Approach to & Insights from Detailed Fire Simulation Studies at Leibstadt NPP

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Abstract: Leibstadt Nuclear Power Plant (KKL) recently performed a detailed full-scope Fire Probabilistic Safety Assessment (Fire PSA), to meet the augmented Swiss regulatory requirements on PSA (Regulation ENSI-A05), whilst also aligning with IAEA, ASME PRA standard and other international best practices. The overall Fire PSA framework was based on NUREG/CR-6850, with application of latest guidance on different areas such as fire ignition frequencies, human reliability analysis, and detailed fire modelling (DFM).

As part of detailed fire modelling task, fire simulations were performed for representative fire scenarios in risk-significant locations like Drywell, Containment, Main Control Room, Remote Shutdown Areas, Cabinet Rooms, Relay Room, and Cable Spreading Room / Shaft Areas. Fire models were developed using CFAST and FDS programs, utilizing the relevant state-of-the-art guidelines, viz., NUREG-1934, NUREG-1805, NUREG-2178, NUREG/CR-7010, NUREG-2232, NUREG-2233, etc. For each fire scenario, the extent of fire damage in terms of equipment impacted and corresponding time to damage were determined.

A bespoke methodology was formulated to ensure consistency among fire models, review and presentation of results, and documentation. Dedicated plant walkdowns were carried out to collect necessary data to develop the fire models. Plant-specific fire parameters (such as Heat Release Rate (HRR), Calorific Potential (CALPOT), etc.) based on equipment configurations were used for better modelling accuracy.

One of the highlights of detailed fire modelling is the drywell lube oil fire scenario, whose objective was to evaluate the possibility of fire spread from one half of the drywell to another, in order to verify the spatial separation between redundant safety division equipment and cables. The simulation was performed postulating maximum fire intensity from the oil spill considering a conservative spill area. The results provided meaningful insights about smoke filling and feasibility of manual fire suppression within the drywell.

This paper discusses the overall methodological aspects of fire modelling including the approach for geometry transformation, characterization of ignition sources and targets, selection of appropriate fire modelling tool and in particular the outcomes of drywell lube oil fire scenario.

Keywords: Drywell, Fire PSA, FDS, Fire Simulation.

1. INTRODUCTION

1.1. Background

The original internal fire analysis of KKL was re-evaluated during the period 2012-2015 to consider the latest enhancements in KKL PSA internal events study existing then and to address the comments of IAEA IPSART mission conducted in 2014. The re-evaluation was limited to update of fire impacts evaluation and re-quantification of a specific set of scenarios. Subsequently, from the Periodic Safety Review (PSR) 2016, the Swiss Regulatory Authority ENSI issued certain action points related to checking the validity of existing detailed analysis and accuracy of earlier fire simulation studies.

In the period 2019-2021, KKL undertook the project to completely revamp the internal fire PSA study based on augmented ENSI-A05 requirements and to align with international best practices prevailing at that time. This project also took benefit of the recent enhancements in KKL databases viz. components list, cable routing, fire loads, ventilation connections between compartments, fire suppression features and latest internal events PSA model.

Fire compartments retained after quantitative screening[1] were considered as risk significant and subjected to detailed refinement stage, where the consequences of fire were analysed at scenario level. Dedicated plant walkdowns were conducted to corroborate the spatial information of ignition sources and targets, that were required for fire scenario development and propagation modelling. A thorough review of the plant documents (like P&IDs, equipment disposition plans, cable tray layouts, HVAC arrangements, etc.) was also taken up during this stage.

Detailed fire modelling was performed for representative ignition sources in most important safety compartments, and fire growth and propagation was analysed for a duration of 2 hours using fire simulations tools - CFAST[2] and FDS[3]. The aim was to obtain a more realistic estimation of fire damage conditions in critical fire compartments. A dedicated methodology was developed to ensure consistency, quality and traceability of the fire modelling task. A total of 19 fire scenarios were modelled (17 using CFAST, and 2 using FDS for Drywell and Containment). Further details are explained in Section 2.

1.2. International Guidance and Methods Used

Table 1 lists the international guidance and methods used for detailed fire modelling task.

Table 1. International Guidelines

Area	Reference Guide
Fire modelling process, methodological guidance & requirements	Fire PRA Methodology for Nuclear Power Facilities, NUREG/CR-6850 [1] and Specific FAQs from Supplement 1 [2].
	Swiss Regulatory Guide ENSI-A05, Probabilistic Safety Analysis: Quality and Scope [3].
	Nuclear Power Plant Fire Modelling Analysis Guidelines, NUREG-1934 [4].
	Fire Dynamics Tools, NUREG-1805 [5].
	Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications, NUREG-1824 [6].
Fire modelling specifics and propagation	Fire PRA Methodology for Nuclear Power Facilities, NUREG/CR-6850 [1] and Specific FAQs from Supplement 1 [2].
	Appendix H – Damage Criteria for Equipment and Cables [1].
	Appendix M – High Energy Arcing Faults [1].
	Appendix R – Cable Fire Modelling Guidance [1].
	Appendix T – Smoke Damage on Vulnerable Equipment [1].
	Appendix Q – Passive Fire Protection Features [1].
	FAQ 08-0042 – Fire Propagation from Electrical Cabinets [2].
	FAQ 08-0043 – Location of Fires within Electrical Cabinets [2].
	FAQ 08-0049 – Cable Tray Fire Propagation [2].
	Refining and Characterizing Heat Release Rates from Electrical Enclosures During Fire, NUREG-2178 [7].
	Cable Heat Release, Ignition, and Spread in Tray Installations During Fire, NUREG/CR-7010 [8].
Fire parameters (HRR, CALPOT, fire growth rate, thermal properties, etc.)	Fire Dynamics Tools, NUREG-1805 [5].
	Refining and Characterizing Heat Release Rates from Electrical Enclosures During Fire, NUREG-2178 [7].
	Cable Heat Release, Ignition, and Spread in Tray Installations During Fire, NUREG/CR-7010 [8].
	Heat Release Rate and Fire Characteristics of Fuels Representative of Typical Transient Fire Events in Nuclear Power Plants, NUREG-2232/ EPRI-3002015997 [9]
	Methodology for Modelling Transient Fires in Nuclear Power Plant Fire Probabilistic Risk Assessment – NUREG-2233/ EPRI- 3002018231 [10].

[1] Fire compartments with 99% cumulative contribution to CDF/ FDF were subjected to detailed refinement stage.
[2] Consolidated Model of Fire and Smoke Transport (CFAST) is a two-zone fire modelling program developed by National Institute of Standards and Technology (NIST), refer https://pages.nist.gov/cfast/index.html.
[3] Fire Dynamics Simulator (FDS) is a large-eddy simulation code for low-speed flows, with an emphasis on smoke and heat transport from fires; this program is developed by NIST, refer https://pages.nist.gov/fds-smv/.

1.3. Quality Assurance

A robust two-stage interactive review process was followed for every fire scenario model. The fire models were developed by an independent consulting organisation (RELSAFE) and reviewed by KKL PSA team, involving participation from plant personnel to support on walkdowns and provide essential information required for fire modelling. The overall fire modelling methodology, individual fire scenario models, results and documentation were peer reviewed, and quality assured by an independent fire modelling expert from Belgium, who has vast experience in NPP applications and other safety critical industries.

2. FIRE MODELLING PROCESS

The fire scenario modelling comprises the following key steps according to NUREG-1934 [4]. Necessary adaptations were made to the modelling process to consider KKL plant specificities (such as fire location, propagation mechanisms, ignition source properties, etc.). Each step is summarized in the following sub-sections.

- Definition of fire modelling goals and objectives
- Characterisation of fire scenarios
- Modelling of rooms, including approach for room transformation (for complex geometries)
- Treatment of ventilation conditions in the model
- Evaluation of fire modelling predictive parameters to select the appropriate fire modelling tool
- Modelling fire loads (ignition source and targets)
- Modelling assumptions
- Treatment of cable failures using empirical and Thermally-Induced Electrical Failure (THIEF) models
- Evaluation of fire-generated conditions in the room/ compartment
- Performance of sensitivity analysis to support the use of results
- Analysis and documentation of fire simulation results

2.1. Methodological Aspects

2.1.1. Definition of Fire Modelling Goals and Objectives

The overall goals of fire modelling are to determine the possible consequences of scenarios in terms of number of affected equipment, and to justify the spatial separation credited for definition of certain fire compartments (such as Drywell and Containment). Following objectives were defined to achieve these goals:

- To determine the time to damage of targets (equipment/ cables) located in the vicinity of ignition sources and those considered within the scenario boundary.
- To determine the extent of fire propagation and conservative fire-generated conditions in the room considering a well-ventilated primary fire[4].
- To estimate the hot gas layer temperature in adjacent rooms due to smoke propagation from the main room.
- To estimate the maximum temperature and heat flux that can be attained on the fire doors and qualitatively discuss the effectiveness of fire doors.

2.1.2. Fire Scenario Characterisation

This step involves characterizing the set of elements needed to model the fire scenario. These include room (enclosure) details, location of ignition source, secondary combustibles and targets within the enclosure, ventilation conditions, fire protection features that will be credited (if assumed in the modelling approach), fire parameters such as HRR, fire growth rate, heat of combustion/ CALPOT, thermo-physical properties of materials and damage criteria for equipment and cables involved in the scenario. Focussed plant walkdowns were performed to provide additional inputs to characterize the fire scenario, for instance, regarding the choice of ignition source, fire location, nature of secondary combustibles, spatial information, orientation, etc.

[4] Primary fire in this context refers to fire originating from the 'primary' ignition source.

2.1.3. Modelling of Rooms

For each fire scenario, all rooms that have connections with the main room where fire is postulated, are identified and modelled. Typically, connections through wall/ceiling/floor vents or doors are modelled if these can affect the fire-generated conditions in the room. The choice of modelling adjacent rooms depends on the objective of the fire scenario.

With respect to doors, KKL has three fire resistance categories, namely: EI30, EI60 and EI90. The former class is non-fire rated whereas other classes are fire rated for 60 minutes and 90 minutes, respectively. All doors in the room are initially modelled in closed configuration. To account for air leakages through door clearances, an opening area equal to 2% of the total door height is modelled from the start of the simulation. For fire-rated doors, this opening area is increased to an additional 8% if the temperature on the exposed side of the door reaches 400 ^{0}C (based on the fact that the gaps around the door can increase due to potential deformation at high temperatures, thereby allowing hot gases to escape out of the room[5]). Non-fire rated doors are opened completely once the temperature on the exposed side reaches 100^{0}C, a conservative assumption based on expert judgement.

Ceiling vents and floor vents, if available in the room, are modelled to aid in reducing the temperature and pressure of the room and as a means of oxygen supply into the room (which helps in maintaining the equivalence ratio within modelling limits).

Room transformation:

Both CFAST and FDS work well with rectilinear geometries, therefore rooms which are non-rectangular in shape have been transformed into a rectangular geometry, considering following principles:

- Preservation of room height – to account for hot gas/smoke filling and to conserve the plume and ceiling jet correlations of the fire modelling tool.
- Preservation of room volume – to account for smoke filling and ventilation conditions. Typically, length and/or width of the room is adjusted to maintain the overall aspect ratios close to original aspect ratios and stay within the validation range of CFAST and FDS.
- Position of surrounding equipment and cables relative to the ignition source and surfaces is maintained to capture the radiation effects of fire.
- Preservation of total surface area of the boundaries - to conserve the heat transfer through walls, floor, and ceiling (depending on the location of target of interest).
- Limitations of fire modelling tool – with respect to aspect ratio validation limits.

2.1.4. Treatment of Ventilation Conditions in the Room

Combustion of fire-loads in the scenario depends on the ventilation conditions in the room (i.e. available oxygen for the fire to sustain). The ventilation conditions are expressed in terms of global equivalence ratio (denoted as Φ[6]), which relates the energy release rate of the fire (HRR) to the energy release rate that can be supported by mass flow rate of oxygen into the room. The calculation of equivalence ratio considers the opening area of wall vents and doors in the room.
Equivalence ratio is calculated as:

$$\Phi = Q / (\Delta H_{O2} \cdot m_{O2}) \quad (1)$$

Where Q is the heat release rate of the fire (kW), ΔH_{O2} is the heat of combustion for oxygen (kJ/kg), m_{O2} and is the mass flow rate of oxygen into the room (kg/s).

[5] The information on gap area is usually not available in test reports, however no significant gaps may be created before the rated time of the door if the door is exposed to same or less severe temperatures as per the ISO 834 curve (as per the temperature curve profile, 60 minutes rated fire door fails when the temperature in the exposed side reaches ~945 ^{0}C).
[6] When the equivalence ratio is equal to 1, the exact amount of oxygen required for complete combustion is available. When the ratio is >1, the environment is fuel rich, and the fire is considered to be under-ventilated. The reverse is true when the ratio is <1, signifying a well-ventilated environment.

Modeling under-ventilated fires is challenging because the HRR profile for the fire is specified by the analyst and is not automatically adjusted by the fire models to the conditions actually present in the room (which changes dynamically based on fire behaviour). To achieve the fire modelling objectives, the room must be well-ventilated to allow complete combustion of the primary fire. This implies that unless additional oxygen supply is available to the room, the fire does not burn as per the defined HRR profile. In such cases, a pseudo (additional) wall vent is provided in the room to ventilate the primary fire. The positioning of pseudo wall vent depends on the specific room configuration, location of fire (ignition source) and targets. Positioning of wall vent plays an important role in FDS however less significant in CFAST models.

2.1.5. <u>Selection of Fire Modelling Tool</u>

Fire models are categorized into three types based on their simplicity and degree to which spatial and temporal issues can be solved. These are Algebraic/ Empirical models (FDTs), Zone models (CFAST) and CFD models (FDS). Choice of the fire modelling tool depends on various factors such as: predictive capabilities, limitations of a particular fire modelling tool, scenario objectives, complexity of the room geometry and so on. The important non-dimensional fire parameters and their relevance to fire scenario modelling are calculated based on NUREG-1824 [6]. These parameters include room aspect ratio, global equivalence ratio, fire Froude number, Flame height to ceiling height ratio and distance from target to fire. These parameters were evaluated for each scenario to decide the appropriate modelling tool. Suitable modifications were performed if the ranges exceeded validation limits of the tool. For instance, the lower and upper limits of fire Froude number (Q^*) for CFAST is between 0.1 to 9.1, and for FDS it is between 0.1 to 63. This largely depends on the HRR of fire. If the value is found to violate the validation range for a given scenario, burning area of the primary fire is modified to be within this range. The modified Q^* will be used to calculate the flame height and plume temperature.

2.1.6. <u>Modelling of Fire Loads</u>

To predict the fire-generated conditions in a room, the location, dimensions, and orientation of fire loads along with their fire characteristics are important. The spatial and dimensional details are obtained from the scenario-specific walkdown checklists supported by disposition plans and photographs taken during walkdowns.

For each fire scenario, the fire loads in the room are categorized into 'Ignition Source' and 'Targets'. Typically, targets are those equipment/ cables that result in initiating events/ affect mitigation functions modelled in PSA or can be as secondary combustibles that aid in fire spread. For KKL detailed fire modelling, the primary fire load is referred to as ignition source and all other fire loads in the model are referred to as targets. If the damage criterion of a target is met in the simulation, it will in turn be treated as an ignition source (secondary fire).
Some key assumptions regarding damage criteria include:

- For motors, switchgears, solenoids, etc. the fire vulnerability is limited to the vulnerability of the cable supporting the component.
- Electronic components based on integrated circuit type devices can fail at lower damage thresholds as observed in fire experiments, the damage thresholds are based on Appendix H of NUREG/CR-6850 [1].
- Electromechanical devices such as relays, switches and circuit breakers are qualified to higher damage thresholds. Since detailed guidance on how to treat them is not available, their damage thresholds are conservatively assumed to be same as solid-state control components.

Passive fire protection features were credited for cables (if available), to account for severity of fire propagation from cables and delay the damage and ignition of cables to a certain extent. Based on Appendix Q of NUREG/CR-6850 [1], a time delay of 20 minutes is considered for cable trays with solid bottom and thermoset cables, and 4 minutes for thermoplastic cables. Additionally, Thermally-Induced Electrical Failure (THIEF) and empirical models were applied to predict the electrical/ functional failure of cables, accounting time delays.

2.1.7. <u>Modelling Assumptions</u>

Some of the key global assumptions taken for fire scenario modelling are listed below:

- Deflagration and detonation of fire loads, and fire-induced structural failures are not considered in the scope.

- Cables within conduits will be considered as potential damage targets but not as ignition sources.
- The incipient and decay phases of the fire growth stages are not considered in modelling of fires. The decay time and its associated CALPOT are accounted in the steady burning phase.
- Pyrolysis rates are independent of irradiation level or gas temperature, except for cable trays.

There are also scenario-specific assumptions in the study. These are not discussed in this paper for brevity.

2.1.8. Sensitivity Analysis

Sensitivity analysis on fire modelling inputs is performed for each scenario if the fire-generated conditions are found to be too conservative and/or contradicts the plant design features.

2.2. Fire Scenario Documentation

A standardised report structure was followed for documenting the modelling of fire scenarios. Each fire scenario report includes the following elements: Fire scenario definition, details on the geometry, model elements, transformation aspects, fire model inputs, ignition source characterization, information about secondary combustibles and targets involved in the scenario, evaluation of non-dimensional fire model predictive parameters, simulation settings, and analysis of fire-generated conditions in the enclosure and model elements (surface temperature & incident heat flux of components/ cables, gas layer temperature, etc.). CFAST/FDS input files, list of equipment and cables, walkdown photographs, temperature and heat flux measurements on components and cables were included as supporting attachments.

3. DRYWELL LUBE OIL FIRE SCENARIO

3.1. Geometry Modelling

Initial Geometry

The Drywell area was partitioned into fire compartments based on spatial separation approach. Each fire compartment covers the entire circumferential area (0 to 360^0) traversing one or multiple elevations. For the purpose of detailed modelling, the drywell area is partitioned into two diagonal halves at 45^0-225^0 based on location of reactor recirculation (RRS) pumps. Accordingly, one diagonal half represents all elevations of drywell in Sectors 1 and 4, and another half represents all elevations in Sectors 2 and 3. The drywell floor has a 50 mm gradient from Sectors 2 and 4 to Sector 3, as shown in Figure 1.

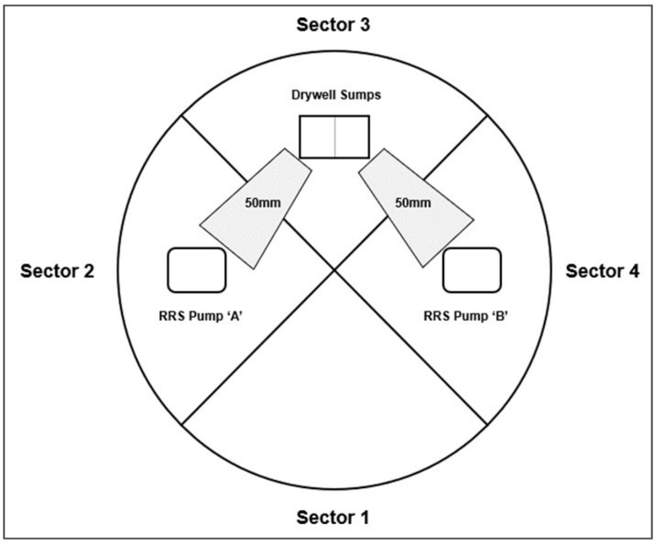


Figure 1. Location of recirculation pumps relative to drywell sumps

Geometry Transformation:

Drywell is a large cylindrical volume which must be transformed into an equivalent cuboidal geometry in order to model and simulate the scenario using FDS. The overall transformation must ensure that the drywell volume and the relative position of components and cable trays with respect to the reference origin in drywell are reasonable conserved. Also, the overall flow field around the components and cable trays should remain similar after the transformation. The degree coordinate (0^0 to 360^0) is translated into distance normalized to the length of the drywell. Figure 2 shows how the drywell circular volume is unrolled and transformed into a cuboidal volume for FDS modelling.

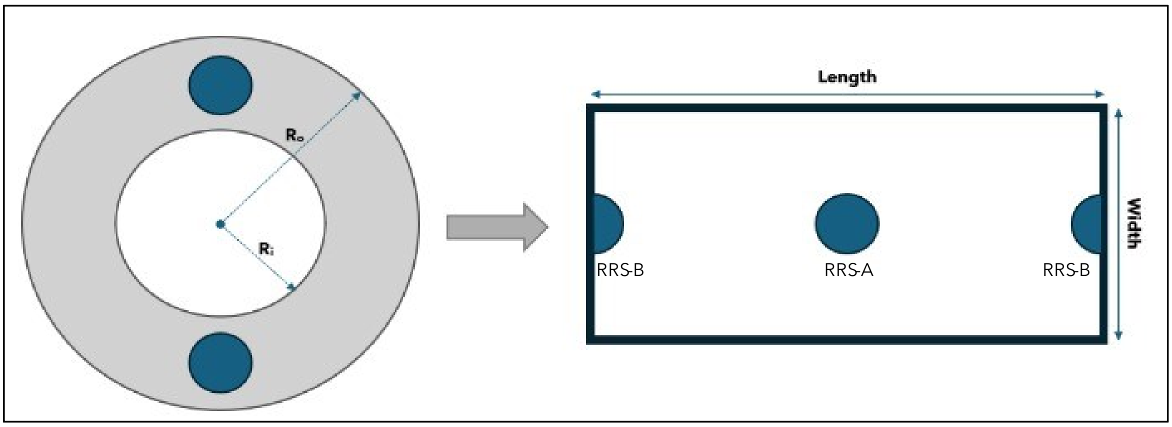


Figure 2. Drywell geometry transformation

The smaller circles in the original geometry denote the position of two reactor recirculation pumps which are relocated (conserved) in the transformed geometry. Note that the two-halves of a pump appear in corners of the resultant rectangular geometry after unrolling the circular geometry.

3.2. Scenario Characterization and Modelling

The postulated scenario for fire simulation is a lubrication oil fire from RRS A pump, at the lowest elevation of drywell (the largest fire source in drywell).

The modelling objectives of this scenario were:

- to evaluate the possibility of horizontal fire propagation from one diagonal half containing RRS-A pump to another diagonal half containing RRS-B pump.
- to determine the maximum exposure parameters attained on targets in the sector where fire originates and in the adjacent sectors.
- to determine the maximum hot gas layer temperature, extent of fire damage & smoke spread and qualitatively assess the possibility of manual fire suppression in drywell.

Each RRS pump contains two unpressurized oil reservoirs, the total quantity of oil in each RRS pump is about 500 litres. For the current simulation, it is hypothesized that the oil leaks from plugged oil inlet / outlet lines, thereby spilling only a certain quantity of oil on the floor of drywell (at bottom elevation) and the recirculation pumps do not contain catch basins to confine the spilled oil. It was not realistic to consider the exposure of entire oil quantity to fire as this would need some explosive force that breaks open the pump. So, the quantity of oil that can burn in this scenario was limited to the oxygen quantity available in the (isolated) drywell – which is about 70% of the total oil quantity.

As seen from Figure 1, the drywell floor has a gradient of ~50 mm that can direct any leaks from Sectors 2 or 4 towards the drywell sumps in Sector 3 (the sumps have a total area of 16 m^2). Based on plant walkdowns and calculations, a static oil spill was considered, and the maximum area of fuel pool was restricted to ~12.5 m^2[(7)]. The corresponding spill depth and total HRR are calculated as 2.7 cm and 22.5 MW respectively, considering

[7] The assumed fire burning area and resulting HRR is conservative as the drain provisions are ignored for the modelling.

the HRR per unit area of lube oil as 1795 kW/m^2. However, based on practical experience, it is noted that the maximum burning rate would be significantly less when the spill depth is less than 4mm. This restricts the overall fire intensity. The total fire duration considered in the simulation is about 13 minutes, wherein the oil burns at its peak HRR for ~7 minutes from the time of ignition.

The drywell geometry, spatial details, material properties of components and cables, fire/ model parameters such as HRR, oil spill area, HRR profile, fire location and mesh size are developed based on dedicated walkdowns and internationally accepted best practices. The model was built using Pyrosim 2020.2.0527 and run in FDS 6.7.4.

Figure 3 shows the layout of transformed drywell model with ignition source, mechanical equipment (pumps, valves, and pipelines) and electrical equipment (junction boxes, panels and cables). Most of the cables in drywell area are routed through metallic conduits or enclosed cable trays and are made of non-burnable insulation. The cable insulation does not ignite however it can fail when exposed to damaging temperature/ heat flux conditions.

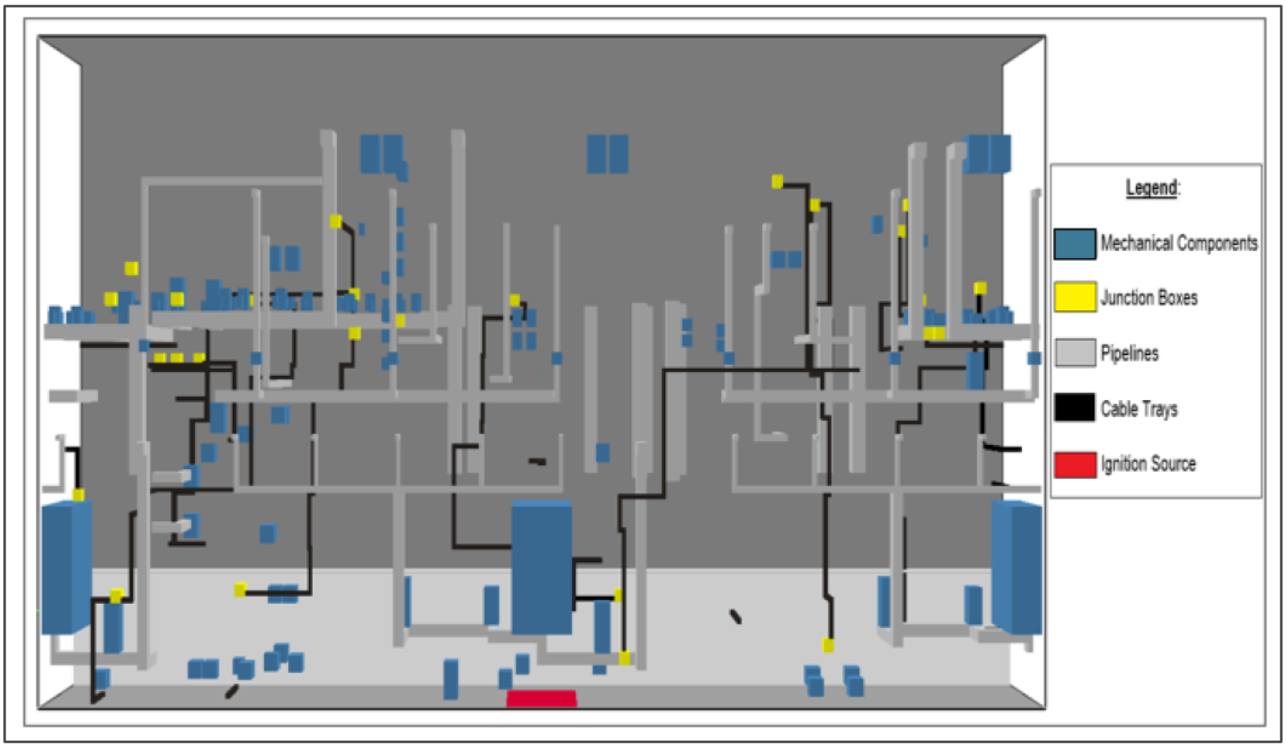


Figure 3. FDS layout of drywell showing ignition source and modelled mechanical and electrical equipment

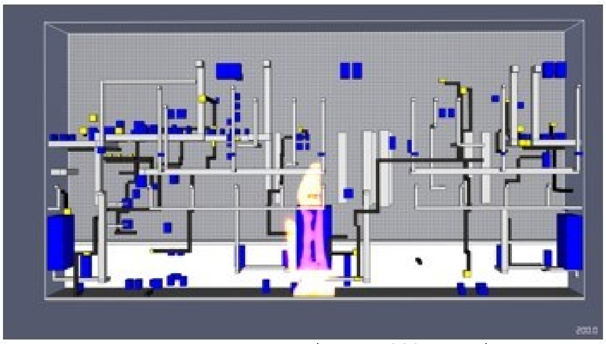
A uniform mesh size of 30 cm was applied over the entire drywell geometry, thereby dividing the drywell into 300’000+ cells. ‘Devices’ were placed on all components and cable trays that are in flame region, plume region and in the extended vicinity of the fire source, to measure following parameters: wall temperature (surface temperature), surrounding gas temperature, adiabatic surface temperature and incident heat flux quantities on targets; gas layer height and upper & lower gas layer temperatures across the drywell. A ‘PERIODIC’ vent was defined in the model to transfer the (fire) boundary conditions from one horizontal direction to another. The simulation time for drywell model was set to 1800 seconds; the estimated CPU time for the simulation using 12 cores was ~80 hours.

3.3. Insights

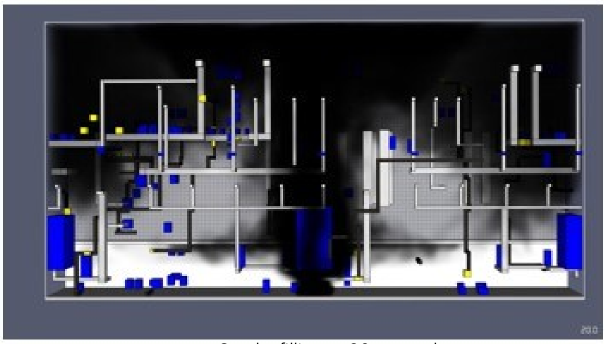
Following insights were drawn based on the fire-generated conditions in drywell. Figure 4 shows the Pyrosim rendering of the FDS simulation.

- Fire originating from Sector 2 damages only the components and cable trays in the same sector. Damage to components/cable trays due to horizontal propagation to adjacent sectors or vertical propagation to higher elevations is not possible. The maximum temperature recorded in adjacent sectors at higher elevation in drywell is 200 °C (when the fire burns at its peak HRR). The layout and arrangement of components and cables in different sectors of drywell prevents fire spread to adjacent sectors.

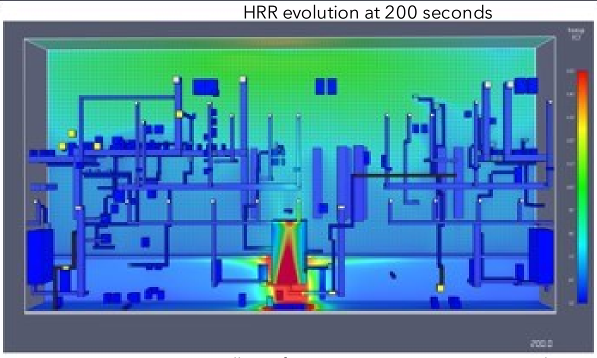
- All components and cables in drywell are qualified to operate under elevated ambient conditions (temperature & pressure). All safety division cables in drywell are either routed in metallic conduits or in enclosed cable trays and they are made of non-burnable insulation material. Flexible armoured shielding is used at connections to components and junction boxes. This prevents ignition of secondary combustibles. Some cable trays in the flame/fire plume region are damaged due to high incident flux or surface temperatures, however there are various structural elements surrounding the RRS pumps which are not included in the model and may shield the targets from flame radiation.
- It is very unlikely that an oil spill of such quantity can occur in drywell as the oil reservoirs are hermetically sealed with no flow of oil in or out of the RRS pumps. It is unlikely that a static oil spill will ignite as there are no open ignition sources in the vicinity to ignite (the ignition point of oil is higher than the temperature of the recirculation system > 279 °C). Further, any oil leak would flow into the drain channels and then to the drywell sumps which may be covered by solid steel plates. This arrangement offers poor burning conditions for the oil in the sump area. So, the current scenario provides the worst-case fire-generated conditions in drywell.
- The simulation results indicate that the conditions in the first 30 minutes of the scenario are untenable to manually intervene the fire scene.



HRR evolution at 200 seconds



Smoke filling at 20 seconds



Wall/ Surface temperature at 200 seconds

Gas temperature at 200 seconds

Figure 4. Pyrosim rendering showing evolution of HRR, smoke, wall and gas temperatures at different time steps

4. CONCLUSION

This paper presents the salient methodological aspects of detailed fire modelling performed for Leibstadt NPP. It also describes the FDS model developed for drywell, fire scenario characterization, fire-generated conditions, and insights from a conservative (and hypothetical) lube oil fire.

The bespoke methodology for fire modelling utilized the relevant state-of-the-art methods/ research activities (NUREG, EPRI), plant-specific data and pragmatic assumptions, which enabled an efficient and realistic evaluation of fire behavior for the defined fire scenarios. Critical aspects of fire modelling/ simulation - such as fire parameters (HRR, CALPOT, fire duration), modelling specifics (scenario definition, spatial details of equipment, cables/ cable trays, structures, choice of fire location, ventilation conditions, etc.) and choice of modelling software (depending on predictive parameters, objective of fire scenario, computing time, etc.) were closely aligned with KKL configuration, which aided in obtaining realistic fire-generated conditions. The outcomes of these fire simulations were used for refinement of scenario consequences in KKL Fire PSA study.

The fire modelling methodology developed as part of KKL`s internal Fire PSA and its implementation provides cost and safety benefits to the plant, in terms of optimizing the time and resources needed for the performance of fire simulations, staying up to date with international best practices, increasing regulatory acceptance and using of simulation results for other safety studies and risk-informed applications.

Acknowledgements

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