A case study for integrated modelling of personnel evacuation with pool fire simulation to increase safety in design for offshore oil and gas projects

Davood Afshari[1]
Richard Welsh[2]
Maryam Moghaddas[3]
Sara Afsharikia[1]
Amir Tavakoli[4]
[1]Lead Technical Safety and Risk Engineer, Complete Fire Design
[2] Managing Director, Complete Fire Design
[3] Senior Loss Prevention Engineer, Complete Fire Design
[4]Loss prevention Engineer, Complete Fire Design

One of the main objectives of the safety analysis in the oil and gas offshore environment is to prove the Escape, Evacuation and Rescue (EER) arrangements (including the escape routes, the Temporary Refuge (TR), the muster stations and the means of evacuation) on-board the platform are satisfactory and efficient, and meet the requirements of the project and specifically the regulations. The basic philosophy is the demonstration of a successful evacuation/escape and recovery to a place of safety for all major accident scenarios including fire and explosion scenarios and other relevant Major Accident Events.

This paper presents a simple sample case of the integrated evacuation modelling with pool fire in an offshore environment. Unlike the normal practices in the industry, the integration of fire analysis inside the evacuation modelling will increase safety in design with

- Designing more effective layouts of escape ways, stairs and ladders;
- Improved demonstration of evacuation procedures for the project stakeholders specifically the regulatory compliance requirements;
- Better review of different scenarios or different behavioural effects on the evacuations time and escape directions;
- Visualise the effect of smoke and Carbon Monoxide, CO, on the evacuation in partially or completely enclosed areas.

During the design phase, the project team is presented with a myriad of escape route decisions on such things as the location and type of escape ways and their connection in the event of fire. By using an integrated fire and escape simulation, however, the project team may investigate the relative quality of the evacuation design showing the real conditions at the time of the evacuation. By modelling the behavior of people in the evacuation period and the simulation of credible fire scenario in the platform, the integrated approach can provide the designers and other project stakeholders with more accurate information pertaining to the correctness and efficiency of escape and evacuation design.

In this paper, the large oil pool fires are simulated through computational fluid dynamics method by means of “Fire Dynamic Simulator (FDS)” software and the results are integrated into escape and evacuation model which set up with “Pathfinder” software. The paper will discuss the results by modelling different evacuation scenarios defined by pool fire impacts and how the integrated modelling will improve the escape and evacuation analysis and design.

Tools & Method

This paper presents a sample case study of the evacuation modelling integrated with a pool fire study in an offshore environmental. For this purpose, the integration of the FDS and Pathfinder softwares has been used. The results of the large pool fire simulation have been considered as an input into the Pathfinder software where the evacuation routes and escape durations are modelled.

FDS uses the Large Eddy Simulation (LES) method to predict large-scale fire and plume behaviour that includes plume characteristics, combustion product dispersion, and heat effects to adjacent objects. The code was developed by the US National Institute of Standards and Technology (NIST). The model has been validated against fires of several types, including many pool fires **[4,5]** LES models offer the opportunity for practical fire modelling simulations to be performed that take into account the detailed behaviour of the fire plume, which is approximated in RANS codes using buoyancy modified k-turbulence models. In particular, the transient nature of the model allows the effects of entrainment to be modelled in detail. Accurate, time-dependent entrainment modelling is very important in fire scenarios as the time-scales are often short and the conditions may change rapidly, details which may be overlooked by a model employing an averaging technique. Although, LES modelling appears as the most promising technique, currently there are still many limits to its precise application to large pool fires. **[6]**

The Pathfinder software is an emergency egress simulator that includes an integrated user interface and animated 3D results. Pathfinder evaluates evacuation models with the capability of adding FDS fire simulation slices so that the evacuation during a fire scenario can be better reviewed.

It should be noted that any other combination of fire modelling and evacuation software can be used depending the fire and evacuation boundaries needing to be addressed. To the best knowledge of this paper, Table 1 shows other available CFD models specifically developed for modelling fire. Table 2 shows other available software for the evacuation analysis purposes. They are ranked for different factors based on end user statements.

Table 1: CFD Models Specifically Developed for Fire Modelling

Software	**Developer**
JASMINE and CRISP	Fire Research Station
Sofie	Consortium initiated at Cranfield University
Smartfire	University of Greenwich
FDS	NIST, USA
Kameloen KFX	ComputIT/NTNU/SINTEF

Table 2 : Ordinal Rank of Importance for Each Factor Stated by Users Of Each Model [7]

	Ordinal Rank (1= more important, 7=less important)						
	1	2	3	4	5	6	7
Cost	FDS+Evac	Legion	Exodus	STEPS	Pathfinder	VISSIM	Simulex
Validation/Verification	FDS+Evac	Legion	STEPS	Pathfinder	Exodus	Simulex	VISSIM
Usability of the software (is it user friendly)	Exodus	Pathfinder	STEPS	Simulex	FDS+Evac	Legion	VISSIM
Emergent Behaviour	Exodus	FDS+Evac	Pathfinder	Simulex	Legion	VISSIM	STEPS
Fire/hazard data importing	FDS+Evac	Exodus	Pathfinder	Simulex	STEPS	Legion	VISSIM
CAD files importing	STEPS	Legion	Pathfinder	Exodus	Simulex	FDS+Evac	VISSIM
Inclusion of data specific to certain environments	Legion	VISSIM	Simulex	Exodus	Pathfinder	FDS+Evac	STEPS
Visual realism of behaviour	Legion	STEPS	Pathfinder	VISSIM	Exodus	FDS+Evac	Simulex
Visual realism of graphics	Legion	Pathfinder	STEPS	VISSIM	Simulex	Exodus	FDS+Evac
Flexibility to control agents	STEPS	Exodus	Legion	VISSIM	Simulex	Pathfinder	FDS+Evac
Documentation (explaining how the model works)	STEPS	FDS+Evac	Pathfinder	Exodus	Legion	Simulex	VISSIM
How much research into human behaviour the model developer does	Exodus	Legion	FDS+Evac	VISSIM	Pathfinder	STEPS	Simulex
Data Output	STEPS	Legion	Exodus	Simulex	FDS+Evac	Pathfinder	VISSIM
Feedback/opinion about the model by other users	Legion	FDS+Evac	Simulex	Pathfinder	VISSIM	STEPS	Exodus
Continual development of the model incorporating new features	Legion	FDS+Evac	Pathfinder	Simulex	VISSIM	STEPS	Exodus

Definition of the Scope

The integrated evacuation and fire studies have been carried out for an FPSO project. The FPSO is a new purpose built FPSO constructed with a double hull. It is turret moored, with electrical driven thrusters positioned aft for main propulsion and operational convenience defining the material with a design life of 20 years. This paper focuses on the M11 module as one of topside production modules where the crude oil stabilization process is located. The location of M11 is shown in Figure 1.

The process equipment is arranged on two deck levels, process deck level at El. 32.75m and upper deck at El.43.75m. Refer to Figure 2, the first level defined as the process deck is fully plated and all decks at higher levels are grated except for local drip trays under vessels, heat exchangers and other equipment. Personnel use the main escape routes located in each deck periphery to escape toward the outboard staircases by which they are able to go down to ship's main deck and then forward to the living quarter as a safe area in the ship aft side.

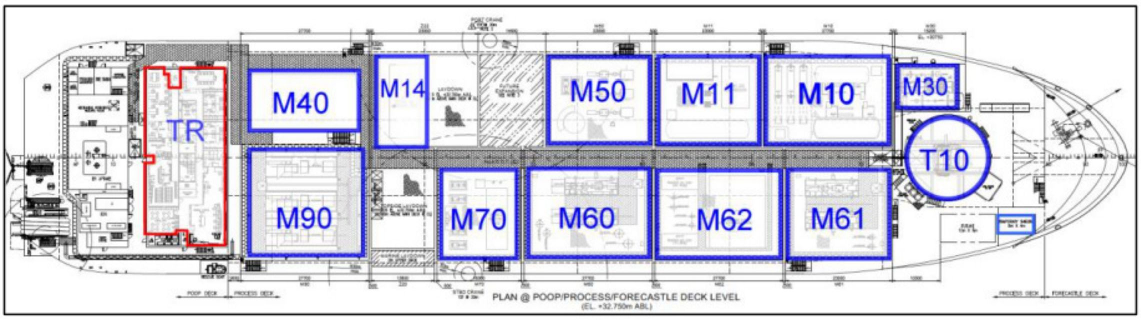


Figure 1: The Location of M11

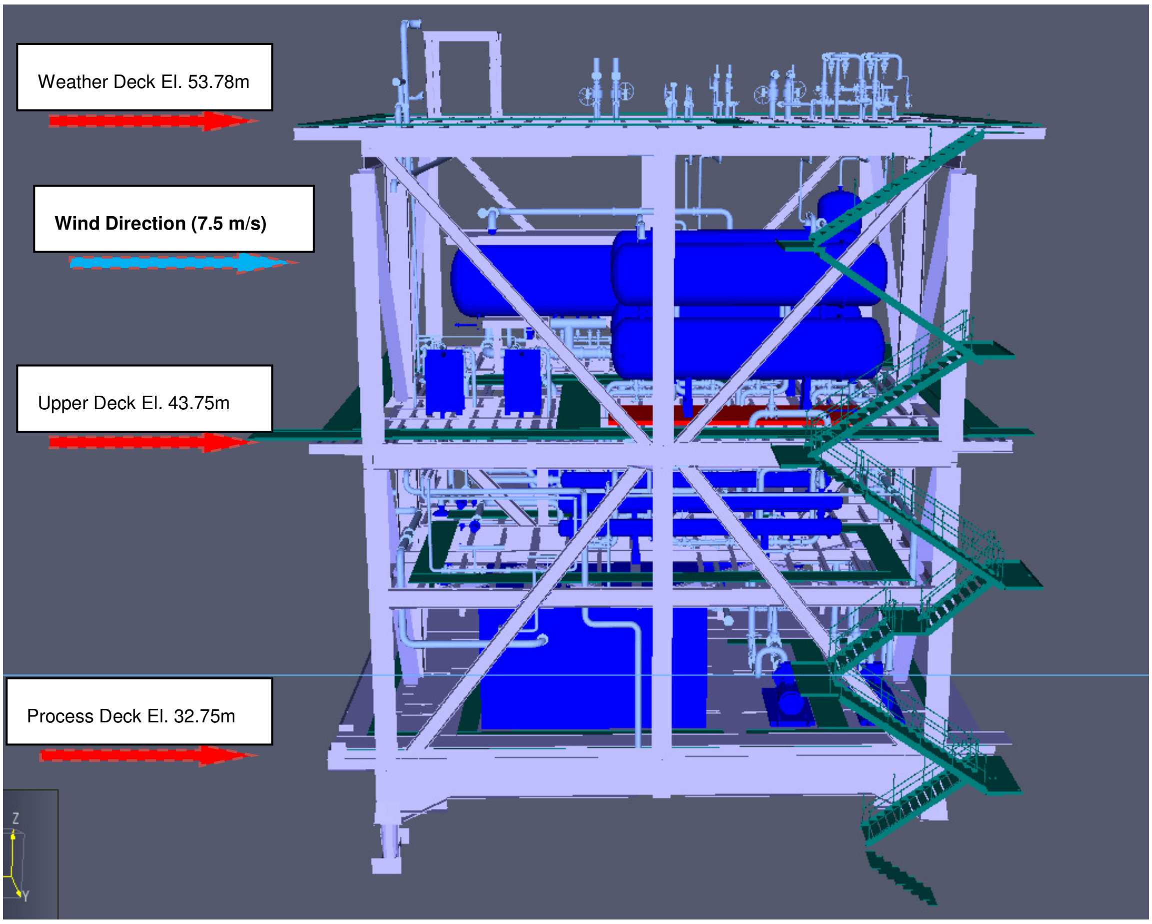


Figure 2: M11 Module- Elevation View and Staircase Location

Evacuation Parameters and Scenarios

For the number of personnel who are likely to be in the area during a fire event, 7 people have been selected based on the “project personnel distribution plan” specifying the maximum number of people in the area by operation and maintenance needs. On a worst case approach, it is assumed that all these 7 people are located in the weather deck which is the longest escape route in the module.

The following travel speeds are considered based on “The Centre for Marine and Petroleum Technology” recommendations.

- Speed along horizontal walkway: 1 m/s
- Speed along moderate slope: 0.8 m/s
- Speed up/down stairs: 0.6 m/s
- Speed up/down vertical ladders: 0.3 m/s

The evacuation time available for a safe escape and evacuation, in the event of fire, starts after the time of alarm. The time taken for the alarm to sound will depend on the time for ignition and detection (fire and/or gas) to occur as well as the control logic of the system (i.e. which voted confirmation or manual action is needed to actuate an alarm). The detection time is dependent on the fire and gas detection system characteristics, noting that a fire could also be detected by personnel. A time of 10 to 20 seconds to detection is considered appropriate and it is considered 10 seconds for large pool fire in this paper.

Once the General Alarm signal is initiated, there is a time delay before personnel start their escape. The time delay consists of perception, interpretation, and action. Perception is the short time personnel take to acknowledge the alarm signal, whilst interpretation of the alarm will involve understanding what the alarm means and what the next course of action should be. On this basis, a delay of 10 seconds before personnel to start their escape is assumed given to that the M11 weather deck is not a normally manned area and the personnel will be there for maintenance with enough communication with control room.

Location and Quantification of Large Pool Fire

Three fire scenarios have been evaluated for the M11 module. They have been listed down in Table 4 and illustrated I in Figure 3- 5. The fires are large pool fires below the Crude Oil Coalescer inside it’s drip tray, below the crude oil pump skid and inside the drip tray of the heat exchanger. The dimension of the pool fires are limited to the dimension of the drip tray located below each equipment and are mentioned in Table 4 with their equal diameter of a pool fire. Also, no allowance has been taken for open drain gullies inside the drip trays. Please note that a 7.5 m/s prevailing wind directed from the forward side of the ship has been considered in all three fire scenarios.

Table 3: Pool Fire Scenarios

Scenario	Location of pool fire	Dimension of pool Fire
F1	Process deck- Inside drip tray at beneath the Coalescer	17.1m X 4.2m (9.6m)
F2	Process deck- Inside drip pan of crude oil pump skid	1.7m X 3.2m (2.6m)
F3	Upper deck- Inside drip tray of crude oil heat exchanger	9m X 2.2m (5.5m)

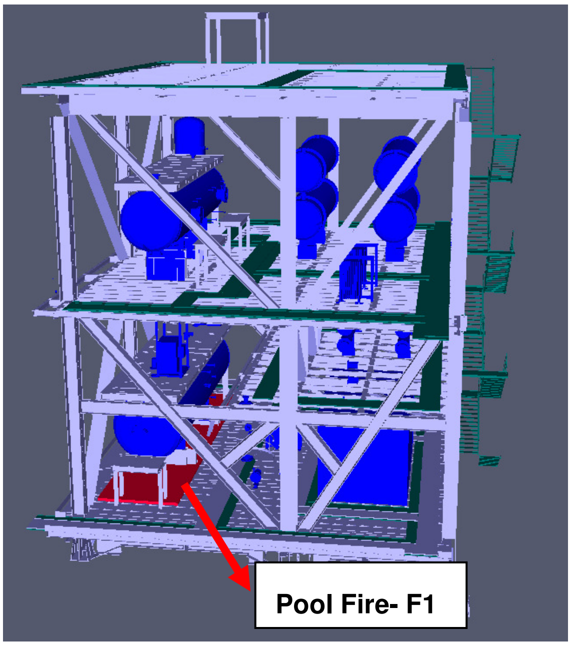


Figure 3: Location of F1 Pool Fire

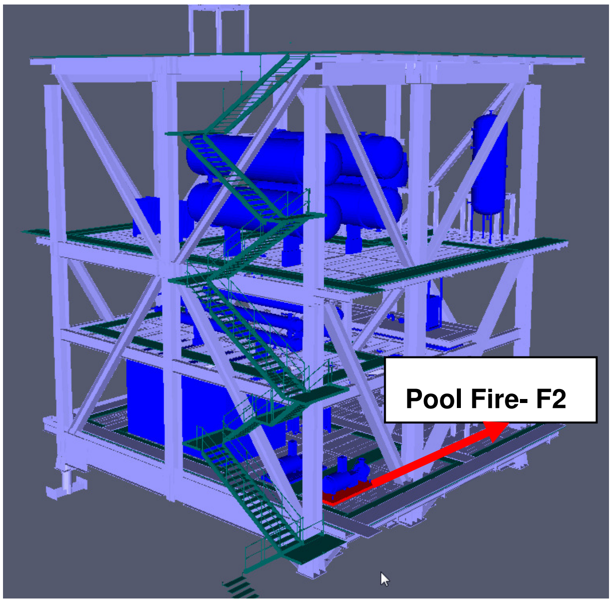


Figure 4: Location of F2 Pool Fire

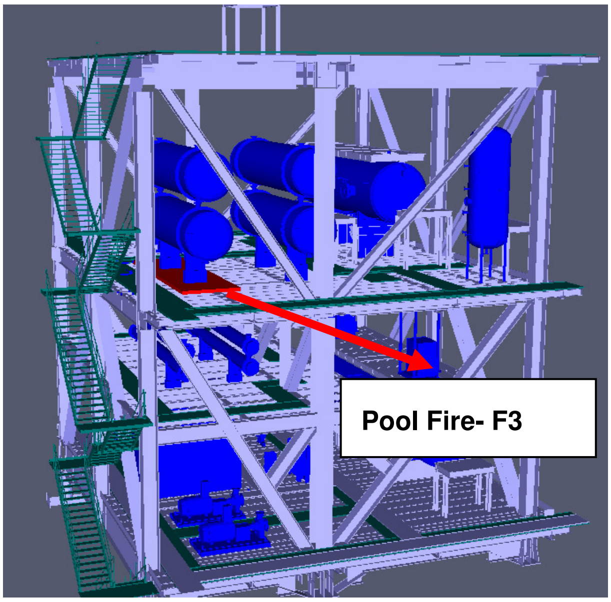


Figure 5: Location of F3 Pool Fire

It is assumed the entire liquid fraction on release can form a pool. As such, no subsequent evaporation of the pool is considered in the analysis. The pool fire in these scenarios can be categorised as a "pan fire" That is the fire of crude oil contained within the walls of drip tray.

Note that in the case of fire water deluge activation, a significant portion of the liquid inventory is diluted with firewater, but this has not been taken into account to ensure a conservative approach to the pool fire modelling.

Large-scale pool fires have been characterized in great detail for several decades. The phenomenology behind them has been qualitatively characterized and many of the specific processes described to great extent.[9] A series of well-defined parameters have been established to classify pool fires in a quantitative manner. [9].

- **Combustion Efficiency**

  In this large-scale regime (D 2-3 m), pool fires of increasing diameter exhibit decreasing values of the combustion efficiency [10] Experimental data on combustion efficiencies or smoke yields in intermediate- or large-scale pool fires are scarce in the technical literature [9] For fuels producing sooty flames such as oil, it decreases to 60 to 70 % in the condition of when sufficient Oxygen is available. So 60% is selected for the modelling.

- **Fraction of Heat Radiated**

  For pool fires, the fraction of heat release rate emitted as radiation is a function of the pool fire diameter. As per Figure 3-10.9 SFPE handbook the value of 0.2 is selected for F1 and F3 crude oil pool fires. While for F2 it increases to 0.4.

- **Soot Yield**

  Increasing the Pool fire diameter increases the values of the Soot yield [10] Soot yields have been found to increase with source diameter, reaching approximately constant values (0.15 mass fraction) at source diameters beyond 2-3m [9]. As such, the value of 0.15 is selected.

In addition, fuel, steel and ambient parameters are defined in Table 5 as input values for Fire modelling inside FDS.

Table 4: Fuel, Steel and Ambient Parameters

Crude Oil Fuel	
C= 15, H=32 , O=0	
Heat Release Rate per unit area (kW.m-2)	1153
Fraction of carbon monoxide	0.006
Thermal conductivity (W.kg-1.K-1)	0.1275
Density (kg.m-3)	845
Specific heat (kJ.kg-1 K-1)	2.37
Solid structures (STEEL)	
Thermal conductivity (W.kg-1.K-1)	45.8
Specific heat (kJ.kg-1 K-1)	0.46
Density (kg.m-3)	7850
Emissivity	0.9
Atmospheric conditions	
Wind-speed is (m.s-1)	7.5
Ambient temperature (^{o}C)	20
The relative humidity (%)	100

Results

Escape times from the weather deck to the safe area have been evaluated in accordance to the assumptions and rule-set defined in the previous section. The arrival times from the weather deck to each below deck level in the M11 module are presented in Table 6 for the first –in and the last out person. Please note that time=0 is the time of fire starting.

Table 5 : Escape Times from M11 Weather Deck

Location	**FIRST IN, (s)**	**LAST OUT (s)**
Weather Deck Exit (W)	33.5	62.4
Upper Deck Entrance (U)	77.1	107.8
Process Deck Entrance (P)	124.1	155.1

Figure 6-8 shows a still photo of a flame front produced by a pool fire F1, F2 and F3. The FDS produced slice files are integrated into the evacuation simulation in order to provide the observer with a clear animation of evacuation of people and the effects of fire on them.

To demonstrate the integrated fire and evacuation animation in this paper, given to dynamic changing of the thermal radiation and smoke concentration levels, smoke and thermal radiation contours in which the visibility due to the smoke would be less than 3m and radiation would be less than 6 kW/m2 are integrated into evacuation model and are shown in specific times when people arrive of each selected points along the escape route. The contour value of 6kW/m2 is the impairment threshold for escape ways selected per API 521 criteria and 3m visibility criteria

Table 6, summarises the Required Safe Egress Times (RSET) with Available Safe Egress Times (ASET) for each deck level.

Table 6 : RSET and ASET values for each deck level and fire scenario

Fire scenario	**RSET (S)**	**ASET (S)**
Weather Deck Exit (W)		
F1	62.4	>180
F2	62.4	>180
F3	62.4	13
Upper Deck Entrance (U)		

F1	107.8	>180
F2	107.8	>180
F3	107.8	13
Process Deck Entrance (P)		
F1	155.1	>180
F2	155.1	~80
F3	155.1	13

The snapshots of integrated fire smoke contours and evacuation model at first person and last person arrival to each deck level are presented in Figure 9, Figure 11 and Figure 13 in each fire scenario. The blue colour represents the visibility equal or higher than 3m and the time is shown on the right corner of each figure. The times are selected around the times identified in Table 5.

Figure 10 , Figure 12 and Figure 14 shows integrated thermal radiation contours into module M11 resulting from large pool fires F1, F2 and F3. The blue colour shows the thermal radiation contours of less than 6 kW/m2.

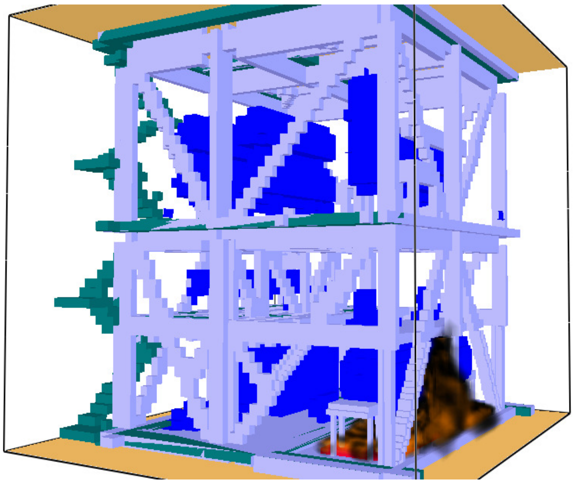


Figure 6: Still Photo of a Pool Fire F1 in FDS

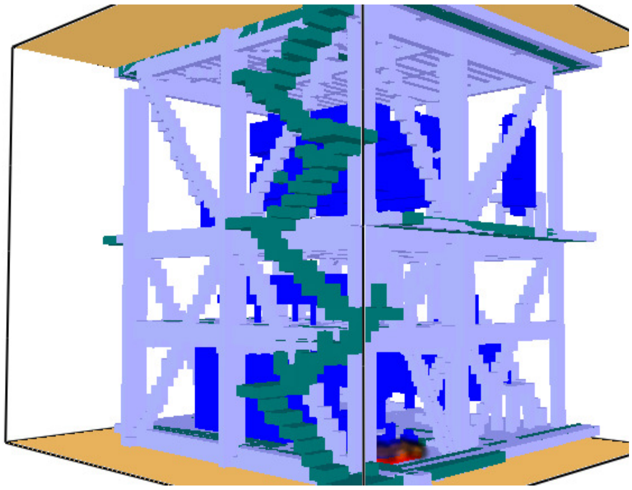


Figure 7:Still Photo of a Pool Fire F2 in FDS

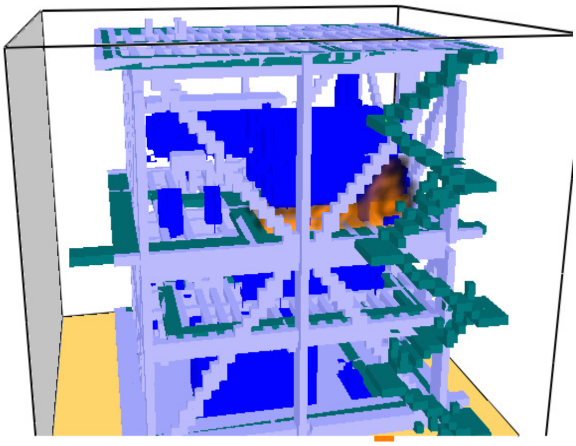


Figure 8: Still Photo of a Pool Fire F3 in FDS

Figure 9: Integrated Escape and Smoke Contours for Arrival Times to Each Deck - Fire F1

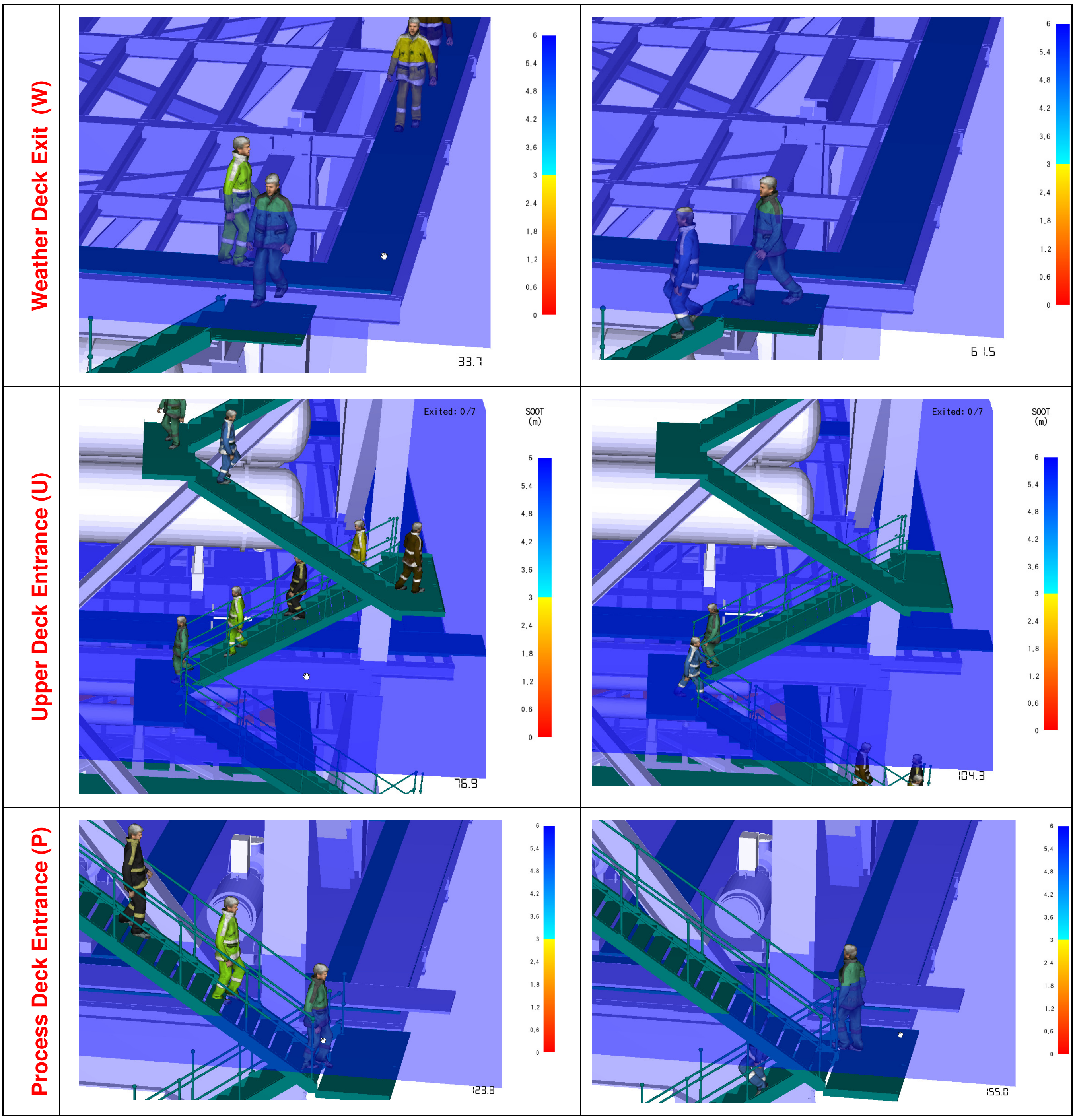


Figure 10: Integrated Escape and Thermal Contours for Arrival Times to Each Deck - Fire F1

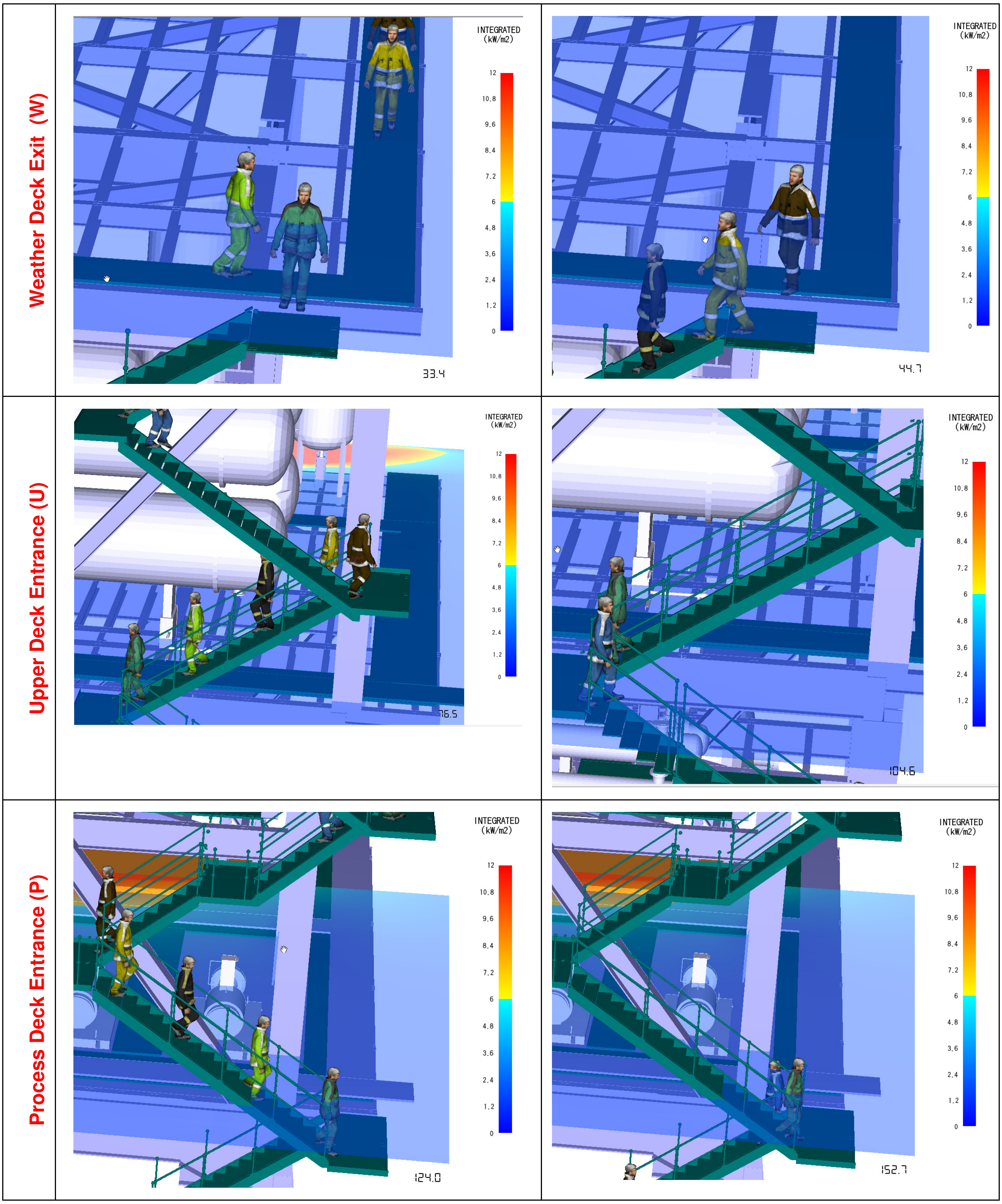


Figure 11: Integrated Escape and Smoke Contours for Arrival Times to Each Deck - Fire F2

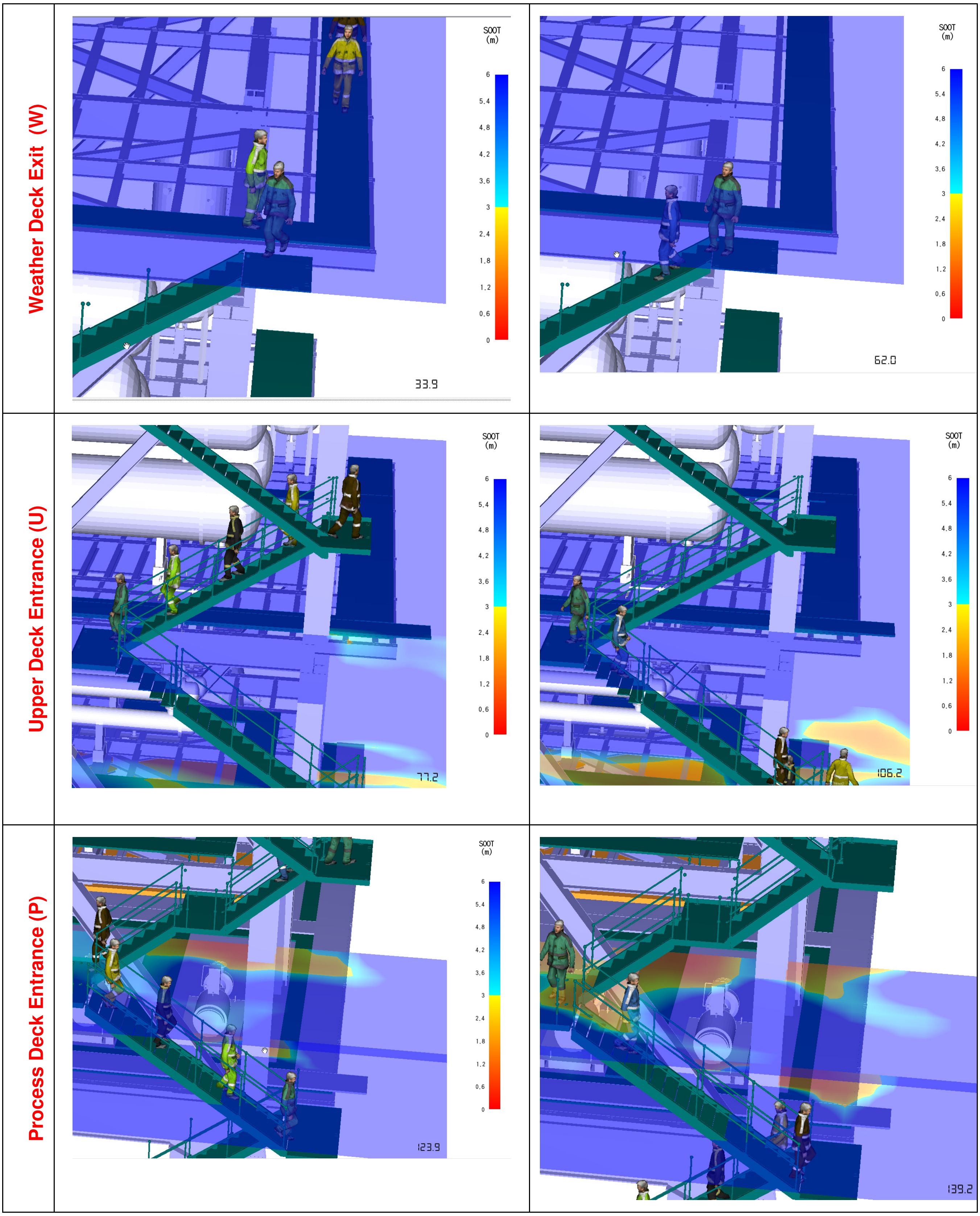


Figure 12: Integrated Escape and Thermal Contours for Arrival Times to Each Deck - Fire F2

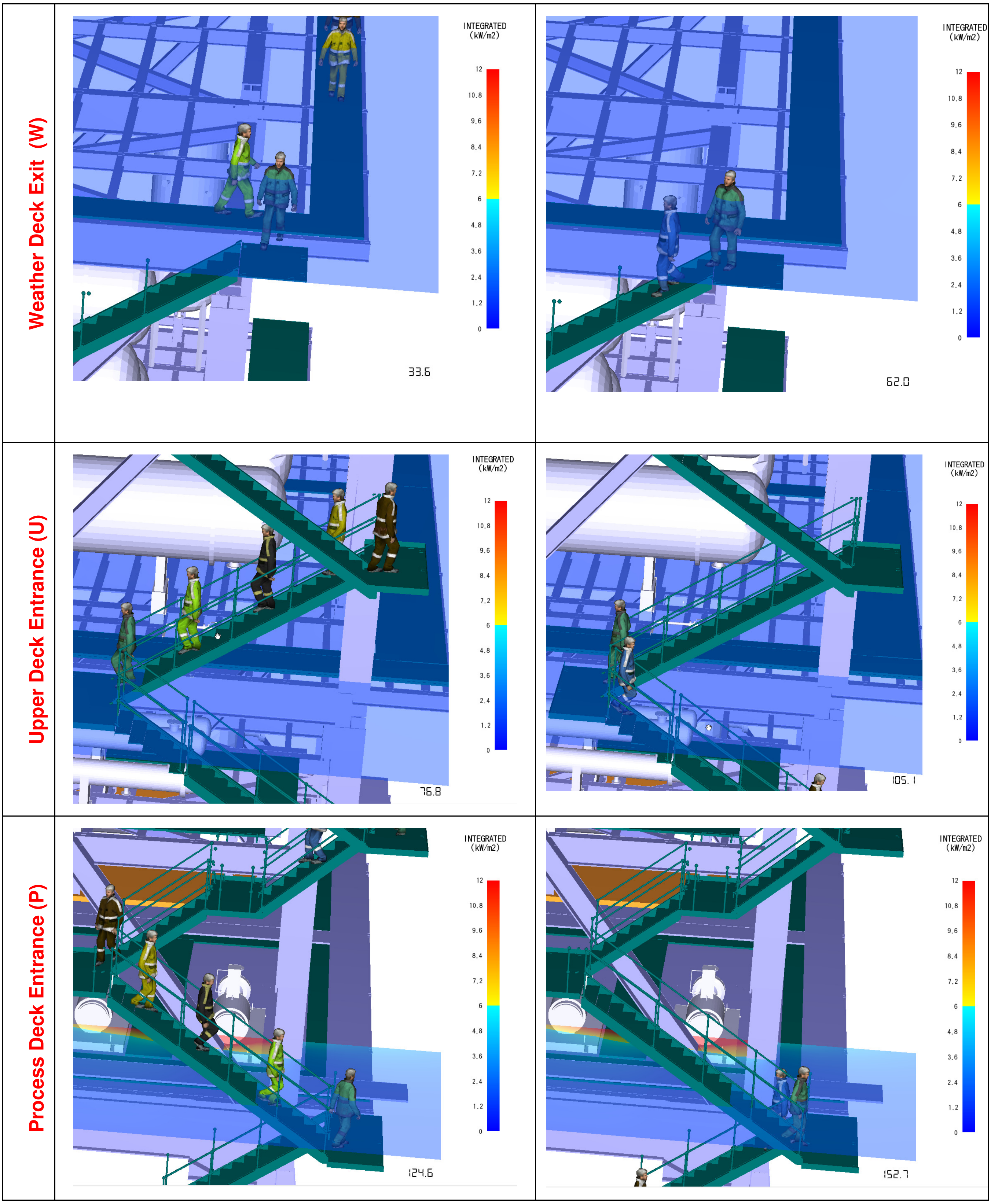


Figure 13: Integrated Escape and Smoke for Arrival Times to Each Deck - Fire F3

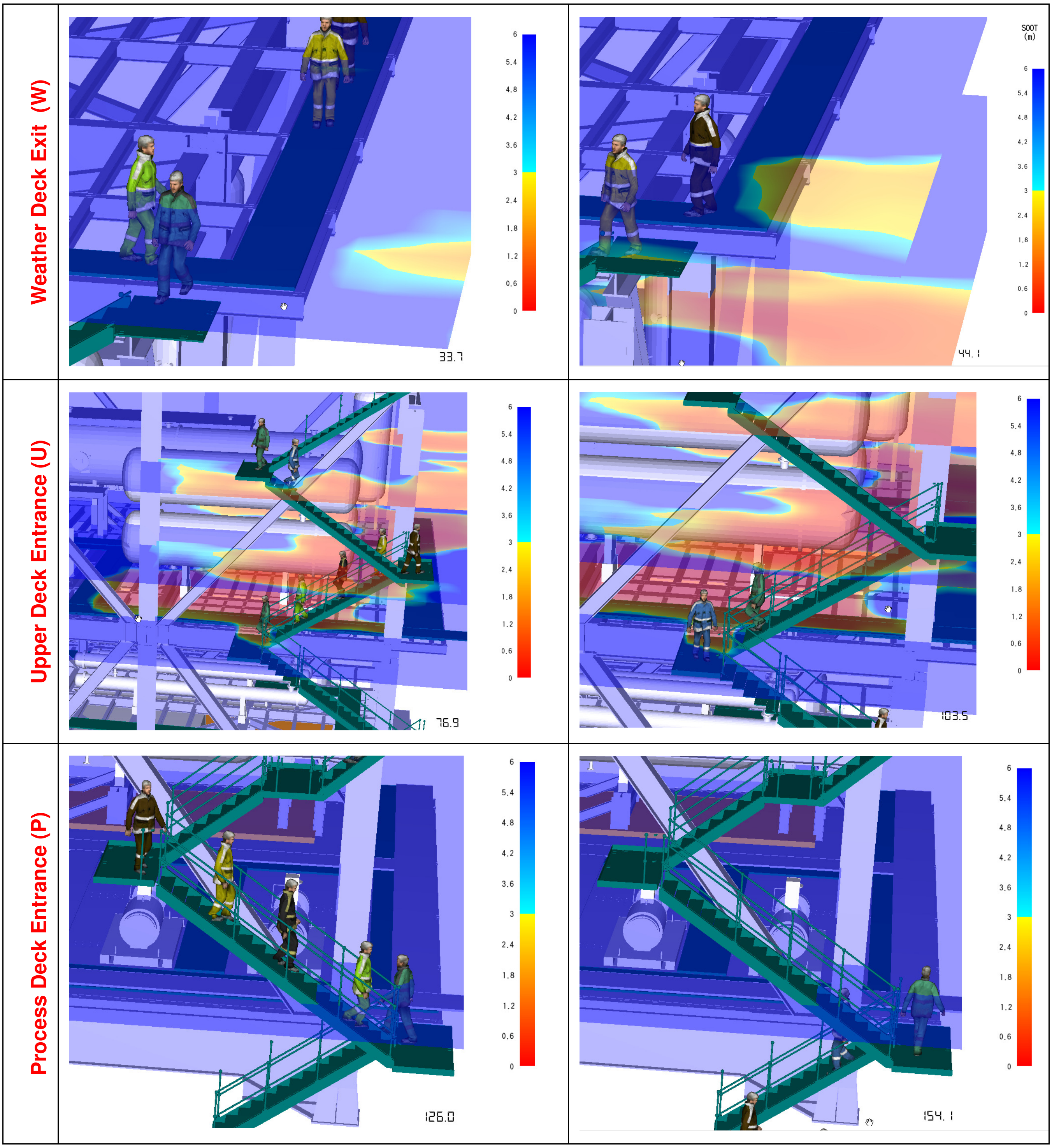
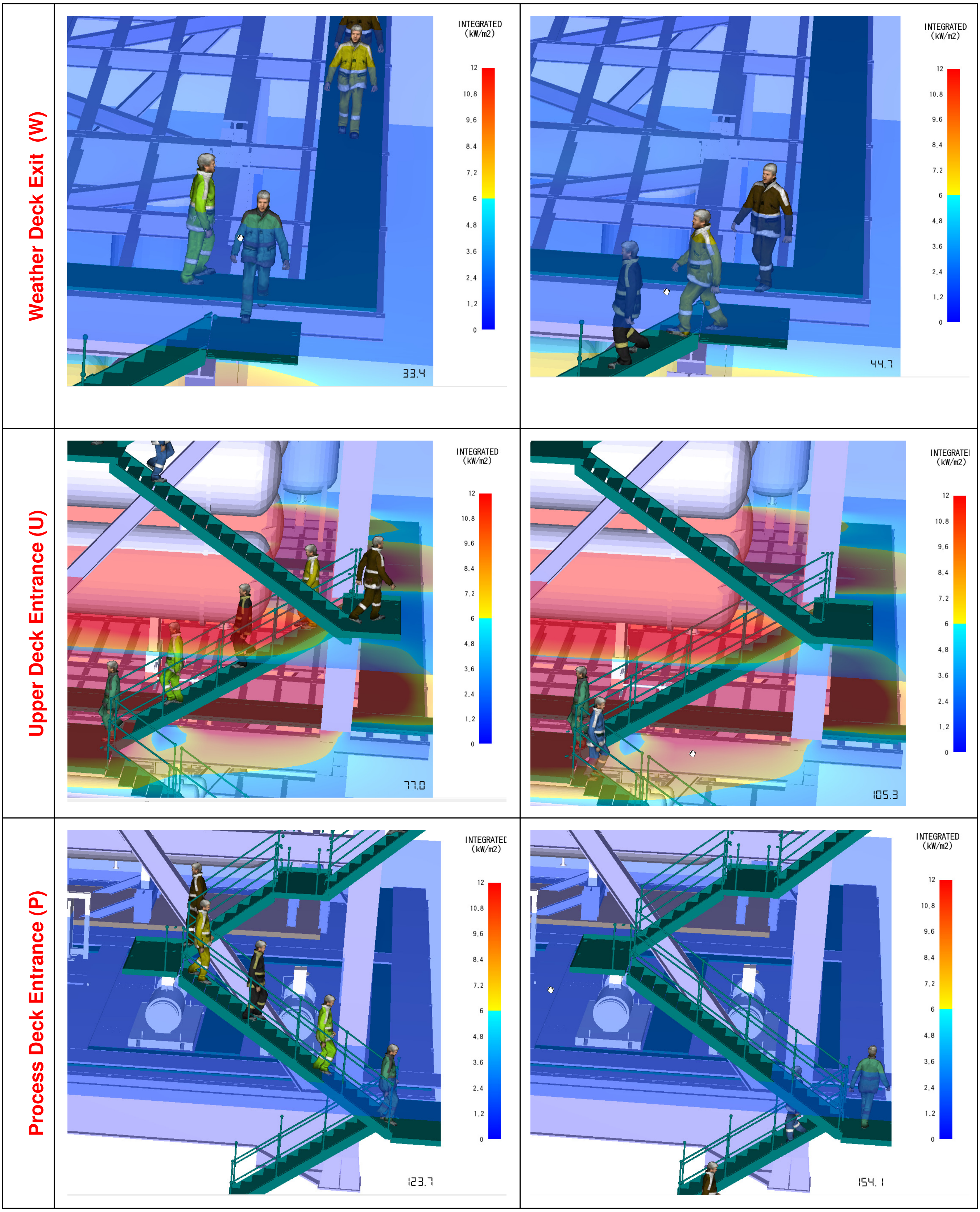


Figure 14: Integrated Escape and Thermal Contours for Arrival Times to Each Deck - Fire F3



Discussion

One of the primary advantages of integrated fire and evacuation simulations is that they are able to provide users with practical feedback when designing escape and evacuation system for offshore platforms. This allows the designer to determine the correctness and efficiency of escape ways in the design phase prior to the system being constructed. Consequently, the project stakeholders may explore the merits of alternative designs and the effect on the people evacuation in the design phase. As a case in point, per Figure 13 and Figure 14, it is easily understood that in the case of pool fire, smoke and heat radiation will reach the escape way and prevent people from exiting. Therefore, escape routes shall be connected to adjacent decks in the weather deck (M10 or M50) in case of the F3 Fire.

More, Table 6 and Figure 11 shows that a F2 Fire will impair the evacuation staircase with its smoke in the process deck level. Therefore, there should be an alternative escape route in the upper deck to allow people to evacuate to adjacent modules.

Another benefit of integrated fire and evacuation modeling is that it can be used as a means for demonstrating safe evacuation to the class or regulatory bodies in the offshore industry. This is particularly true of the integrated approach that makes intelligent use of computer graphics and animation to provide assurance to the class or regulatory expectations and performance standards. Such integrated modelling shows the behaviour of the fire and impacts of the fire on evacuating people, thereby providing the regulatory bodies with an understanding of the selected evacuation design. Such a simulator should also allow class or regulator representatives to engage in evacuation design review in the design stage of the offshore project to incorporate any early comments or feedback. This is true when integrating smoke effects on the evacuation which may stop different views and arguments for provision of escape tunnel in FPSOs. With regard to this benefit, the safe evacuation during fire F1 can be easily demonstrating by Figure 9 and Figure 10 snapshot. However, it may also be communicated through animation which is much easier to understand.

Another advantage is that while no merging flow conditions are currently reviewed in offshore oil and gas projects, the integration of fire and evacuation can better specify any merging flow conditions slowing down the evacuation toward the muster area. It could be critical for common main escape routes where personnel from different topside modules, turret and hull may arrive simultaneously. In this case, no merging flow will occur during escape from Module M11 according to each Figure 9 to 14 snapshots. However, again an animation will communicate any merging flow issues much more efficiently than still time snapshots.

Summary

This paper presents a sample case of the evacuation modelling integrated with pool fire study in an offshore environmental. For this purpose, integrating the FDS and Pathfinder softwares has been applied. The large pool fire results from FDS have been considered as input values into the Pathfinder software where the evacuation routes and durations are modelled.

As a study case, a normal evacuation scenario has been examined with the Integration of three large pool fires (F1, F2, F3) results from a FDS software in the M11 topside module of a new build FPSO. The purpose is to assess the possibility for individuals to survive a fire on escape into a safe location. Visibility and the thermal radiation emitted by the pool fire has been evaluated through FDS and applied as an input to the Pathfinder evacuation model. In this case, it is concluded that escape routes in the weather deck shall be connected to the adjacent decks. Also it was found that considering alternative escape routes for the upper deck is critical.

As a result, it is understood the integration approach has a positive impact on the review of the evacuation period in the design stage with respect to smoke and thermal impact. It also improves addressing escape and evacuation correctness and efficiency. In addition, it could be a valuable method to prove compliance with performance standard from class or regulatory bodies for offshore installations.

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