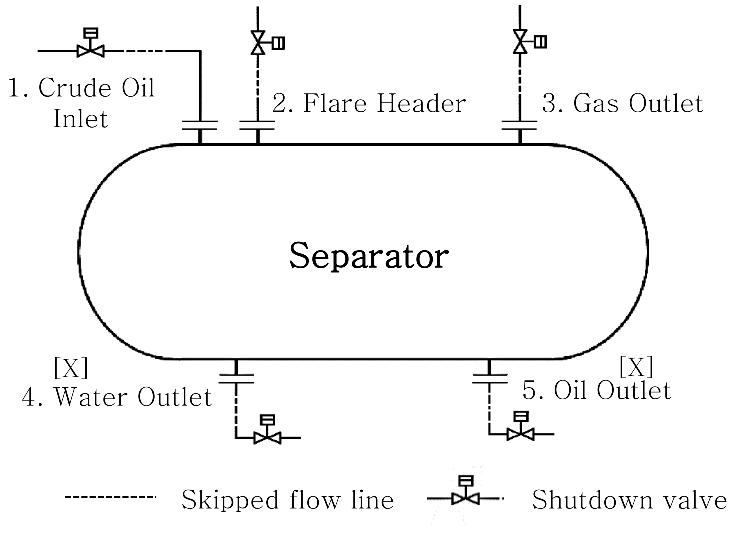


Fig. 25 Separator in test module

The main inventory in the test module is a great deal of oil & gas contained in the separators. There are 5 nozzles connected to each separator, but two of them are separated water and oil outlets, which hardly cause a fire accident. Therefore, only the rest three flow lines associated with nozzle 1~3 are considered during the scenario identification. Following figure 26 shows the total number of cases considered in the example under the condition of both successful and unsuccessful activation of ESD & EDP system. Furthermore, for each case three types of initial leak rates i.e. large, medium, small are also taken into consideration and each of them is called as a fire scenario.

Table 10 Leak frequencies for 3 hole sizes on process deck

Type	Diameter	Process Deck			Quantity	Modification factor	Large	Medium	Small
		Large [65mm]	Medium [46mm]	Small [6mm]					
Flange	30"	6.00E−06	2.95E−05	7.35E−05	6	1.5	5.40E−05	2.66E−04	6.62E−04
	24"	5.10E−06	2.50E−05	6.20E−05	6	1.5	4.59E−05	2.25E−04	5.58E−04
	20"	4.43E−06	2.23E−05	5.47E−05	23	1.5	1.53E−04	7.69E−04	1.89E−03
Actuated Valve	20"	1.15E−05	5.50E−05	1.35E−04	0	1.5	0.00E+00	0.00E+00	0.00E+00
	24"	1.10E−05	5.40E−05	1.30E−04	1.5	1.5	2.48E−05	1.22E−04	2.93E−04
Manual Valved	20"	7.53E−06	2.80E−05	5.20E−05	2	1.5	2.26E−05	8.40E−05	1.56E−04
Pipe [mm]	30"	1.40E−06	6.50E−06	1.50E−05	13305	1.5	2.79E−05	1.30E−04	2.99E−04
	24"	1.40E−06	6.50E−06	1.50E−05	51715	1.5	1.09E−04	5.04E−04	1.16E−03
	20"	1.40E−06	6.50E−06	1.50E−05	90475	1.5	1.90E−04	8.82E−04	2.04E−03
Vessel	30"	2.80E−04	3.50E−04	5.60E−04	2	1.0	5.60E−04	7.00E−04	1.12E−03
Total							1.19E−03	3.68E−03	8.17E−03

Table 11 Leak frequencies for 3 hole sizes on upper deck

Type	Diameter	Upper Deck			Quantity	Modification factor	Large	Medium	Small
		Large [65mm]	Medium [46mm]	Small [6mm]					
Flange	30"	6.00E−06	2.95E−05	7.35E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	24"	5.10E−06	2.50E−05	6.20E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	20"	4.43E−06	2.23E−05	5.47E−05	7	2.0	6.20E−05	3.12E−04	7.66E−04
Actuated Valve	20"	1.15E−05	5.50E−05	1.35E−04	0.5	2.0	1.15E−05	5.50E−05	1.35E−04
	10"	1.10E−05	5.40E−05	1.30E−04	0	2.0	0.00E+00	0.00E+00	0.00E+00
Manual Valve	20"	7.53E−06	2.80E−05	5.20E−05	2	2.0	3.01E−05	1.12E−04	2.08E−04
	10"	6.14E−06	2.13E−05	4.00E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
Pipe [mm]	30"	1.40E−06	6.50E−06	1.50E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	24"	1.40E−06	6.50E−06	1.50E−05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	20"	1.40E−06	6.50E−06	1.50E−05	58170	2.0	1.63E−04	7.56E−04	1.75E−03
Vessel	30"	2.80E−04	3.50E−04	5.60E−04	0	1.0	0.00E+00	0.00E+00	0.00E+00
Total							2.67E−04	1.24E−03	2.85E−03

Table 12 Leak frequencies for 3 hole sizes on top deck

Type	Diameter	Top Deck Large [65mm]	Top Deck Medium [46mm]	Top Deck Small [6mm]	Quantity	Modification factor	Large	Medium	Small
Flange	30"	6.00E-06	2.95E-05	7.35E-05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	24"	5.10E-06	2.50E-05	6.20E-05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	20"	4.43E-06	2.23E-05	5.47E-05	12	2.0	1.06E-04	5.35E-04	1.31E-03
Actuated Valve	20"	1.15E-05	5.50E-05	1.35E-04	0	2.0	0.00E+00	0.00E+00	0.00E+00
	10"	1.10E-05	5.40E-05	1.30E-04	0	2.0	0.00E+00	0.00E+00	0.00E+00
Manual Valve	20"	7.53E-06	2.80E-05	5.20E-05	6	2.0	9.04E-05	3.36E-04	6.24E-04
Pipe [mm]	30"	1.40E-06	6.50E-06	1.50E-05	22000	2.0	6.16E-05	2.86E-04	6.60E-04
	24"	1.40E-06	6.50E-06	1.50E-05	0	2.0	0.00E+00	0.00E+00	0.00E+00
	20"	1.40E-06	6.50E-06	1.50E-05	10000	2.0	2.80E-05	1.30E-04	3.00E-04
Vessel	30"	2.80E-04	3.50E-04	5.60E-04	2	1.0	5.60E-04	7.00E-04	1.12E-03
Total							8.46E-04	1.99E-03	4.02E-03

Table 13 Probability of ignition and ESD & EDP

ESD & EDP			Cox & Lee Model		
Failure Probability on Demand			Ignition probability		
L	M	S	L	M	S
12kg/s	5kg/s	1kg/s	12kg/s	5kg/s	1kg/s
0.05	0.05	0.05	0.0778	0.0444	0.0158

Table 14 Leak frequency for each leak location

	Total Leak Frequency on Each Deck			Leak Frequency per Leak Location		
Size	L	M	S	L	M	S
Process	1.19E−03	3.68E−03	8.17E−03	1.98E−04	6.14E−04	1.36E−03
Upper	2.67E−04	1.24E−03	2.85E−03	8.88E−05	4.12E−04	9.51E−04
Top	8.46E−04	1.99E−03	4.02E−03	4.23E−04	9.94E−04	2.01E−03
Total	2.30E−03	6.90E−03	1.50E−02	7.10E−04	2.02E−03	4.32E−03

Table 15 Fire frequency with successful activation of ESD & EDP

Fire Frequency per Leak Location for Sucessful ESD & EDP			
Size	L	M	S
Process	1.46E-05	2.59E-05	2.04E-05
Upper	6.57E-06	1.74E-05	1.43E-05
Top	3.13E-05	4.19E-05	3.01E-05
Total	5.25E-05	8.52E-05	6.49E-05

Table 16 Fire frequency with unsuccessful activation of ESD & EDP

Fire Frequency per Leak Location for Unsuccessful ESD & EDP			
Size	L	M	S
Process	7.69E-07	1.36E-06	1.08E-06
Upper	3.46E-07	9.14E-07	7.52E-07
Top	1.65E-06	2.21E-06	1.59E-06
Total	2.76E-06	4.48E-06	3.41E-06

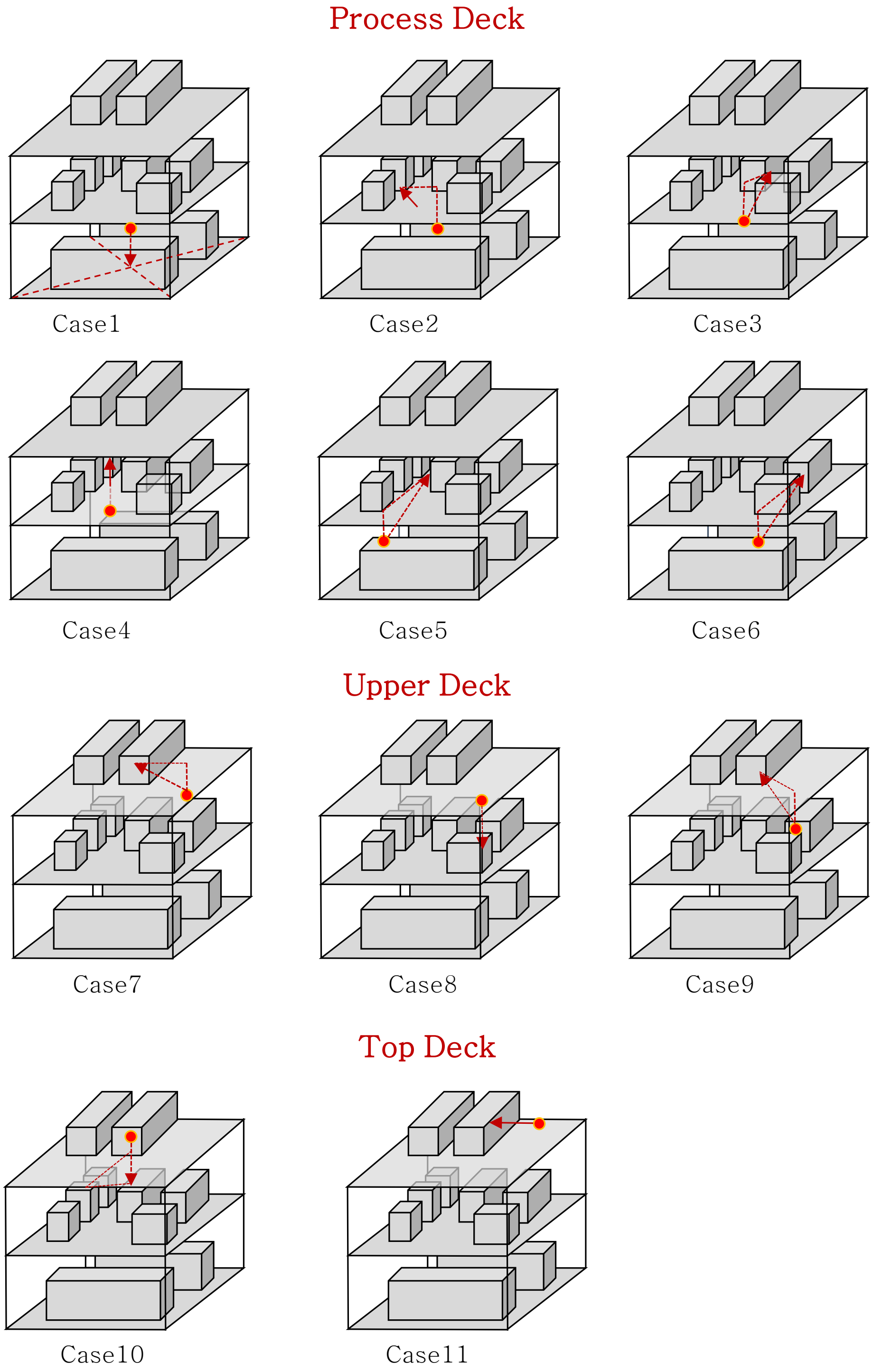
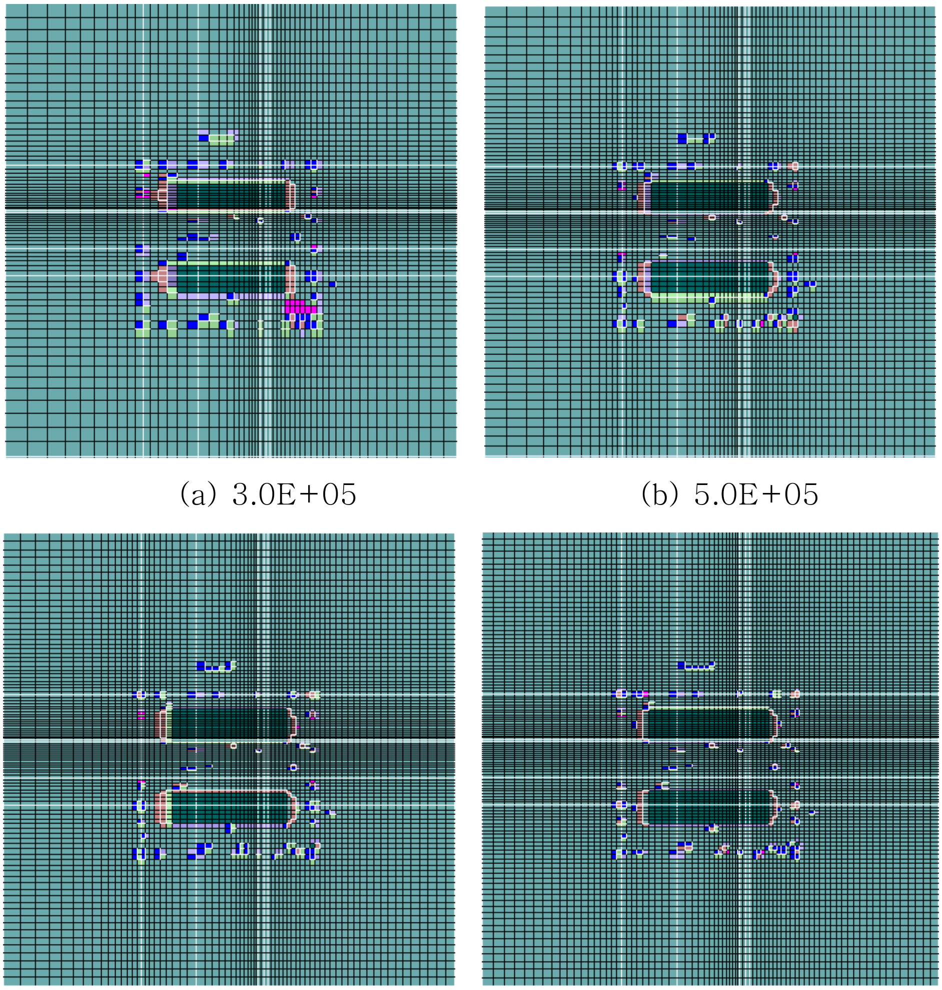


Fig. 26 Total cases considered in the example

5.2. Determination of Grid for Fire Simulation

In order to determine a proper number of grid for the identified fire scenario, 4 cases of fire simulation with different number of grid are carried out in the example. Following figure shows the 4 different cases with different number of grid.



(a) 3.0E+05 (b) 5.0E+05

(c) 7.0E+05 (d) 1.2E+06

Fig. 27 4 cases of considered grid number

The scenario used for grid testing is the large fire of case7 presented in Fig. 26, and the 4 types of fire simulation with different number of grid are continued until steady state. Through the comparison of heat flux distributions on x, y, z plane of the leak location showed in Fig 28~32, it is concluded that the proper number of grid should be 7.0E+05, because the heat flux distributions are almost unchangeable from that case. However, judging from the structural point of view, the area of interests is concentrated on the internal side of the test module, and the heat flux distributions inside the module are almost identical except for the first case with 3.0E+05 grids. Therefore, the proper number of grid applied in the example is determined as 5.0E+05.

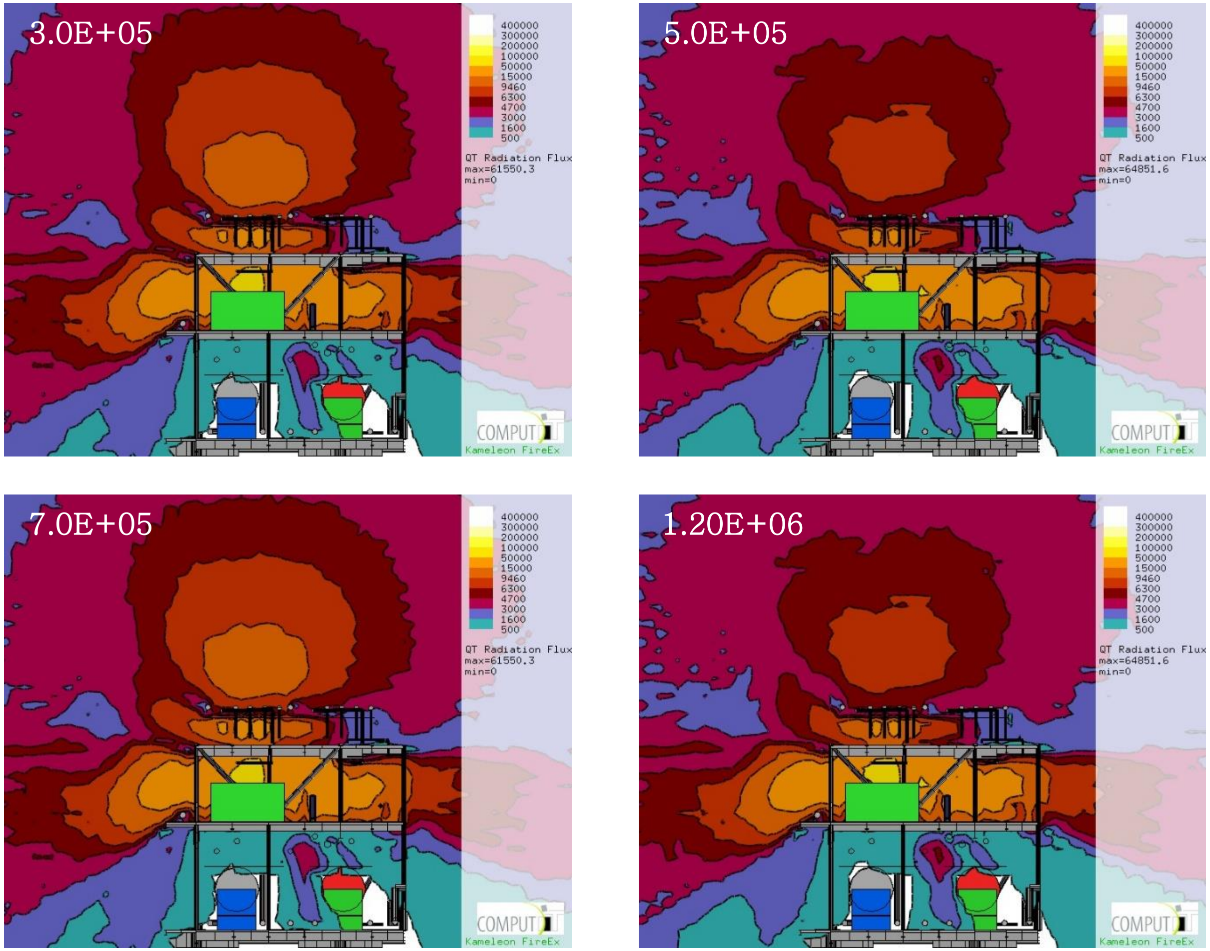


Fig. 28 Comparison of simulation results for 4 different number of grid, x plane

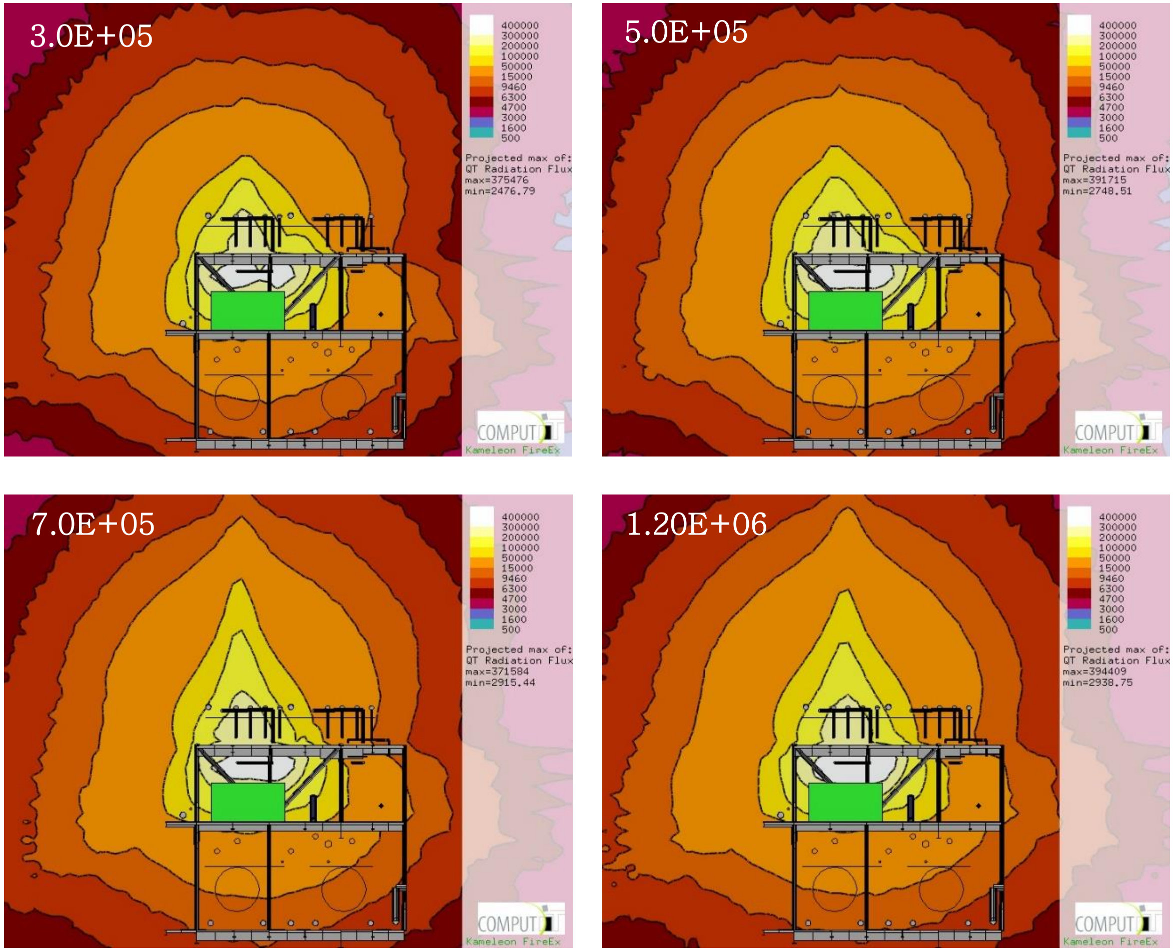


Fig. 29 Comparison of simulation results for 4 different number of grid, x projection

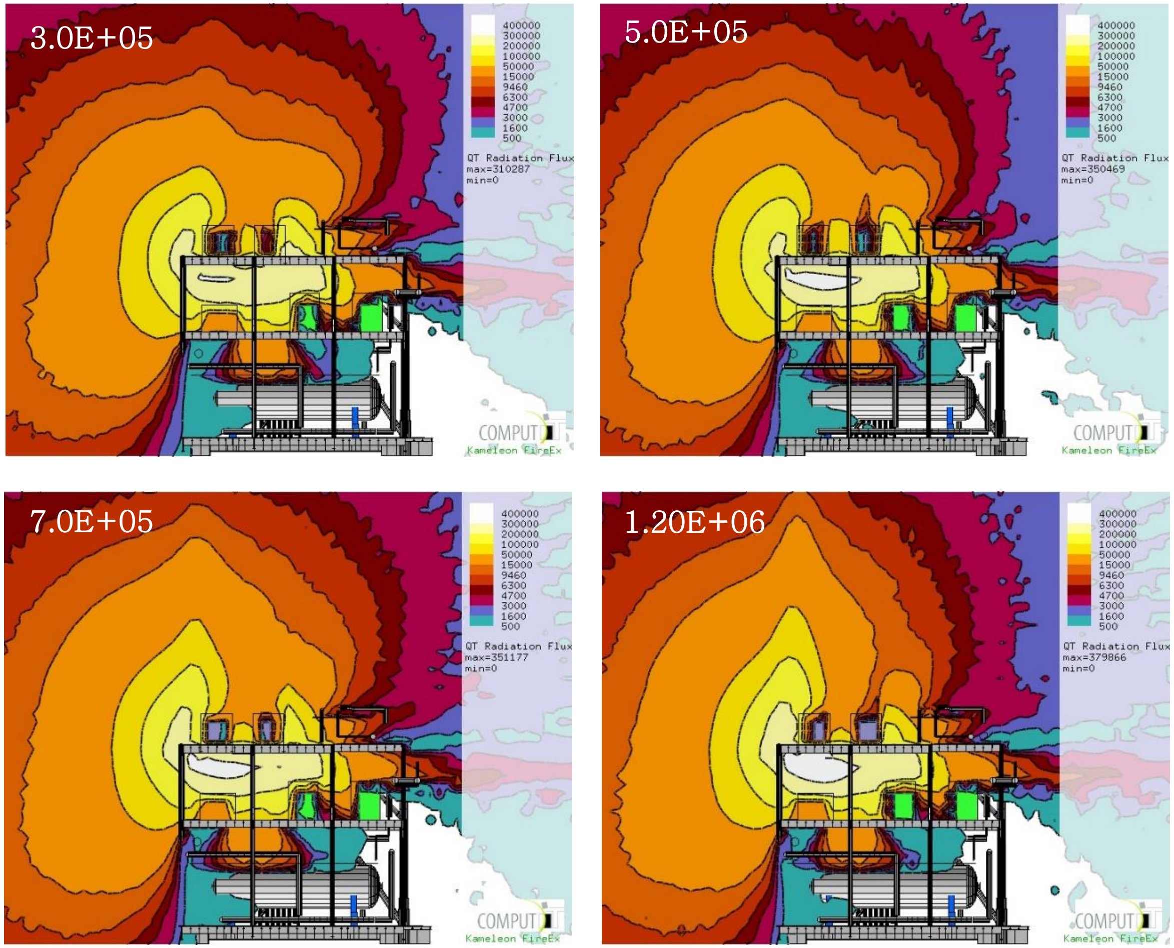


Fig. 30 Comparison of simulation results for 4 different number of grid, y plane

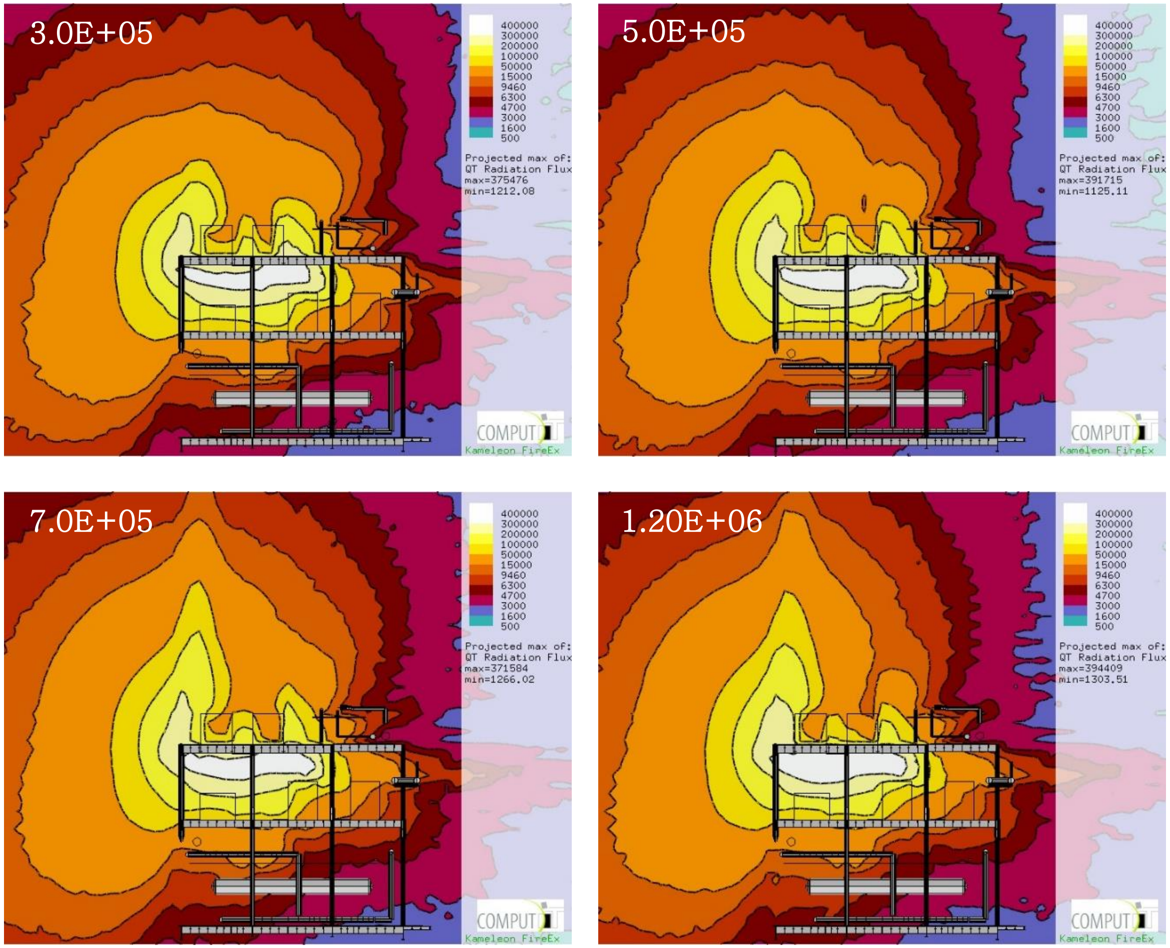


Fig. 31 Comparison of simulation results for 4 different number of grid, y projection

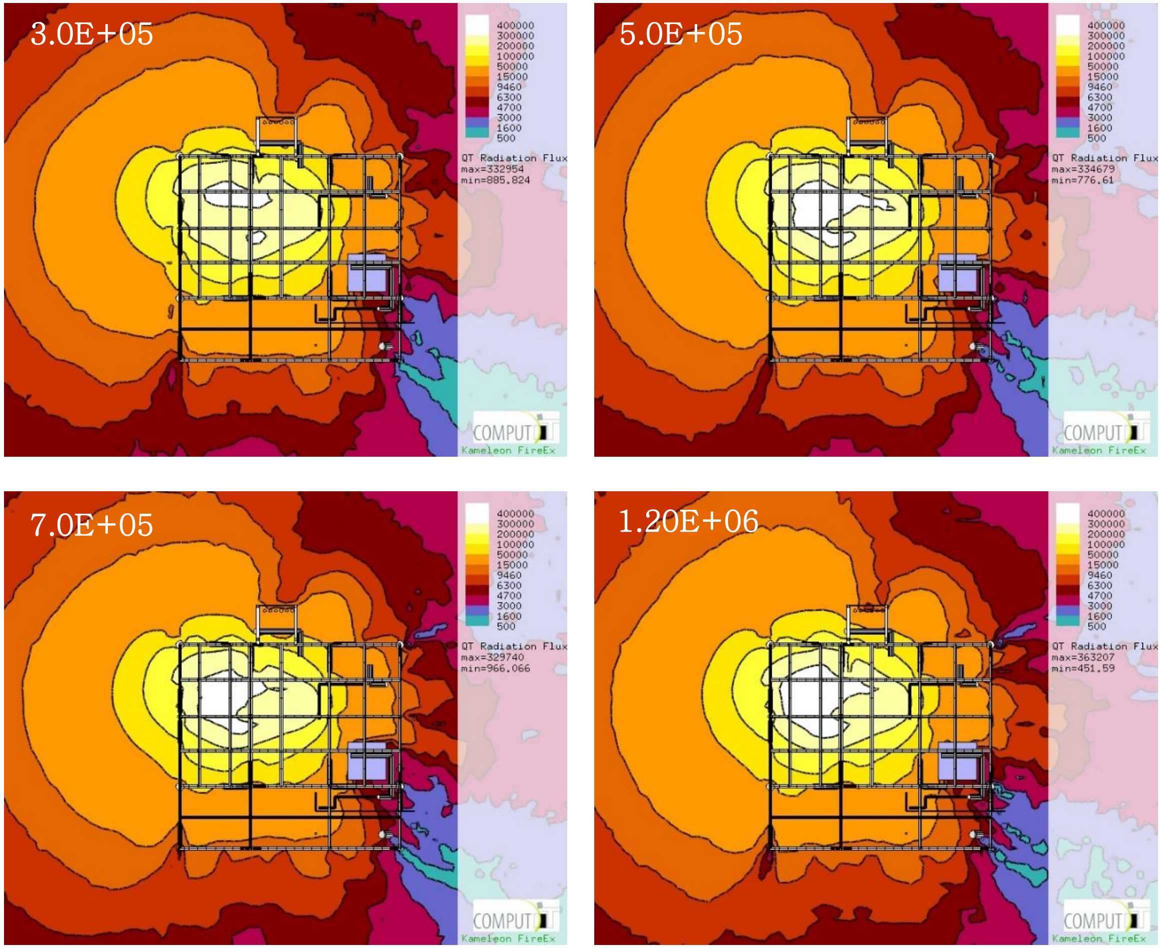


Fig. 32 Comparison of simulation results for 4 different number of grid, z plane

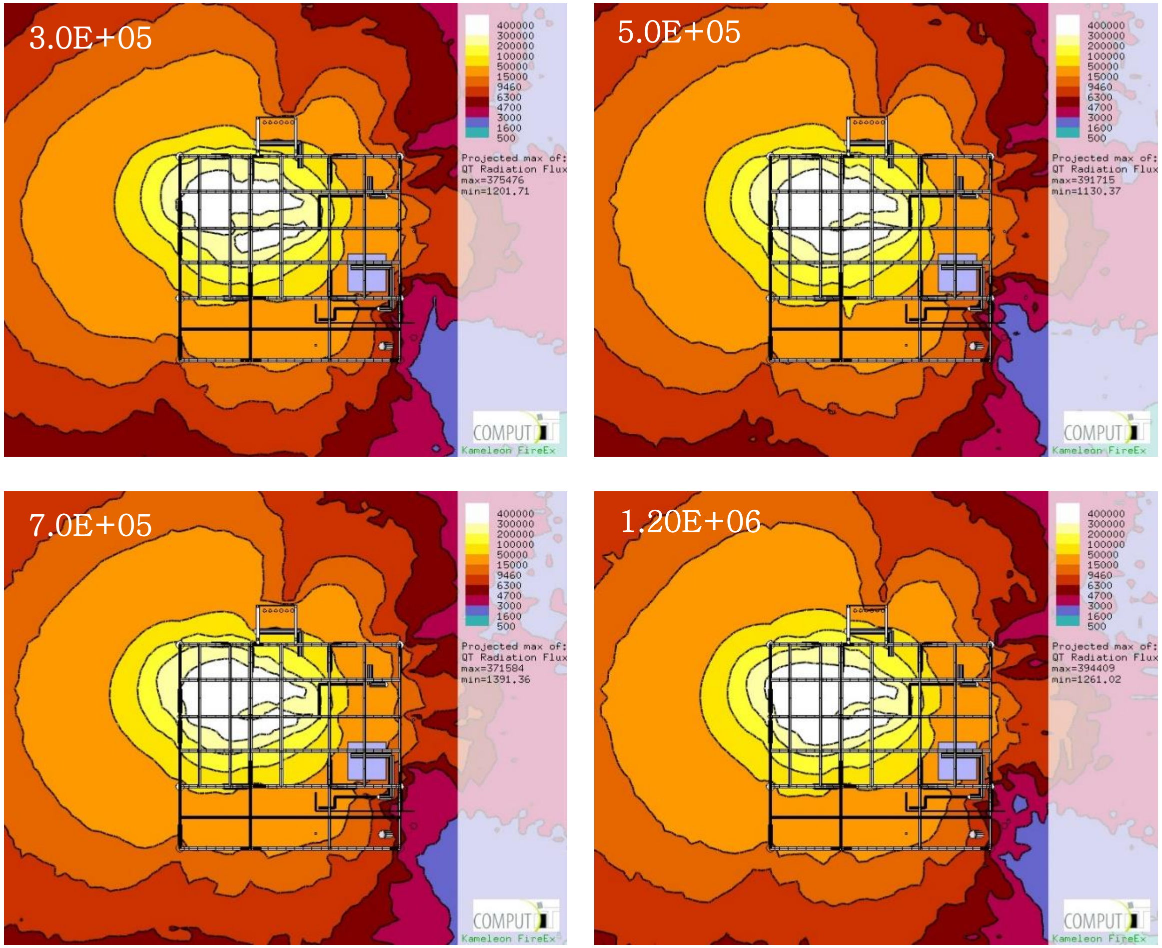
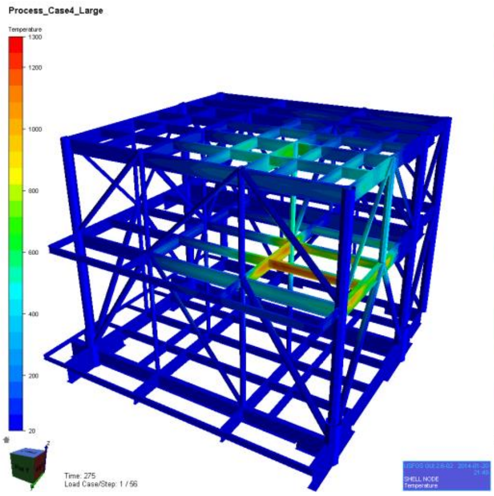


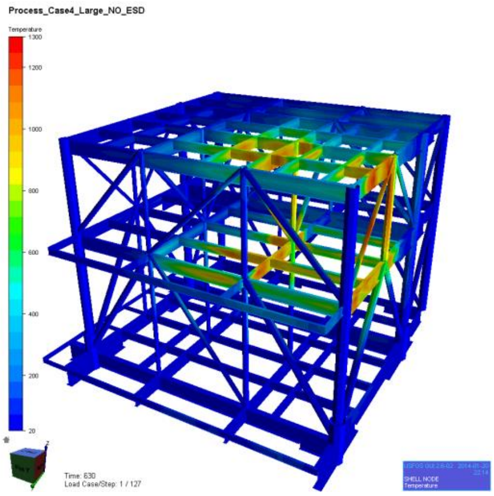
Fig. 33 Comparison of simulation results for 4 different number of grid, z projection

5.3. Structural Consequence Analysis

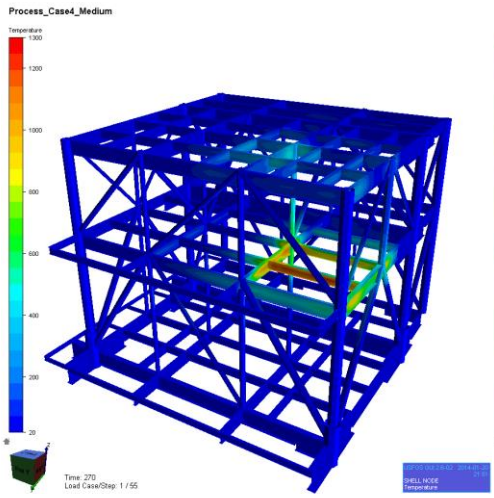
In the example totally 11 cases are considered for calculating cumulative failure frequency, and case 4 is representatively presented in the following figures.



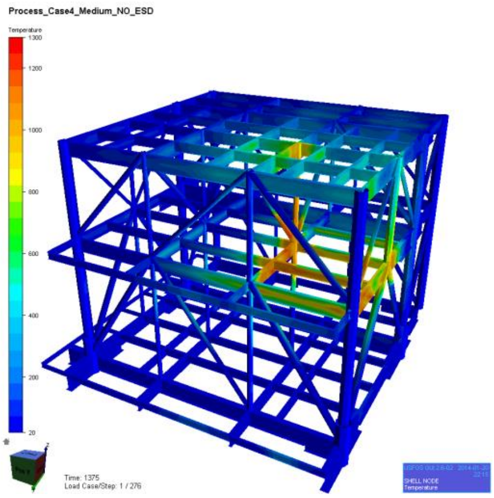
Large, successful ESD & EDP



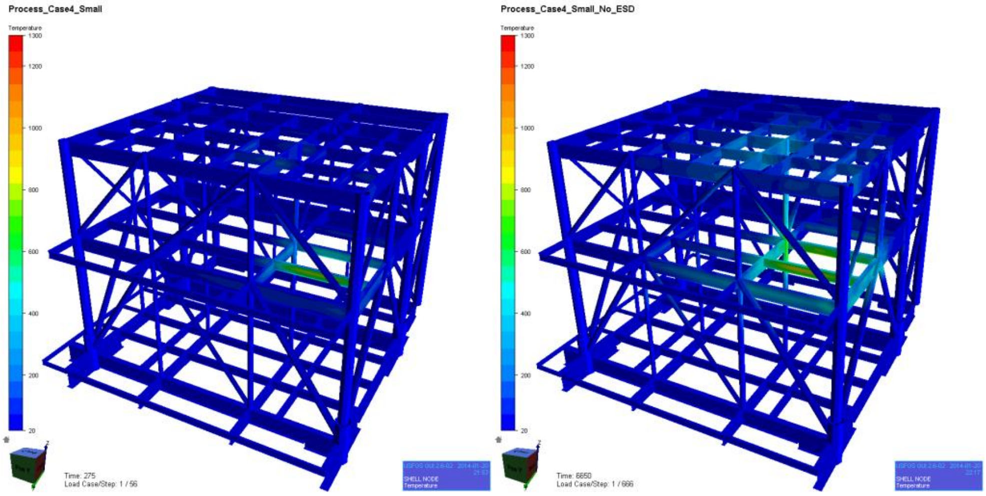
Large, unsuccessful ESD &EDP



Medium, successful ESD & EDP

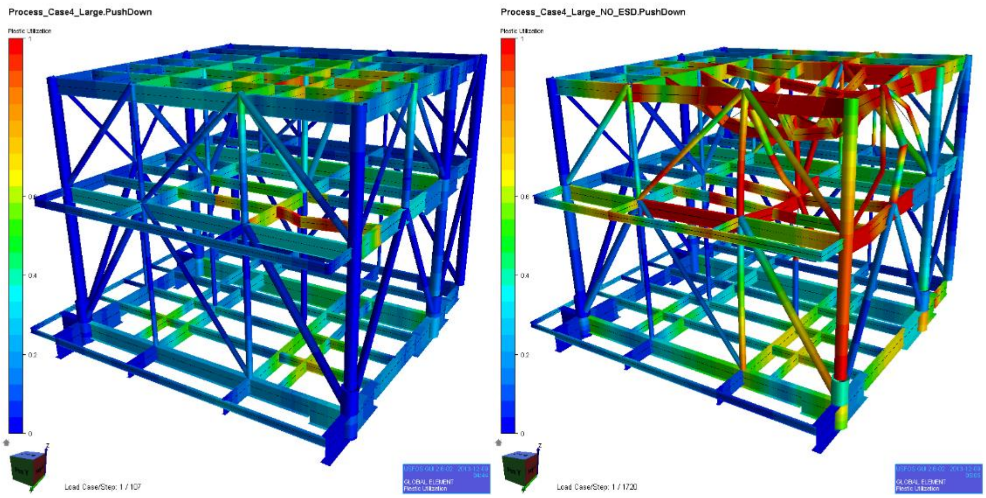


Medium, unsuccessful ESD & EDP

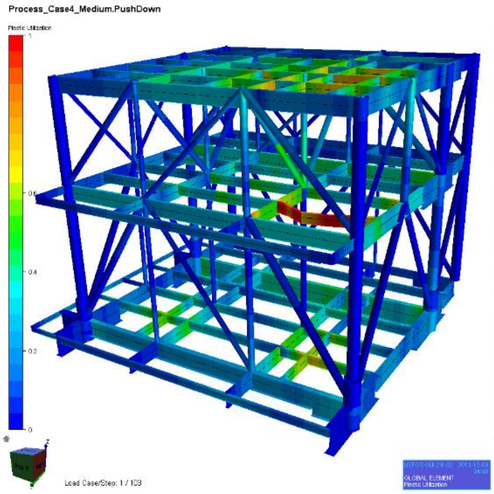


Small, successful ESD & EDP　　Small, unsuccessful ESD & EDP

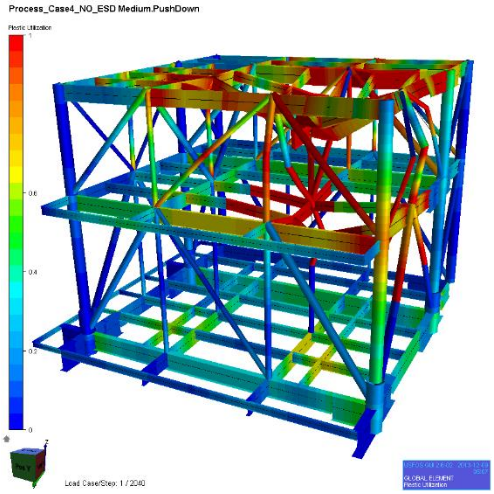
Fig. 34 Results of heat transfer analysis for Case 4



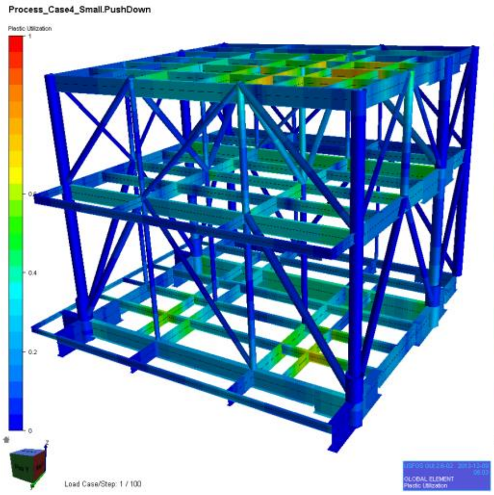
Large, successful ESD & EDP　　Large, unsuccessful ESD &EDP



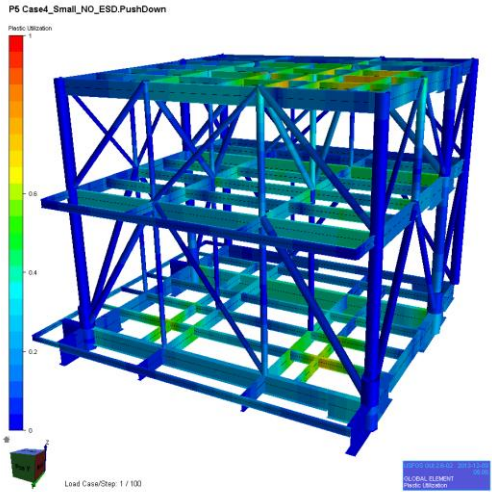
Medium, successful ESD & EDP



Medium, unsuccessful ESD & EDP



Small, successful ESD & EDP



Small, unsuccessful ESD & EDP

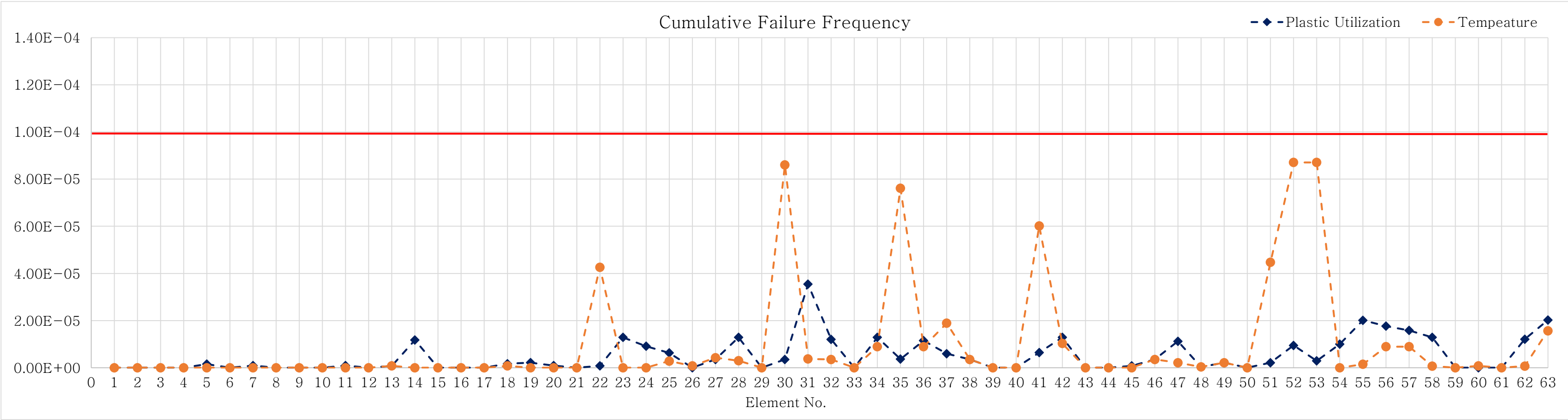
Fig. 35 Results of structural analysis for Case 4

According to the results of heat transfer analysis and structural analysis, it is obviously concluded that ESD, EDP system has a significant effect on the fire consequence and moreover most of small fires in the example hardly cause considerable failure of the test structure.

Furthermore, through a detail observation of other cases, it is also not difficult to find that structural parts which do not locally bear the equipment load are hardly to fail even if they are exposed to a high temperature load.

5.4. Calculation of Cumulative Failure Frequency

In the example, cumulative failure frequency of test module is calculated by using the formulae presented in section 4.5.2, and it is considered respectively by applying the two different structural failure criteria mentioned in section 4.5.1. The total number of elements for the test USFOS structure model is 379, and the results of cumulative failure frequency for each element is plotted in figure 29~30. X axis is the number of element and Y axis is the cumulative frequency.



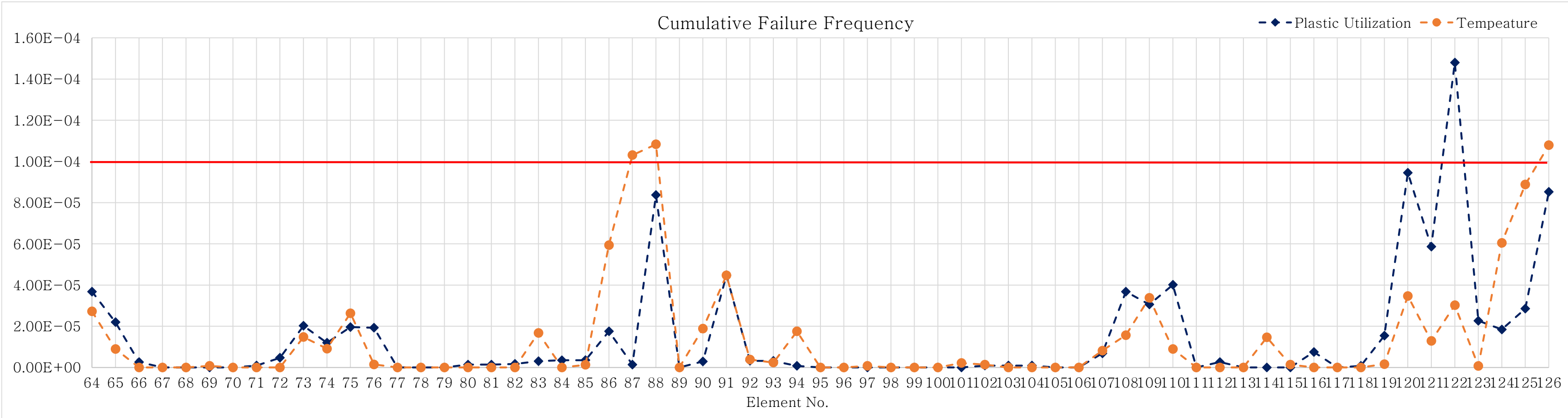
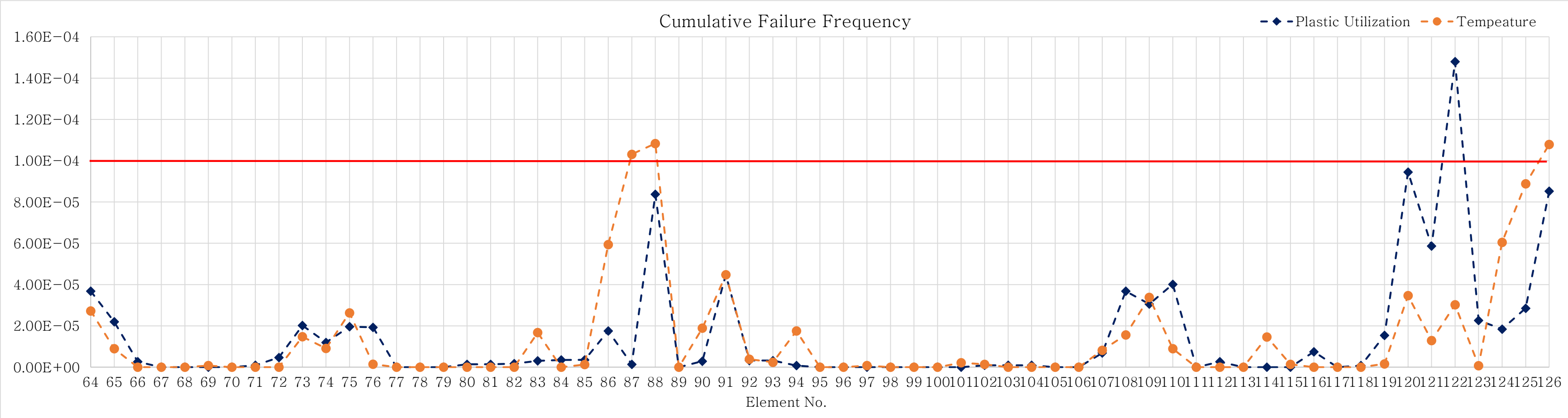


Fig. 36 Cumulative failure frequency of test module (1)



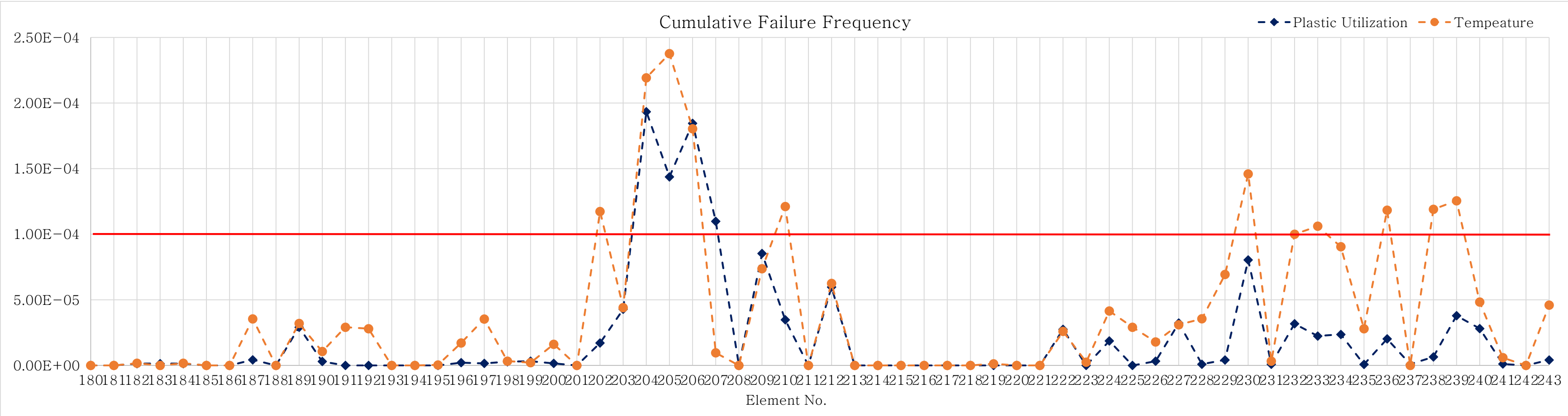
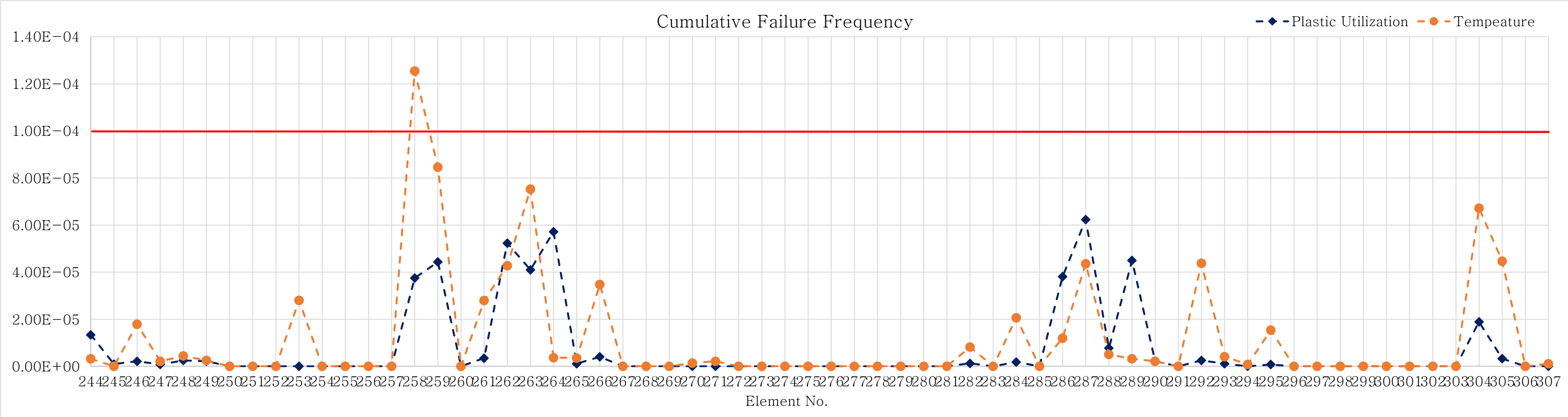


Fig. 37 Cumulative failure frequency of test module (2)



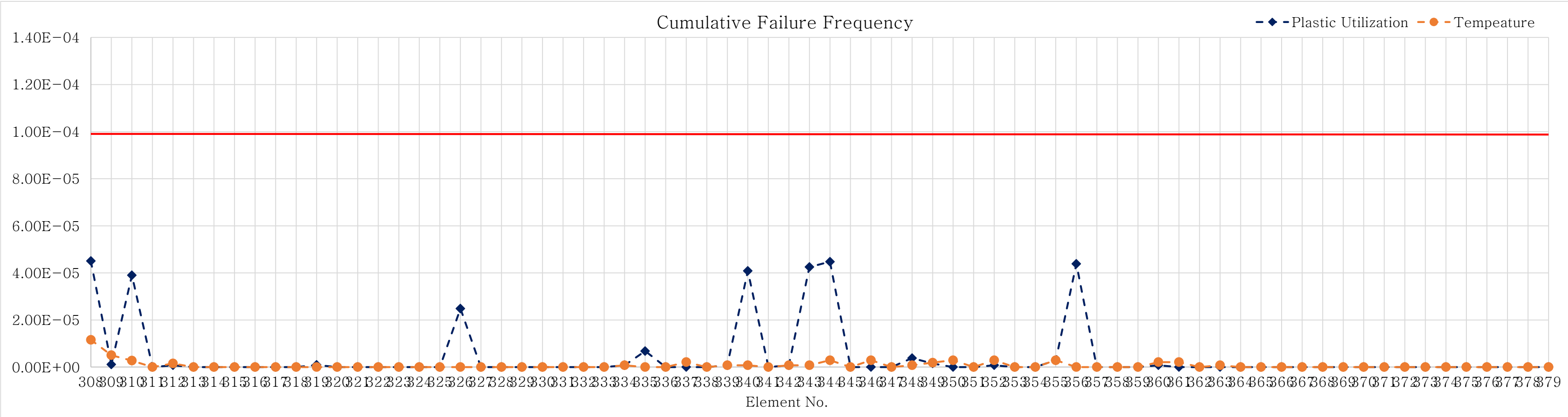
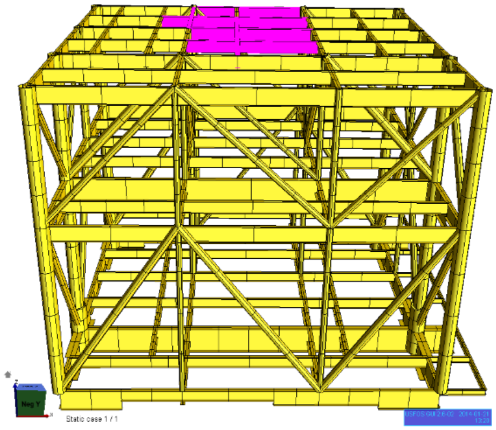


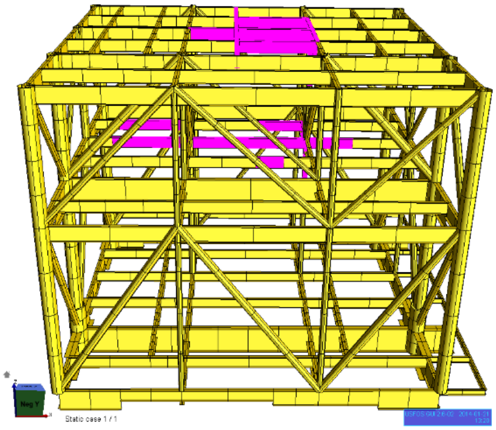
Fig. 38 Cumulative failure frequency of test module (3)

5.5. Determination of PFP Application area

In order to find the failed element that needs PFP protection, a risk criterion i.e. 1.0E−04 is applied to the graphs of cumulative failure frequency plotted in the previous section. The highlighted parts in the Fig. 38 are the identified failed elements.



(a) Structural analysis



(b) Heat transfer analysis

Fig. 39 Failed structural elements

Through an observation of the failed element, following conclusions can be drawn.

- **For the failed elements of top deck:**
  - They are both identified as the failed elements through heat transfer analysis and structural analysis because

they are simultaneously subjected to high temperature and equipment weights.

- **For the failed elements of upper deck:**
  - They are identified as the failed elements through heat transfer analysis because the temperature is higher than 450 ℃.
  - Whereas, they are identified to be safe through structural analysis because the imposed equipment weights is relatively smaller than the ones on the top deck.

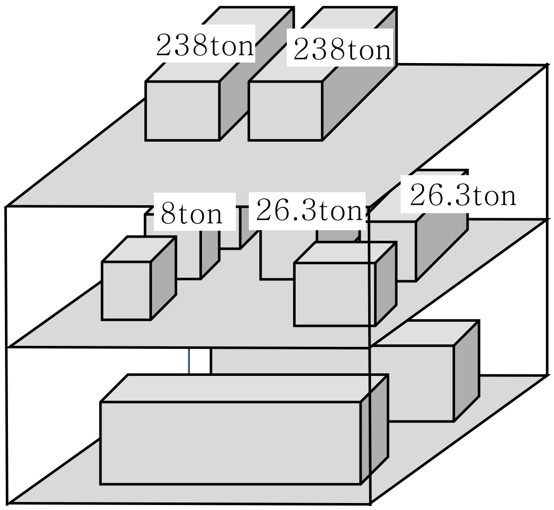


Fig. 40 Equipment load of test module

6. Conclusion

In the former FRA procedures the structural thermal consequence analysis is hardly to be accomplished, because those determined design loads are commonly just certain single physical variable, which are difficult to be applied for structure analysis. This indicates that the connection between determined design load and structure analysis always becomes a big problem in the former FRAs. To solve this, a new FRA procedure is proposed in this thesis. The most worthy point to be mentioned in the new procedure is including the result of structural response analysis at the stage of frequency analysis, and the specific method for this is calculating the cumulative failure frequency of structural element. Compared to the traditional exccedance curve, using cumulative failure frequency is much easier and more intuitively for determining the PFP application area, and this is proved by the example in this thesis.

In order to explain the new FRA procedure in more detail, an example is demonstrated with a test separation module. Through the observation of the example, it is summarized that that structural parts which do not locally bear the equipment load are hardly to fail even if they are exposed to a high temperature load. Consequently, this indicates that the structural analysis is a necessary part for evaluating the fire risk or determining the proper application area of PFP.

However, there are still a lot of uncertainties for identifying the fire scenarios by present. Especially for the part of determining the leak location and direction. Not only in the existing FRAs but also in the new one proposed in this thesis, there are too much subjective judgments involved in leak location and direction. Hence, as a future work, further studies will be focused on the leak location and direction to find more reliable and rational probabilistic models to depict their random characteristic.

Reference

[1] Andreas Falck, DNV, (2011). Leak Frequency Modeling for Offshore QRA based on the Hydrocarbon Released Database", FABIG ISSUE 57, pp.9~18.

[2] Cox, Lees, Ang, (1990). Classification of Hazardous Locations, Institute of Chemical Engineers.

[3] EN 1993-1-2, (2005). Eurocode 3 Design of steel structures - Part 1-2: General Rules - Structural fire design.

[4] FAHTS, (2011). User's manual for FAHTS, USFOS A/S, Norway.

[5] Hydro Carbon Release Database, (2005). HSE, http://www.hse.gov.uk/hcr3

[6] Jan Reier Huse, Ulf Danielsen, Joar Dalheim, Scandpower AS, SPE, (2011). Integrated Analysis of Fire Exposed Structures Introducing Probabilistic Analysis into Fire Modeling and Structural Analysis, Society of Petroleum Engineers.

[7] KFX, (2010). User's manual for Kameleon FireEx (2010). Computational Industry Technologies A/S, Stavanger, Norway.

[8] NORSOK, (2001) Risk and emergency preparedness analysis, NORSOK Standard Z-013, Oslo, Norway.

[9] OGP, (2010). Process release frequencies, Risk Assessment data directory, Report No.434-1.

[10] Sávio Vianna, Asmund Huser, (2010). Fire CFD Modelling Applied to Offshore Design, Det Norske Veritas.

[11] SCI, (2009). Probabilistic Assessment of Fire loads and Structural Response, FABIG Technical Note 11.

[12] Total, (2008). Technological Risk Assessment Methodology, GSEP SAF 041.

[13] USFOS, (2012). User’s manual for USFOS, USFOS A/S, Norway.

[14] Viken Chinien, Asmund Huser, (2013). Adoption of risk based assessment method for Fires and Explosions in Design, FABIG ISSUE 62, pp. 24~30.

[15] 박정효. 해양플랜트 Topside 화재 CFD 시뮬레이션에 관한 연구. 2011. 부산대학교 석사학위논문.

[16] 유권철. 해양플랜트 Topside 가스폭발 위험도 평가에 관한 연구 – 가스폭발사고 시나리오 선정. 2010. 부산대학교 석사학위논문

초록

FPSO 상부구조에 대한 확률론적 화재 위험도 해석 및 구조 안전성에 관한 연구

많은 해양 플랜트는 가연성 오일 & 가스 정제 프로세스를 가지고 있기 때문에 탄화수소 화재 사고가 발생할 가능성이 크다. 화재 사고는 전체 해양플랜트 위험도에서 큰 비중을 차지하고 있다. 그렇지만 기존의 실제 프로젝트에 많이 적용되었던 화재위험도 해석 방법들은 여전히 해양플랜트 화재 사고 위험도를 평가하는데 있어서 많은 부족한 점을 가지고 있다. 이러한 이유 때문에 본 논문에서는 새로운 화재 위험도 해석 프로시저를 제안하여 기존 방법들의 문제점들을 극복하고자 한다.

새로 제안한 화재위험도 해석 프로시저에서는 우선 화재 시나리오 구성에 필요한 변수를 적절한 확률모델, historical database, 프로세스 P&ID, PFD 등 다양한 정보를 이용하여 신중히 고려하였고 3d CFD 기반의 수치 화재 시뮬레이션을 적용하여 각 구성된 시나리오의 화재 현상을 해석하였다. 그리고 snapshot 방법을 적용하여 시간에 따라 변화하는 화재의 동적인 특성을 수치시뮬레이션에 효율적으로 반영하였고 화재에 노출되어 있는 FPSO 상부구조의 응답을 평가하기 위해서 열 전달 및 비선형 구조해석을 새로 제안한 프로시저에

포함시켰다.

기존의 화재 위험도 해석은 화재시뮬레이션 결과에 초점을 두고 exceedance 곡선을 이용하여 확률론적으로 DAL 값을 결정하였다. DAL 값은 흔히 FPSO 상부구조나 장비의 설계에 반영 된다. 하지만 exceedance 곡선을 통하여 얻은 DAL 값은 흔히 화염의 길이, heat dose, heat flux contour 등 단일 물리 량으로 표현되었기 때문에 실제 구조해석에 적용하기에는 많이 부족하다. 이를 해결하기 위하여 본 논문에서는 각 시나리오의 구조해석 결과에 초점을 두고 exceedance 곡선 대신에 새로 제안한 구조의 누적 파괴 빈도를 이용하여 화재에 노출되어 파괴될 가능성이 높을 구조 부재를 직접적으로 찾아냈다.

보편적으로 해양 플랜트에서 가장 많이 사용되는 있는 화재 위험도 경감 방법은 PFP를 구조 또는 장비 표면에 부착 하는 것이다. 하지만 PFP는 고가의 제품이기 때문에 해양플랜트의 많은 부분에 적용하게 되면 자체의 안전성은 크게 향상 시킬 수 있으나 반면에 경제적으로 엄청난 비용을 부담해야 된다. 그 이유로 PFP의 적용 면적을 최적화 하는 부분은 실제 해양 프로젝트에서 아주 중요한 문제로 간주되고 있다. 그러한 의미에서 본 논문에서 제시한 화재위험도 해석 프로시저는 구조 관점에서 정립된 방법이고 특히 구조의 누적 파괴 빈도를 기반으로 파괴될 가능성이 큰 구조 부재를 판단하기 때문에 PFP 결정을 하는데 있어서 아주 유용하게 이용될 수 있다.

본 논문의 앞 부분에서는 새로 제안한 화재 위험도 프로시저에 대하여 상세히 소개하고 마지막 부분에서는 실제 FPSO separation module을 테스트 모델로 선택하여 하나의 예제를 보여 주었다.

주요어: QRA(Quantitative Risk Assessment), FRA(Fire Risk Analysis), PFP(Passive Fire Protection), CFD, Snapshot

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