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Performance Based Risk Informed Fire Modelling Evaluation of Electrical Equipment Functionality in Nuclear Power Plants

Josip Vuković, Davor Grgić

Summary **— Introduction of risk-informed and performance-based analyses into fire protection engineering practice exists in both the general fire protection and the nuclear power plant fire protection applications. Risk-informed and performance-based approach relies on application of validated and verified fire modelling to estimate fire generated effects that are arising in predefined fire scenarios for fire protection related applications in nuclear power plant. Regulatory bodies have used risk-informed insights as a part of its regulatory decision making for the past thirty years. Before performance-based approach came out, all regulatory prescribed requirements relied on deterministic approach with ultimate condition that one complete shutdown train together with auxiliary support features is free of fire damage. Performance-based approach relies upon calculable performance results to be met but provides more flexibility in achieving established performance criteria during all phases of plant operations. Nevertheless, fire modelling is finding its benefits in design basis engineering, fire hazard analysis, nuclear safety capability assessment and probabilistic risk assessment. To demonstrate such capabilities, an example on fire development in Nuclear Power Plant Safety Related Pump Room with respect to possible loss of one safety shutdown path is modelled with a fire simulator computer tool.**

Keywords **— fire, fire model, verification, validation, nuclear, fire protection, deterministic, risk-informed, performance-based, experiment, electrical equipment**

I. Deterministic vs Performance-based Risk-informed Approach

From the regulatory perspective nuclear power plant (NPP) licensees back in late eighties were committed to evaluate their fire protection program to Branch Technical Position APCSB 9.5-1 which provided detailed fire protection guidance for the protection of safety related systems and components. Regulatory requirements were formalized with 10CFR50.48 Appendix R focused on fire protection requirements for safe-shutdown related equipment to the extent that compliance has been established with BTP APCSB 9.5-1, Appendix A.[1]

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Past Fire Hazzard Analysis were made in accordance with above mentioned regulatory legislative and is based on the use of fire area (compartment) deterministic approach. (one Safe Shutdown train free of damage) While analyzing fire effects on the plant safe shutdown capability, Safe-Shutdown Separation Analysis states that alternate shutdown train remains unaffected given the other train is unavailable due to fire.

Title 10, Section 50.48(c) of the Code of Federal Regulations (10 CFR 50.48(c)) permits existing reactor licensees to voluntarily adopt fire protection requirements contained in (NFPA) Standard 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants," 2001 Edition following a performance-based risk-informed approach as an alternative to the existing deterministic fire protection requirements. U.S. Nuclear Regulatory Commission (NRC) adopted the policy of using risk-informed methods to make regulatory decisions whenever possible. While much of the guidance provided in Regulatory Guide 1.189, "Fire Protection for Nuclear Power Plants" has been incorporated in current Fire protection programs (FPPs) of these plants and will continue to be appropriate for a risk-informed, performance-based FPP, the guidance provided in Regulatory Guide 1.205, "Risk-Informed, Performance-Based Fire Protection for Existing Light-Water Nuclear Power Plants", will take precedence over the guidance provided in RG 1.189 for plants that adopt a risk-informed, performance-based FPP in accordance with 10 CFR 50.48(c).[2]

Based on above mentioned utility should assess and understand the challenges that need to be addressed to realize the full benefit of fire modelling and performance-based fire protection considering the purpose. Among the licensing commitment, the purpose is prioritizing maintenance, testing, and inspection activities of fire protection equipment. Transitioning to a performance-based program should be achievable and cost-effective especially for operational nuclear power plants. One important element in a performance-based approach is the estimation of fire hazard using mathematical fire models. Fire modelling is often used in constructing fire PRAs to determine the effects of fire hazard so that the associated risk can be quantified.[3]

The fire models discussed in this paper are classified as deterministic to distinguish them from stochastic models. In essence, this means that each model takes as input a set of values, known as input parameters, that describe a specific fire scenario, and the model's algorithms then calculate the fire conditions within the compartment. The output of the models usually takes the form of time histories of the various predicted quantities of interest, such as temperature, heat flux or smoke concentration. In a sense, the

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model calculation is a virtual experiment because the design of a model simulation often involves the same thought process as the design of a physical experiment.[4]

The results of the calculation are likewise expressed in terms similar to those of an experiment, including an estimate of the uncertainty. The sources of uncertainty in a model prediction are different than those in an experimental measurement. While analyzing the fire modeling uncertainties, there are practically three types of uncertainty that we have to deal with [4]:

- Parameter Uncertainty - the contribution of the uncertainty as seen from the input parameters to the total uncertainty of the simulation
- Model Uncertainty - effect of the model assumptions, simplified physics, numeric, etc.
- Completeness Uncertainty - physics that are left out of the model that can be seen as a form of Model Uncertainty.

II. Fire Phenomena

There are many aspects of fire behavior that are of interest when applying fire models, depending on the purpose of the modeling application. One could also model Main Control Room fire, Cable Spreading Room fire, Switchgear Room Cabinet fire, etc. User can seek to determine the effects associated with heating of targets submerged in smoke or receiving radiant heat from the flames, the response of ceiling-mounted detectors or sprinklers to the fire environment, or other phenomena. Main aspects of interest are:

- Smoke production rate;
- Smoke filling rate;
- Ceiling jet properties;
- Hot Gas Layer (HGL) properties;
- Target response.

In modeled fire scenario output thermal response properties are governed and impacted by:

a) Heat Release Rate (HRR): HRR is function of time termed as a "design or source fire" if object is assumed to ignite and burn at known rate as per (1). Most important factors that are controlling HRR are fuel characteristics, ignition scenarios and enclosure effects.[5]

$$\dot{Q} = \dot{m}''A\Delta H_c \tag{1}$$

$\dot{Q}$ heat release rate in kW

$\dot{m}''$ mass loss rate per unit area in g/$m^2\,s$

A area of fuel that is burning in m^2

ΔH_c heat of combustion in kJ/kg

b) Hot Gas Layer Temperature: As smoke and heat are transported to the HGL via the smoke and fire plumes, the properties of the HGL will change. The HGL that forms in compartment fires descends within the opening until a quasi-steady balance is struck between the rate of mass inflow to the layer and the rate of mass outflow from the layer. [5] Temperature can be seen as a function of the amount of energy from fire that is carried along the plume as per (2).

$$T_g - T_\infty = 6.85\left(\frac{Q^2}{A_0\sqrt{H_0}h_k A_T}\right)^{\frac{1}{3}} \tag{2}$$

A_0 area of the opening in m^2

H_0 height od the opening in m

$h_k = k/\delta_w$ heat transfer coefficient in kW/m^2/K

A_T total compartment surface area

T_g hot gas layer temperature

T_∞ ambient temperature

c) Heat flux: Radiative heat flux can be divided in radiative emmison form fire which is directly related to HRR and radiative emmision from hot upper layer of fire. The calculation by computational fluid dynamics (CFD) software of the convective heat flux in her discused model depends on whether one is performing a direct numerical simulation (DNS) or a large eddy simulation (LES). LES is utilized to model the unresolvable or "subgrid" motion of the hot gases. The effectiveness of the technique is largely a function of the ratio of the fire's characteristic diameter, D*, to the size of a grid cell, δx.[8]

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(k_s \frac{\partial T_s}{\partial x}\right) + \dot{q}_s''' \tag{3}$$

k_s thermal conductivity of the gas

$\rho_s c_s$ volumetric heat capacity of the solid

T_s solid phase temperature

$\dot{q}_s'''$ heat flux source term

Heat conduction equation for the solid phase temperature is shown in (3). Heat flux parameter is further on used to predict local conditions at the specific location of the target surfaces (i.e. walls and cables). Governing material property for ignition is kρc while k, ρ, and c denote, respectively, the thermal conductivity, density, and specific heat of the solid. These thermal properties may be functions of temperature. Following table TABLE I. gives information of mostly used solid materials in FDS calculations.[6]

Table I.
Thermal Properties of Compartment Enclosing Surface Materials (Klote and Milke, 2002, ASHARE)

Materials	Thermal Inertia kρc (kW/m^2-K)^2-sec	Thermal Conductivity k (kW/m-K)	Thermal Capacity c (kJ/kg-K)	Density ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.0895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1.0	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20

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Convective heat transfer that is heat flux at the surface as per (4) is determined via an empirical heat transfer coefficient, h, and the convective heat flux at the boundary:[5]

$$k\frac{T_g - T_w}{\delta x/2} = h\left(T_g - T_w\right) \quad (4)$$

k	thermal conductivity
$\delta x/2$	distance between the surface and center of the adjacent gas phase cell
T_g	hot gas layer temperature
T_w	surface temperature

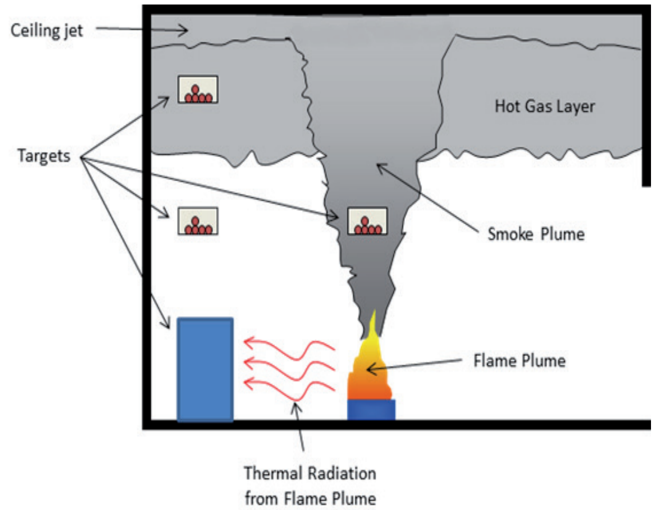

Fig. 1. Characteristics of compartment fires

III. Fire Scenario Objective

A fire scenario is a set complete set of elements representing a fire event:

- The ignition source, e.g., electrical cabinets, pumps;
- Intervening combustibles, e.g., cables;
- Damage targets (e.g., power, instrumentation or control cables) whose fire-induced failure may cause an initiating event and/or failure of mitigating equipment;
- Fire protection features (detection and suppression) that could mitigate fire damage, e.g., automatic sprinklers;
- The compartment where the fire is located and its characteristics;
- An event timeline.

Fire Induced Circuit Failure (power cable) modeling in this paper is an outcome of fire development in Safety Related Pump Room with postulated loss of one safety shutdown path. Fire scenario is modeled with the lubricating oil as ignition source normally used for motor/pump rotating parts lubrication. Generated fire creates fire plume and smoke develops creating heat effect that affects room atmosphere as shown on Fig 1. The goal is to assess the possible fire damage on power cable feeding the medium voltage motor driving the safety related pump used for emergency core cooling safety function. Fire scenario objectives are to collect cable surface temperature-time distribution during the fire accident.

Safety Related Pump Room is mechanically ventilated with air handling unit suppling fresh air in the atmosphere of the room when the corresponding emergency core cooling pump is in operation. There is other combustible equipment in the room, i.e. motor operated valves actuators, electrical boxes with corresponding cabling, rubber ventilation duct flanges, air filters and lightning that can be affected by fire.

There is no automatic actuated fire protection equipment in the room utilized for fire detection and suppression. Smoke detectors, fire resistant doors, equipment with fire resistant properties and fire-retardant cables are utilized together with available fire brigade and hand fire extinguishers.

Power voltage cables have flame retardant coating that protects the cable from fire propagation. Such testing is shown on Fig 2. Cable coating itself can burn but the cable should keep structural geometry in greater manner. Nevertheless, it is possible that the cable insulation could suffer from breakdown or insulating characteristics could be deteriorated with short circuit faults to ground causing the motor to trip utilizing protection relays.

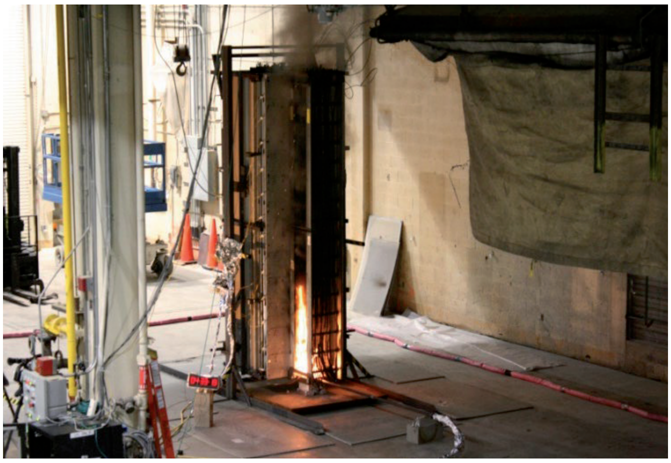

Fig. 2. Vertical cable fire spreading testing

Regarding cable separation which is of most importance in fire protection program looking from the electrical functionality view, the areas through which Class 1E and associated circuits cables are routed and in which equipment is located should be reviewed to identify the existence of potential hazards such as high energy piping, missiles, combustible material, ignition sources, and flooding. Electrical cubicle testing is utilized to asses cable separation as shown in Fig 3. These areas shall be classified as follows:

a) Nonhazard areas
b) Limited-hazard areas
c) Hazard areas

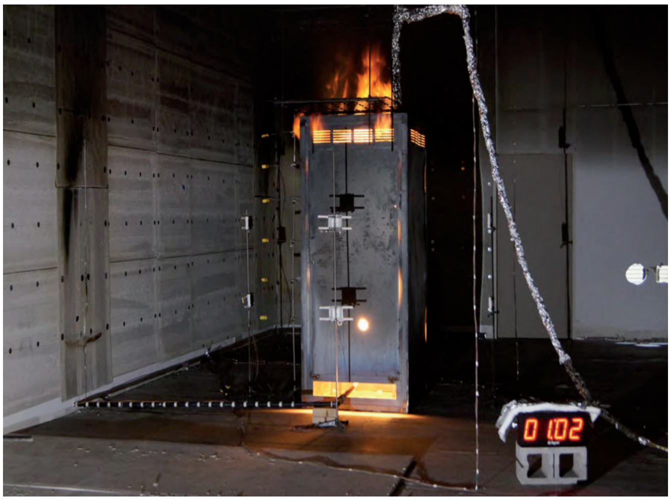

Figure 3: Electrical cubicle fire testing experiment

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Separation commensurate with the damage potential of the hazard shall be provided for early in the design through the use of features such as separate rooms, barriers, etc. Opposite sides of rooms or areas may be used provided that there is an adequate heat removal capability.

Table II.
Damage Criteria for Electrical Cables[7]

Cable type	Radiant Heating Criteria	Temperature Criteria
Thermoplastic	$6kW/m^2$	205°C
Thermoset	$11kW/m^2$	330°C

IV. Fire Modeling Tool

CFD models are sophisticated algorithms that solve a simplified version of the Navier-Stokes equations. To run CFD codes, the enclosure must be divided into a large number of control volumes, and the equations solved for each control volume. CFD models then provide a detailed estimate of temperature profiles because calculations are performed for each control volume specified in the enclosure. CFD models also handle turbulent gas flows. Another advantage of CFD models is their ability to simulate fire conditions in geometries other than rectangular floor compartments with flat ceilings. Some CFD models also attempt to estimate HRR values based on fuel flammability properties provided by the analyst. The drawback of CFD models is the computational time and the level of effort required to set up a scenario, even though modern processing options have made a huge step regarding this matter. The time required to set up a problem usually depends on the complexity of the geometry.

Another consideration when selecting a CFD-type model is that the amount of detail supplied to the model is significantly greater than it is for the simpler empirical and zone models. Given the large amount of information required for input, there is an intrinsically higher likelihood of errors being introduced into the input, which is different from the model uncertainty and parameter uncertainty as it will explained in the paper. Furthermore, the features that may be described in the input could include ductwork, cable trays, electrical cabinets, and other fixed contents that may later be modified, relocated, or removed. New cabinets, cable trays, or other fixed contents that would have been included in the fire model had they been present may be added to an area. Fig 4 shows example of a modeled cubicle geometry by FDS. Although these changes may be minor, at the very least they would require an assessment by a fire modeler as to whether the original analysis is still applicable or whether the model needs to be adapted for the change. In some situations, such as the determination of a sprinkler actuation time, such small modifications could have a significant effect on the model results.[4]

Fire Dynamics Simulator (FDS) is a CFD software tool used in fire protection engineering for modeling fire transients, smoke development and heat transport. As explained above this software solves conservation equations of mass, momentum and energy (a form of the Navier-Stokes equations) for an expandable mixture of ideal gases for low speed flow. A mixture fraction model is used for most of the fire modeling applications which practically means that combustion is controlled by the rate at which fuel and oxygen mix with in most cases instantaneous reaction. Radiative heat transfer is included via the solution of radiation equation for non-scattering gray gas, and in some cases using a wide band model.[8]

FDS provide us ability to simulate fire conditions in complex geometries and with complex ventilation conditions. Application of fire models in NPP fire scenarios requires a good understanding of their limitations and predictive capabilities of the tool used for fire modeling calculations. Such application and the methodology for utilization is guided by the process in which the user has to [6] [9]:

- Define fire modeling goals and objectives;
- Characterize fire scenarios;
- Select verified and validated fire models;
- Calculate fire-generated conditions;
- Conduct sensitivity and uncertainty analyses;
- Document the results.

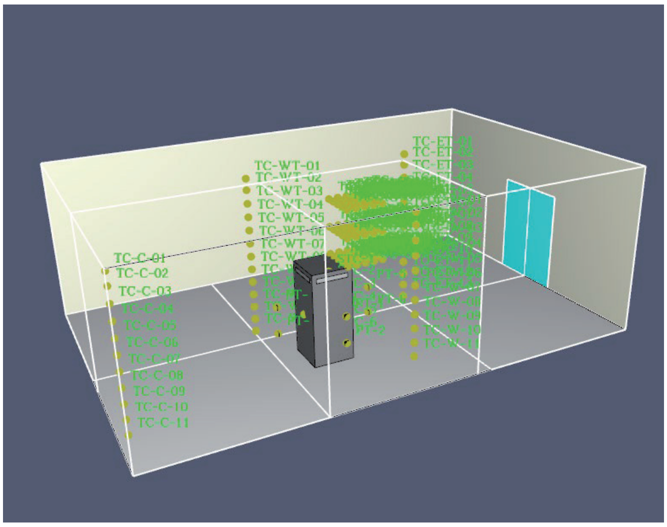

Fig. 4. FDS model of electrical cubicle

FDS calculation is performed inside volumes that is meshes, each mesh is divided in rectangular cells. User choses resolution of flow dynamics setting the number of uniform cells by defining and inputting mesh dimensions. Computing of temperature, density, pressure, velocity and chemical composition happens within each numerical grid cell at each discrete time step. The grid size is the most important numerical parameter in the model, as it dictates the spatial and temporal accuracy of the discretized partial differential equations.[6]

- FDS outputs following main quantities:
- Gas temperature
- Gas velocity
- Gas species concentration
- Smoke concentration
- Pressure
- Heat release rate
- Mixture fraction
- Gas density
- Water droplet mass
- Surface and interior temperature
- Heat flux
- Burning rate
- Sprinkler and detector activation times
- Mass and energy fluxes

Above all, heat release rate (HRR) is the source term in the energy equation solved by FDS. That is because FDS was originally designed for fire scenarios where heat release rate of the fire

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is specified while heat transport and smoke development that is fire growth and spread are simulated by fire scenario.

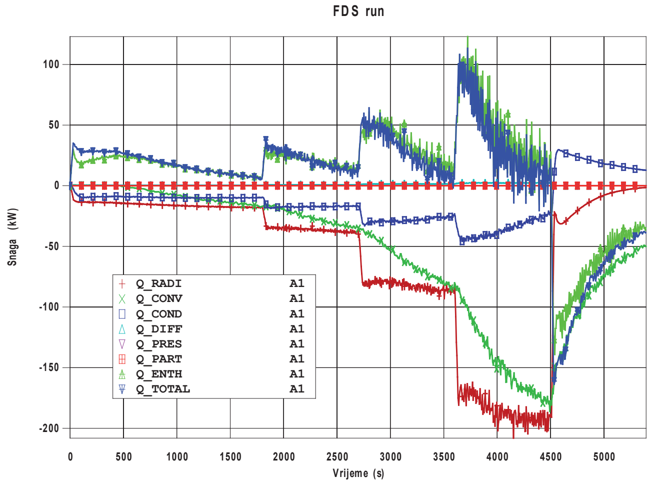

Fig.5. Heat balances from the control FDS run

Fig 5 displays example of total heat balance for the given heat release rate and different integral heat balances that can be calculated or determined by FDS. HRR is above all the most important parameter controlling the temperature of HGL and cable temperature.

Following that uncertainty of the model is higher for predicted versus prescribed fire scenarios. Main reasons for that are:

- Real material properties and real fuel are sometimes difficult to obtain:
- Physical processes of combustion, radiation, and solid phase heat transfer are more complicated than their mathematical representations in FDS;
- Calculation results are sensitive to both numerical and physical parameters.
-

A target is an object of interest that can be affected by the fire-generated conditions and typically consists of cables in conduits, cables in raceways, or plant equipment. Targets are characterized by their location, damage criteria, and thermophysical properties. Property data which are characterized with thermophysical properties, like the thermal conductivity, density, heat of vaporization, heat capacity, etc., ought to be assessed in terms of their influence on the heat release rate. User should always check that the material property values are appropriate for their specific application, as the resulting fire conditions may be sensitive to these parameters.[4]

The model evaluation process consists of two main components: verification and validation. Verification is a process to check the correctness of the solution of the governing equations. Verification does not imply that the governing equations are appropriate; only that the equations are being solved correctly. Validation is a process to determine the appropriateness of the governing equations as a mathematical model of the physical phenomena of interest. Typically, validation involves comparing model results with experimental measurement. Verification and validation of chosen fire modeling tool ensure the correctness, suitability, and overall quality of the method.

Table 2.
Summary of Selected Normalized Parameters for Application of the Validation Results to NPP Fire Scenarios (NUREG-1824/EPRI 1011999, 2007).[6]

Quantity	Normalized Parameter	General Guidance	NUREG-1824 Validation Range
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^2 \sqrt{gD}}$	Ratio of characteristic velocities. A typical accidental fire has a Froude number of order 1. Momentum-driven fire plumes, like jet flares, have relatively high values. Buoyancy-driven fire plumes have relatively low values.	0.4 – 2.4
Flame Length Ratio	$\frac{H_f + L_f}{H_c}$ $\frac{L_f}{D} = 3.7\,\dot{Q}^{*2/5} - 1.02$	A convenient parameter for expressing the "size" of the fire relative to the height of the compartment. A value of 1 means that the flames reach the ceiling.	0.2 – 1.0
Ceiling Jet Distance Ratio	$\frac{r_{cj}}{H_c - H_f}$	Ceiling jet temperature and velocity correlations use this ratio to express the horizontal distance from target to plume.	1.2 – 1.7
Equivalence Ratio	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2} \dot{m}_{O_2}}$ $\dot{m}_{O_2} = \begin{cases} 0.23 \times \frac{1}{2} A_0 \sqrt{H_0} \text{ (Natural)} \\ 0.23\, \rho_\infty \dot{V} \text{ (Mechanical)} \end{cases}$	The equivalence ratio relates the energy release rate of the fire to the energy release that can be supported by the mass flow rate of oxygen into the compartment, $\dot{m}_{O_2}$. The fire is considered over- or under-ventilated based on whether φ is less than or greater than 1, respectively.	0.04 – 0.6
Compartment Aspect Ratio	L/H_c or W/H_c	This parameter indicates the general shape of the compartment.	0.6 – 5.7
Radial Distance Ratio	$\frac{r}{D}$	This ratio is the relative distance from a target to the fire. It is important when calculating the radiative heat flux.	2.2 – 5.7

Model verification consists of a broader range of activities, from checking the computer program itself to comparing calculations to analytical (exact) solutions to considering the sensitivity of the dozens of numerical parameters. In some cases, once a model is well-established and validated it may actually be used as a form of verification.[10]

Validation studies have shown that FDS predicts well the transport of heat and smoke when the HRR is prescribed. In such cases, minor changes in the properties of bounding surfaces do not have a significant impact on the results. However, when the HRR is not prescribed, but rather predicted by the model using the thermophysical properties of the fuels, the model output is sensitive to even minor changes in these properties.[11]

00identifies normalized parameters that are used to compare NPP fire scenarios with validation experiments. The validation range for the normalized parameters shown in 0were derived from NUREG- 1824 (EPRI 1011999), are intended to provide guidance on which groups of validation experiments to consider when evaluating a certain attribute based on the validation results. These parameters may not be the only ones appropriate for evaluating the applicability of a specific experiment; 0also lists the ranges of values for different physical characteristics and normalized parameters based on the experiments considered in the validation study.

The user could calculate the normalized parameters that are relevant to the fire scenario being evaluated. If the parameters fall within the ranges evaluated as in 0, then the results of this study offer appropriate validation for the scenario. If they fall outside the range, then a validation determination cannot be made based on the results in this study. For any given fire scenario, more than one normalized parameter may be necessary for determining applicability of the validation results.[6]

A. *Smokeview - A Tool for Visualizing Fire Dynamics Simulation Data*

Output field data are visualized by post solver application named SmokeView, a software tool specifically designed to analyze data generated by FDS to show simulation results in order to visualize numerical calculations generated by fire models such as the FDS. SmokeView is able to perform visualization by animating particle flow, contour slices of computed gas variables and surface data plus vector plots of static data at the fixed time.

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SmokeView visualizes smoke and other attributes of the fire using traditional scientific methods such as displaying tracer particle flow, 2D or 3D shaded contours of gas flow data such as temperature and flow vectors showing flow direction and magnitude. Smokeview also visualizes fire attributes realistically so that one can experience the fire. This is done by displaying a series of partially transparent planes where the transparencies in each plane (at each grid node) are determined from soot densities computed by FDS.

FDS and Smokeview are primarily used to model and visualize time-varying fire phenomena. FDS and Smokeview are not limited to fire simulation, however. Smokeview also visualizes static data at particular times again using 2D or 3D contours of data such as temperature and flow vectors showing flow direction and magnitude.

Smokeview is used before, during and after model runs. Smokeview is used in a post-processing step to visualize FDS data after a calculation has been completed. Smokeview may also be used during a calculation to monitor a simulation's progress and before a calculation to setup FDS input files more quickly.[12]

V. Large Lubricating Oil Leakage Fire in a Fire Compartment

Various scenarios can be modeled. This scenario is propagating in relatively simple geometry. Lubricating oil is a mixture of various hydrocarbons, mostly alkanes with formula C_nH_{2n+2}. Fire compartment contains one door and one ventilation duct with one supply and one discharge, mechanical ventilation is to be modeled. Physics inside the compartment is practically the same as every fire inside a control volume.

Large lubricating oil fire (this source fire is the forcing function for the fire scenario) is postulated by oil leakage in Safety Related Pump Room and modeled to display the fire propagation and influence on thermal response of power cable and possible cable failure, that is to determine if the Room could keep the safety function. Fire compartment may also include secondary combustibles, overhead raceways, cable air-drops, stored materials, electrical panels, construction materials, etc. Such compartment modeled by FDS is shown on Fig 6.

Fire development in compartments is often divided into phases depending on the dominant processes at any given stage of development. Ignition is dictated by the characteristics of the fuel item being ignited (i.e., ignition temperature, geometry, orientation, and thermophysical properties) and the strength of the ignition source.

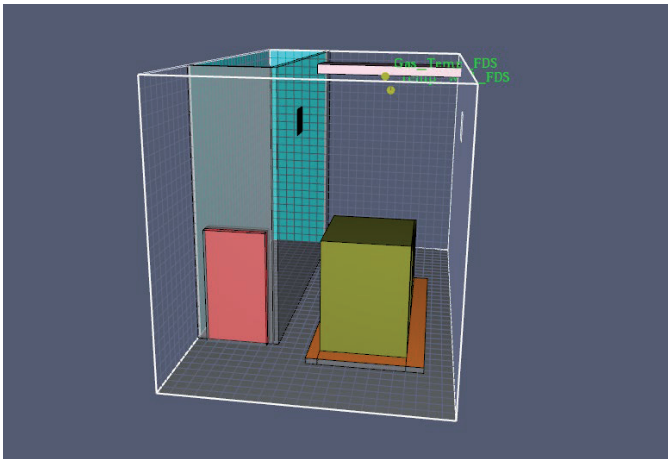

Figure 6: FDS modeled Safety Pump Room with pump-motor set

Once the flames are sustained on a burning fuel item, a smoke plume develops, transporting mass and heat vertically as a result of the buoyancy of the smoke. The plume will entrain air as it rises, thereby causing the smoke to cool and become diluted; as a result, the quantity of smoke being transported will increase with increasing elevation. After a smoke plume strikes the ceiling, the smoke travels horizontally under the ceiling in a relatively thin layer, referred to as a ceiling jet. As the ceiling jet travels, the smoke cools with increasing distance from the plume impingement point, in part because of air entrainment into the ceiling jet as well as heat losses from the ceiling jet to the solid ceiling boundary. In an ideal situation, once the ceiling jet reaches the enclosing walls, a HGL develops. As a result of the continuing supply of smoke mass and heat via the plume, the HGL becomes deeper, and its temperature increases. Other properties of the smoke in the HGL also increase (including concentration of gas species and solid particulates). Radiant heat from the HGL to other combustibles not involved in the fire increases their temperature. Similarly, the temperature of non-burning combustibles will also increase as a result of thermal radiation from the burning item(s). As the other combustibles reach their respective ignition temperatures, they will also ignite. In some cases, the ignition of many other combustibles in the space caused by heating from the HGL occurs within a very short time span. This is commonly referred to as flashover.[4]

Affected targets of interest in this scenario were also the walls and ceiling of the enclosure, which are fire barriers, as well as other safety-related equipment but primarily cables located in the room. These target cables shall be exposed to direct flame impingement or flame radiation or plume, ceiling jet, and hot gas layer conditions.

The walls, ceiling, and floor are all constructed of concrete. The single cable tray in this compartment is filled with PE/PVC cables with copper conductors. Damage criterion is taken to be the point at which the cable temperature reaches 205 °C as shown in 0. The protected cable tray is modeled as a rectangular box with the same dimensions as the tray. A cable target is positioned within the box pointing downwards, as this is the hottest surface of the box. What matters is that the cable within the box is exposed to the heat that penetrates the thermal blanket. The cable tray is protected by an electrical raceway fire barrier system (ERFBS), which is two layers of ceramic fiber insulation blankets, covered by 0.0254 mm foil. ERFBS has undergone a fire endurance furnace test in which the average temperature of the electrical raceway was maintained below 121 °C and the maximum temperature below 163 °C for an hour when exposed to the standard ASTM E 119 temperature curve. The ERFBS protected cable raceway is modeled with three layers: ceramic fiber blanket (5 cm), PE/PVC (4.4 mm), and copper (3.1 mm).[4]

There is one supply and one return air vent, each with an area of 0.25 m2, providing a volume flow rate of 0.25 m3/s. The pump compartment has one door; it is 1.1 m wide and 2.1 m tall. The door is normally closed, but it is opened 10 min after ignition by the fire brigade. The pump is surrounded by a dike designed to contain any lubricating oil that may leak or spill, with a maximum capacity of 190L. For the purpose of modeling, the fuel is specified to be $C_{14}H_{30}$.

VI: Results Summary

The fire occurs following an accidental release of pump oil and ignition of oil that leaked into the dike area. Fig 7 shows the conditions inside the modeled compartment at the start of the accident. Due to the limited amount of validation data available for scenarios of this type and the considerable uncertainties involved, the approach taken is to specify, rather than attempt to predict, the burning rate of the fuel, even though the FDS model does provide

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the physical mechanisms to estimate burning rates. The primary advantage of a CFD model for this fire scenario is that FDS modeling include combustion algorithms that estimate near- and post-flashover conditions.

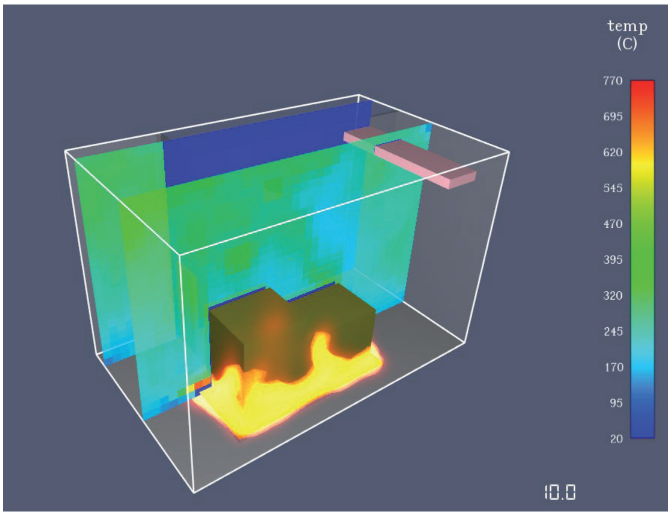

Fig. 7. Flame volume and temperature in control plane at t=10s

At the start of the scenario, the mechanical ventilation is operational, the door is closed, and the fire output immediately jumps to the peak heat release rate (HRR). Calculated peak HRR is 4,934kW (1). With specified burning rate, 0.039 kg/m^2m^2/s, is applied directly to the model over an area of 2.75 m^2m^2 yielding a burning rate of 0.107 kg/s. The density of the oil is 0.76 kg/L, which means that the oil burns at a rate of 0.141 L/s. At this rate, 190 L will require 1,348 s to burn out. The fire duration computation for FDS converts the mass data to volumetric data, thus introducing an additional step and some rounding.[4]

Predicted cable temperature from FDS, including an assessment of the model uncertainty is 145°C. The result is based only on a direct calculation of cable temperature. Critical value of cable temperature is not exceeded.

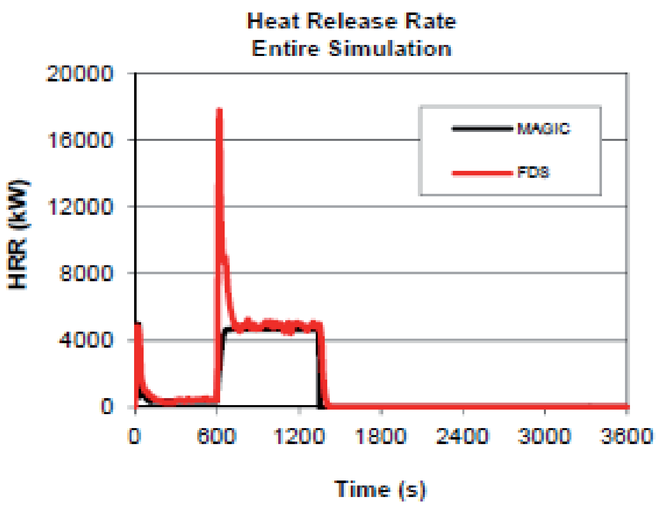

Fig. 8. HRR predicted by FDS – entire simulation

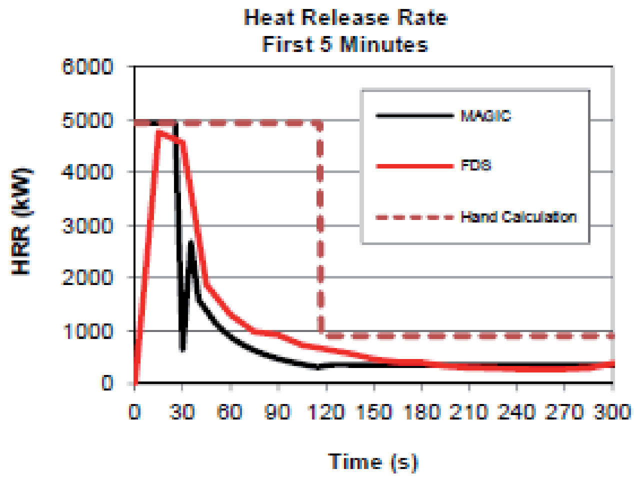

Fig. 9. HRR predicted by FDS – start of simulation

As can be seen from HRR curves (Fig 9&10) FDS models pronounced drop in the HRR soon after the start of fire, which shows that there is insufficient oxygen in the room to sustain the fire. At high temperatures, FDS expects all of the oxygen is consumed. The sudden jump in the HRR, predicted by FDS at 600 seconds, is caused by the unburned fuel igniting as the door is opened. The model indicates that the HRR decreases from about 4900 kW to about 350 kW in approximately 2 min. When the oxygen is insufficient to maintain the fire, FDS also continues to vaporize the unburned fuel, and it continues to transport the fuel gas until the door is opened after 10 min, at which time this excess fuel mixes with incoming air and burns. This rapid burning of built-up excess fuel gas in an under-ventilated compartment is known as a "backdraft," and it is apparent from the HRR curve in Fig 8. However, much of the heat from this rapid burning of fuel is immediately exhausted from the compartment and does not significantly affect the temperature of the ERFBS.

To predict cable damage due to temperature and incident heat flux, FDS estimates the temperature of the HGL as a function of time, as shown in Fig 10. As expected, the HGL temperature changes in accordance with the as above described (oxygen-starved) HRR. Once the door opens at 600 seconds, the increased HRR causes the HGL temperature to rapidly increase until the fire consumes the available fuel. After the fire burns out, the HGL temperature slowly drops as heat leaves the HGL through the bounding surfaces and open door. FDS has heat conduction algorithms to account for the multiple layers of insulation and cable materials, further on ERFBS has a large impact on the temperature of the target cable.[4]

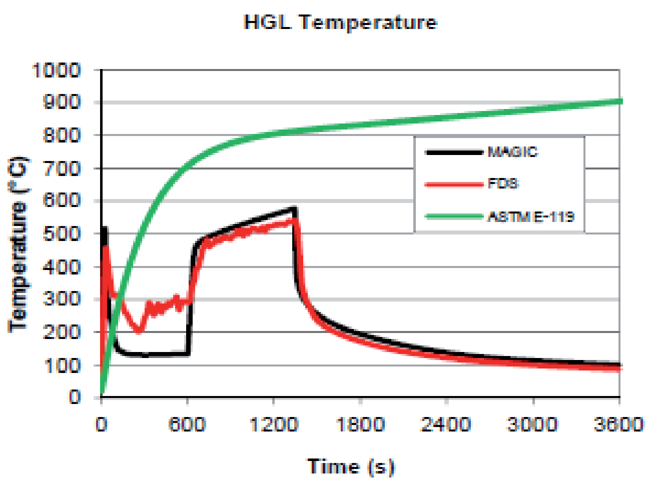

Fig. 10. HGL predicted by FDS for pump room fire

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The HGL temperature for this case reaches 640 °C, compared to 580 °C for the base case, which is still significantly lower than the ASTM E119 temperature curve. However, the predicted cable surface temperature is 200 °C, falling just below the failure criterion of 205 °C. This five-degree margin suggests that further validation may be needed to ensure that the thermal properties of the ERFBS are accurate.[4]

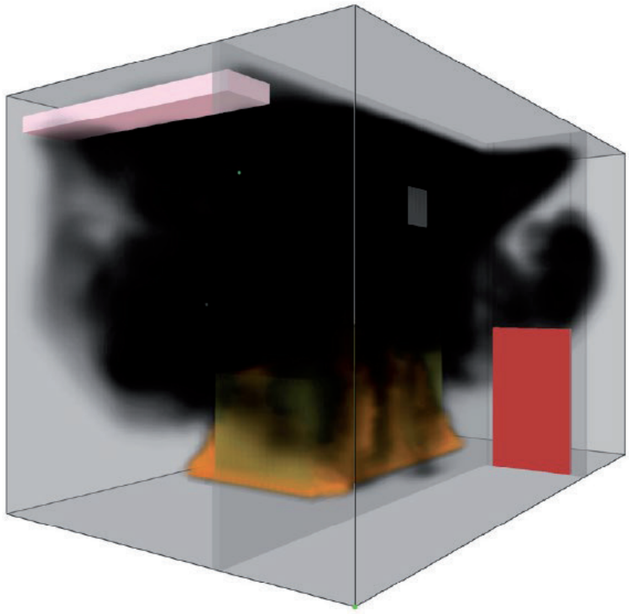

Fig. 11. Smoke buoyancy in the Safety Pump Room

In addition to HRR and temperature, as can be seen from the Fig 11, air is entrained into the flame and/or smoke plume. Consequently, the rate of smoke production at a particular height in the plume is the combination of the generation rate of combustion products and air entrainment rate into the flame and/or smoke plume between the top of the fuel and the height of interest.

Rate of smoke filling rate of is dependent on the rate of smoke production, the heat release rate (HRR), floor area, height and configuration of the space, and time from ignition. For a fire with a steady HRR, the rate of smoke filling in a compartment will decrease with time due to a decrease in the smoke production rate, which decreases as the height available to entrain air decreases when the HGL deepens.

Analysis suggests that to avoid rapid fire escalation, doors to such rooms should not be opened until firefighters are prepared to suppress the fire, and, even then, the potential for rapid fire escalation should be considered. ERFBS is expected to prevent the cables from reaching temperatures that would limit their functionality in the event of a fire involving burning spilled lubricating oil. This conclusion is based on certain expected burning behavior of the lubricating oil during the under-ventilated stages.

Further validation of the thermal properties of the ERFBS is needed in this case to reduce the impact of parameter uncertainty on the surface temperature calculation. Also, a detailed analysis of the cable surface temperature that would limit cable functionality and therefore set the pump-motor inoperable to perform safety function is essential to conform with performance-based risk informed utilization of fire protection. Probability of cable failure is of the most concern when assessing target damage and is to be further analyzed.

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