Light Water Reactor Sustainability Program

Industry Level Integrated Fire Modeling Using Fire Risk Investigation in 3D (FRI3D)

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ABSTRACT

The software Fire Risk Investigation in 3D (FRI3D) has been developed over the last 2 years to integrate 3D spatial modeling with existing fire probabilistic risk assessment (PRA) models and fire simulation codes. The goal of this research and development is to automate many of the fire analysis manual tasks to reduce industry efforts in the initial fire modeling and operational costs for the model maintenance and evaluations required during normal plant operations. The tasks for Fiscal Year (FY) 2021 include first testing the FRI3D modeling capabilities by importing an industry fire model into FRI3D and making a 3D model of a complex/high-risk significant area. (For this work, the switchgear room was chosen.) Then, the second task of FY 2021 is to develop a dynamic fire PRA process that can help optimize traditional fire PRA models. The switchgear room model will be used for the dynamic fire PRA work. This report describes the work and insights learned when using FRI3D software to model both a Nuclear Regulatory Report (NUREG) example models and a full industry switchgear room.

ACKNOWLEDGEMENTS

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ACRONYMS

CAFTA   Computer Aided Fault Tree Analysis

CDF   core damage frequency

CFAST   Consolidated Fire and Smoke Transport

EFW   emergency feedwater

EMRALD   Event Modeling Risk Assessment using Linked Diagrams

FLASH-CAT   Flame Spread over Horizontal Cable Trays

HRR   heat release rate

HRRPUA   Heat Release Rate Per Unit Area

LiDAR   Light Detection and Ranging

LWRS   Light Water Reactor Sustainability

NIST   National Institute of Standards and Technology

NPP   nuclear power plant

NRC   Nuclear Regulatory Commission

PDMS   Plant Data Model System

PRA   probabilistic risk analysis

RHR   reactor heat removal

THIEF   thermally-induced electrical failure

1.   FRI3D MODELING CAPABILITIES

This section outlines the features used in the FRI3D modeling examples.

1.1   Multiple Tool Integration

The design goal of FRI3D is to integrate the key aspects of fire PRA modeling, namely the PRA logic model, spatial model, and fire simulation, into single easy-to-use platform. The software can import a plant's existing FRANX fire PRA model and plant data bases such as Plant Data Model System (PDMS). FRI3D is currently coupled with Consolidated Fire and Smoke Transport (CFAST) for fire simulations and Computer Aided Fault Tree Analysis System (CAFTA) for risk analysis. The interactions between tools are shown below in Figure 1 for more information on this process see [1].
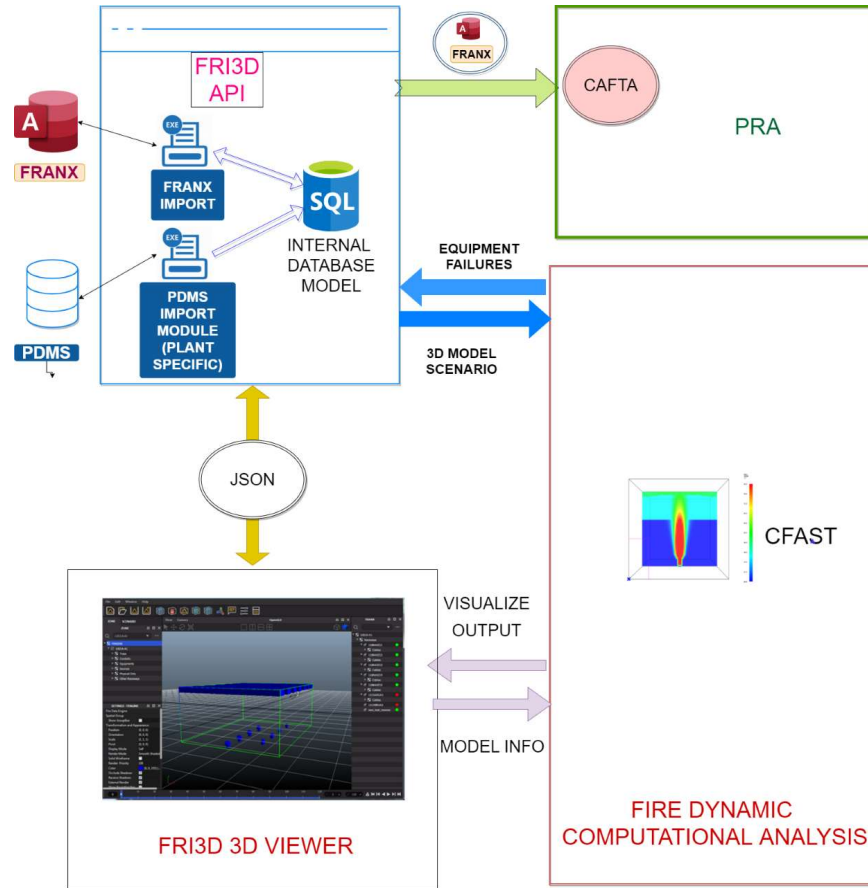
Figure 1. Integration and data flow for the different areas of FRI3D.

For the industry switchgear room model, the plant's full FRANX and PDMS data were imported. The 3D viewer/editor was used to make the physical representation, and CFAST ran a few scenario examples.

1.2   3D Modeling Features

Several features were added to the user interface of FRI3D to facilitate and speed up model generation. The initial features and planned capabilities are outlined in [1]. These new capabilities were identified and added while developing the switchgear room scenarios.

World grid. By default, a 2D horizontal, regular grid is displayed in the 3D viewer to help the user correctly align the different item positions, sizes, and distances in 3D space. A second cell-level was added to the world grid: each first-level cell (e.g., 1x1 m^2) now contains smaller cells (e.g., 25 cells with a size of 0.2x0.2 m^2). This makes it possible to estimate distances and alignments of items easily, especially if the plant items are

organized in a regular fashion and distances separating items are multiples of the smaller cell size. In addition, the colors and thicknesses of grid lines were adjusted to obtain a better contrast with the background color.

Snap. A snapping mode was added so that when interactively translating an item by a simple click-drag-release, and it is now possible to force the item to be snapped onto another item in the direction of translation. The item and its face being snapped is automatically computed, based on which position the item is released. A regular plant item can be snapped onto either a boundary, another plant item, or the world grid; a vent can only be snapped onto a boundary.

Constrained resizing. If the user interactively resizes an item that is snapped onto another, the resizing can now be constrained with respect to the face of the other item it is snapped onto. If the direction of resizing was coplanar with the snapped face, then the effective resizing is limited to the extent of the dimensions of the snapping to face of the other item. If the direction of resizing was orthogonal to the snapped face, then the resizing is effectively applied only at the opposite side of the item. This feature is ideal for aligning cabinets and similar items that have a common length in one or more directions. (Currently, this feature is not correctly supported if the item being resized has several faces simultaneously in a snapped state but is being fixed.)

Incremental translation and resizing. The ability to force the interactive translation or resizing of an item was added through a click-drag-release and done incrementally based on a user-specified increment size. This enables the user to reposition items easily if their correct locations are known with a given rounding place. For example, if the locations are known up to the closest centimeter, then a relevant choice would be to set the increment size to 1 cm.

Distance measurements. An interactive tool to measure and display distances was added. This works by putting a marker on the edge of an item and another on the edge of another item, and the orthogonal distance between the two markers is calculated and displayed. The measured distance is dynamically recalculated, whenever one of the associated items is moved.

Drawing import. The ability to import a 2D drawing and display it in the floor of the 3D viewer was added. This makes it possible to import a floor plan, which can facilitate the modeling process and its verification.

Duplication of items and properties. The ability to duplicate items and to copy and paste properties was added. Duplicating an item leads to the creation of an item of the same type and with same properties, except the id and name. Properties can also be transferred from an item to another, possibly of a different type, by a two-step copy-paste process. There are several paste options: either paste only the properties related to 3D information, paste only the other properties, or paste all of them. This simplifies the creation of trays, as they are typically modeled in sections instead of one long piece.

Item type conversion. It was made possible to perform some conversions between item types. A natural vent can now be turned into a mechanical vent, and the other way around. The type of a plant item can be converted.

2. IMPLEMENTING FIRE MODELING STANDARDS

When creating a fire model, there are specific steps and methodologies that need to be taken into account. NUREG 6850 [2] outlines the Nuclear Regulatory Commission (NRC)'s guidance on how to create an acceptable fire model and all of the elements to be considered. There are ten steps that outline the general process for creating a fire PRA and describes where FRI3D can simplify or automate the process:

1. Characterize Relevant Features of the Compartment – This step identifies all of the aspects of the fire compartment that would impact the fire-like room dimensions, construction materials, doors and vents, etc. This information impacts fire growth and development when assessing ignition sources. The room dimensions and other critical fire features are modeled within the 3D area of FRI3D along with all the relevant component information and data within its databases. Research is being done on using Light Detection and Ranging (LiDAR) scans to import spatial information.

2. Identify and Characterize Fire Detection and Suppression Features in Fire Compartment – Once the general features of the compartment have been identified the fire suppression and detection features of the compartment are then identified. Relevant features include locations, detection and suppression types, actuation details, suppression and detection zones, etc. This helps establish details for the non-suppression probability that is incorporated into the fire scenario analysis. While this will always be a manual engineering process, the FRI3D model allows the user to add sources associated with components and easily adjust properties and modify and visualize them in 3D. The source information, such as the heat release rate (HRR), is tied directly to the model instead of residing in a separate system or document.

3. Identify and Characterize Fire Ignition Sources – Finding all available ignition sources within the compartment is important in establishing the ignition frequencies and creating the fire scenarios. There are specific guidelines within NUREG 6850 that identifies what types of ignition sources to include in the analysis and how to count them and establish their fire profiles. While this will always be a manual engineering process, the FRI3D model allows the user to add sources associated with components and easily adjust properties and modify and visualize them in 3D. The source information, such as the HRR, is tied directly to the model instead of in a separate system or document.

4. Identify and Characterize Secondary Combustibles – After identifying the ignition sources, the next step is to identify the secondary combustibles that would be impacted by the fires and specific information about the combustibles that would change the scenarios such as cable material, location, and fire protection measures that might be in place. These combustibles can add additional heat into the scenarios that can change the dynamics of the entire fire scenario. While determining this information is also a manual engineering process, the user can apply the data directly to the components in the model. After doing so, the model contains all the relevant combustible information and data so that secondary combustibles can be automatically calculated in Step 7.

5. Identify and Characterize Target Sources – Finding the specific targets that are impacted by the fire is important to get an idea for how the fire impacts the plants ability to shut down and what mitigation equipment would still be available for shut down if a specific fire were to occur. It is important to track not only the components themselves but also cables that provide power to the component and control cables that control specific safety functions within the PRA. The severity factor takes into account the ignition source and its ability to impact its nearest combustible or target. Cable tracing and determining the connection logic is also a manual engineering process. However, if this has already been done and saved in a format such as FRANX then it can be imported; if it has not been constructed, then the user will be able to do the logic modeling directly in FRI3D.

6. Define Fire Scenarios to be analyzed – There are four possible scenarios that can be analyzed for each ignition source. If the ignition source is unable to impact either a secondary combustible or another target, the scenario is already accounted for within the internal events failure frequencies. The other three scenarios need to be assessed within the fire PRA itself. The first scenario assesses if the fire can damage targets or combustibles within a radial or horizontal impact zone. The second scenario looks if the fire can create a hot gas layer that is hot enough to damage targets or combustibles beyond the zone of influence and could possibly fill and fail all components within the compartment itself. The third and final scenario assesses whether the fire and any additional combustibles can release enough energy to fail boundaries and spread into adjacent compartments and impact additional targets within. Once modeling is done, FRI3D contains all the relevant information to create full room burn up scenarios, as well as auto-generate a scenario for each specified fire source. Future work will include auto-generating multi-compartment scenarios.

7. Conduct Fire Growth and Propagation Analysis – Computational fluid dynamic software can be used to analyze how the fire and heat flows within the compartment to identify when and what targets and combustibles will be impacted by the fire. FRI3D uses the Flame Spread over Horizontal Cable Trays (FLASH-CAT) method, where applicable, to determine fire propagation and the heat soak or thermally-induced electrical failure (THIEF) methods to identify affected targets.

8. Conduct Fire Detection and Suppression Analysis – Assessing how a fire is impacted by the fire suppression and detection systems changes how the scenario can develop. The automatic suppression and detection systems should be considered as well as any manual suppression activated by operations. While FRI3D does not analyze the detection and suppression itself, future development will use CFAST to determine detection times and suppression effects. Detection or suppression times will be available to the user for use in quantification for relevant scenarios.

9. Calculate Non-Suppression Probability and Severity Factor – The fire growth profile, target, and combustible information will help identify the severity factor. The suppression and detection analysis will help establish the non-suppression probability. These are multipliers that will impact the core damage frequency of the fire scenarios. While FRI3D does not specifically perform the non-suppression and severity factor calculations, the final version will display all the relevant information for the user to make the calculations and apply them to relevant scenarios. Future work could further develop this feature.

10. Calculate Scenario Frequency – Once the severity factors and non-suppression probabilities have been calculated, they can be multiplied by the ignition sources, ignition frequency, and the random failure probability of the plant components or the conditional core damage probability to find the scenario frequencies. FRI3D ties to the PRA FRANX model, modifies it, and opens CAFTA for quantification of the scenarios. The user can click to generate a scenario, then click to quantify without passing data between applications (i.e., a much faster and simpler workflow compared to the traditional approach).

2.1 CFAST Fire Simulation

All the items that are modeled in the 3D area of FRI3D are used to construct a CFAST model. Property values from the items are copied from FRI3D and assigned to the equivalent properties in CFAST. FRI3D tries to simplify the requirements from the user by providing conservative default values as described in Appendix C. The values from the user can be found in the setting in the bottom left after selecting an item as shown in Figure 2. If a scenario has a high-risk contribution, they can spend more time determining exact values to reduce those scenarios.
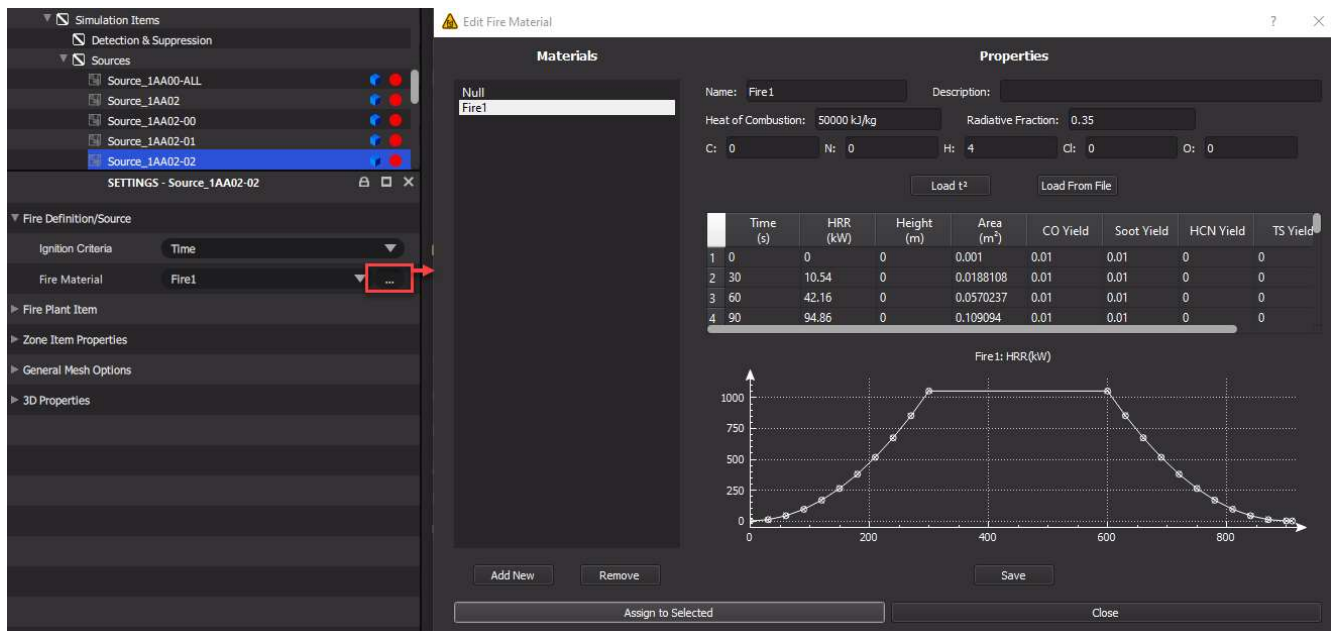
Figure 2. Example of properties that can be set by the user after selecting an item.

A CFAST model is generated whenever a user right-clicks on a source and selects "Simulate CFAST" button. The CFAST model is generated and stored in the "Working Data Dir" (defaulting to c:/users/[username]/ AppData\Roaming\FRI3D\[source or scenario name]\). After CFAST simulates the fire, the surface temperature

and incident flux for all the components are read from the cfast_devices.csv results file, columns TRGSURT, and TRGFLXI respectively. These results are used to determine cable and component failures and the FLASH-CAT calculations for secondary combustibles.

2.2 Automatic Scenario Generation Overview

A key feature of FRI3D is to automatically generate failure scenarios using the most accurate methods approved by the NRC guidance depending on the fire simulation tool capabilities and information provided by the user. This is done by analyzing the data available for all components/cables and only using conservative default values where necessary. FRI3D also allows the user to add suppression items; this could be used to assist developing a non-suppression probability, but FRI3D requires a user assigned non-suppression probability assigned for the scenario. Figure 3 shows the flow process for running CFAST and using model data to determine the failed items for a scenario. The next three sections describe specific areas in the process.
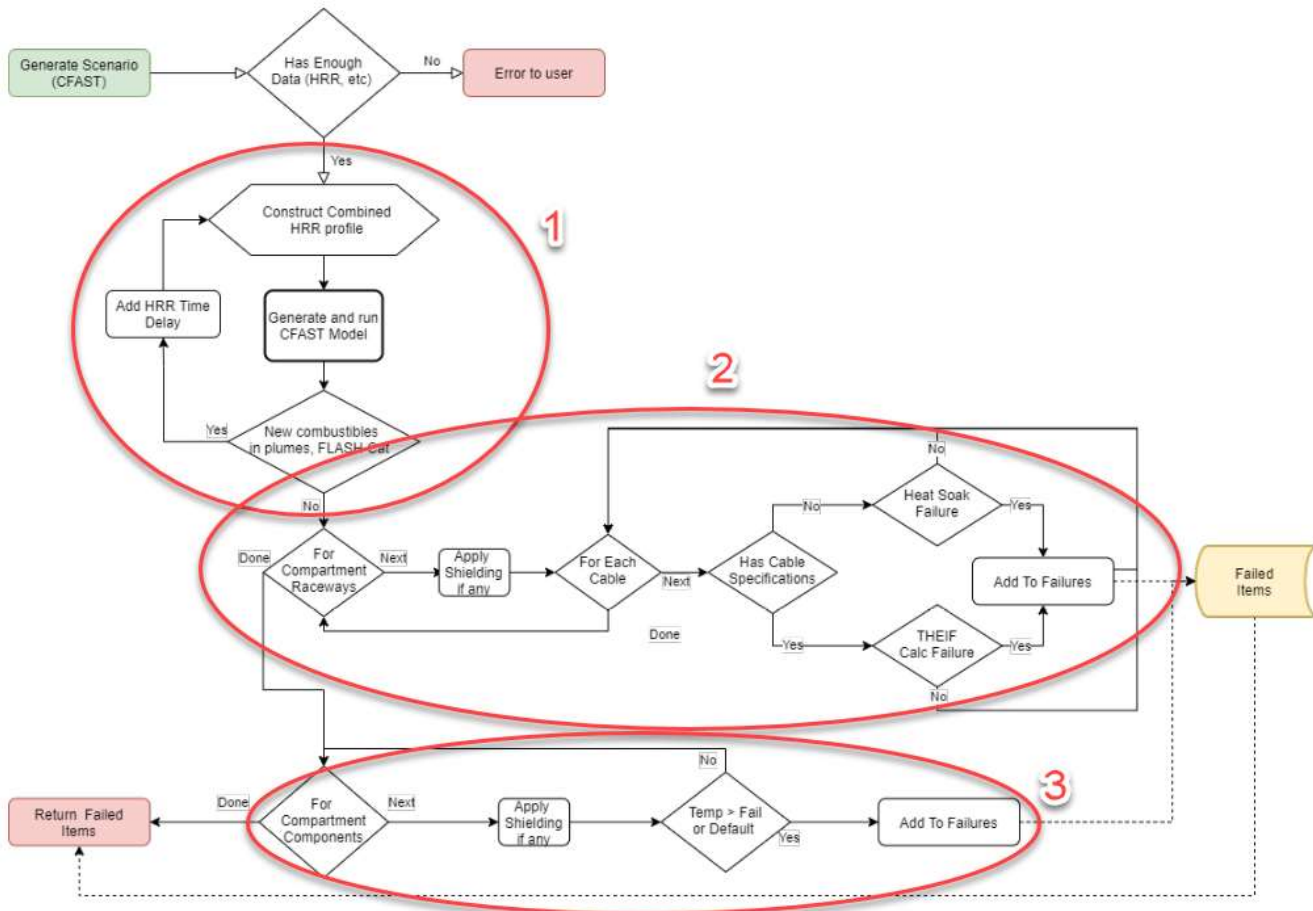
Figure 3. Flow diagram showing the process for auto-generating failed items for a scenario using CFAST.

2.3 Secondary Combustibles

The initial fire source may ignite electrical raceways and cables in the compartment, which are termed as secondary combustibles in this report. Despite the term "secondary," these objects may not combust simultaneously but rather at different timings. The secondary fires can add to the heat released by the initial fires, which eventually changes the fire and temperature calculations. In order to estimate the total heat from the initial and secondary fires, the FLASH-CAT empirical methodology developed by the National Institute of Standards and Technology (NIST) [3] is adopted in this work. Circled area 1 in Figure 3 shows the application of FLASH-CAT in the scenario generation flow.

2.3.1 Calculation Process

The FLASH-CAT methodology estimates the HRR from the burning cables, the timing and duration of fire, and the length of cable burned during the initial combustion. These values are approximated from controlled fire experiments conducted by NIST. For that reason, this methodology requires certain assumptions that fit the experiment conditions to be met. The FLASH-CAT assumptions are:

- The cable trays are horizontal and stacked vertically with a spacing of less than 0.45 m (18 in)

- The cables burn in the open; that is, they are away from walls and well below the ceiling

- The cables are not exposed to elevated temperature sources except for the ignition source below

- There are no barriers separating the trays, and the tray tops and bottoms are open

- The cables are not protected with coatings, armor shielding, or thermal blankets of any kind

- There is a fire beneath the lowest tray

- The initial extent of the fire in the lowest tray is equal to the width of the source fire

- Each tray has at least a single row of cables or roughly 25 % of the NRC limit.

Under these assumptions, the fire is assumed to propagate upwards through the array of cable trays according to an empirically determined timing sequence. The length of cables within a given tray that ignite initially increases as the fire spreads upwards. Lateral spread of the fire begins as soon as the cables within the tray ignite. This produces a solid V-shaped burning pattern that expands laterally with time. As the mass of combustible material within the center of the V is consumed, the V-shape becomes an expanding, open wedge of burning cable. The fires in each tray continue to spread until the end of the tray is reached. This process is illustrated in Figure 4.
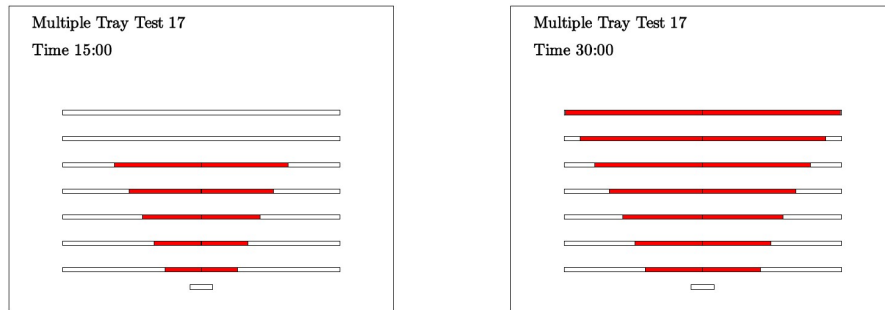
Figure 4. V-Shaped burning pattern in FLASH-CAT model.

The initial length of fire on the raceways is determined by the raceway's vertical distance from the fire, and the order of the raceway among other raceways. For the first raceway (i.e., the raceway closest to the fire), the initial length is the same with the length of the fire itself. Once this first raceway combusts, the other raceways on top of it will eventually burn. The initial length of fire on those other raceways are calculated as:

$$L_{(i+1)} = L_{(i)} + 2h_i \tan (35^0) \tag{1}$$

Where $L_{(i)}$ denotes the fire length of the current raceway, $L_{(i+1)}$ is the fire length for the next raceway in the vertical order, and the h_i is the vertical distance between the two raceways. The fire spreads laterally with a rate of 1.1 m/hour for thermoset cables and 3.2 m/hour for thermoplast cables. If there are multiple cable types in the same raceway, the fire spread rate is assumed to be the fastest among the cables (i.e., thermoplast).

Cables consist of metal and plastic elements. The amount of combustible mass in a raceway depends on the plastic mass of cables in it. A variable called the combustible mass per unit area m_c'' is calculated as:

$$m_c^{''} = \frac{\sum_j (Y_p(1-v)m')_j}{W} \tag{2}$$

Where j is the index of a cable in the raceway, Y_p is the plastic mass fraction of the j-th cable, v is the char yield of the cable, m' is the mass per unit length of the cable, and W is the tray's width. The amount of combustible mass in a raceway determines how long the fire burns, which is denoted as Δt:

$$\Delta t = \frac{m_c^{''}\Delta H}{5\dot{q}_{avg}^{''}/6} \tag{3}$$

Where ΔH is the heat of combustion, and $\dot{q}_{avg}^{''}$ is the HRR per unit area which is 150 kW and 250 kW for thermoset and thermoplast cables respectively. To calculate the time-dependent HRR profile, the raceway is divided into spatial grids, and the distance from the center of the fire is measured as x. The time when a spatial grid begins to combust, $t_{ign,i}(x)$, is calculated as:

$$t_{ign,i}(x) = t_{ign,i,0} + \max\left(0, \frac{|x| - \frac{L_i}{2}}{S}\right) \tag{4}$$

Where S is the fire spread rate in m/s, and $t_{ign,i,0}$ is the time when the tray first ignites. If the grid is located within the original section of raceway that first ignites, the two ignition times will be the same. After calculating the combustible mass $m_c^{''}$, the fire burn period Δt, and the ignition time $t_{ign,i}(x)$, each of the raceway grid will have a local HRR per unit area as shown in the Figure 5. HRR starts to increase from $t_{ign,i}(x)$ until reaching the peak Heat Release Rate Per Unit Area (HRRPUA) at one-sixth of Δt later, remains stable until $5\Delta t/6$, and then decreases linearly to zero.
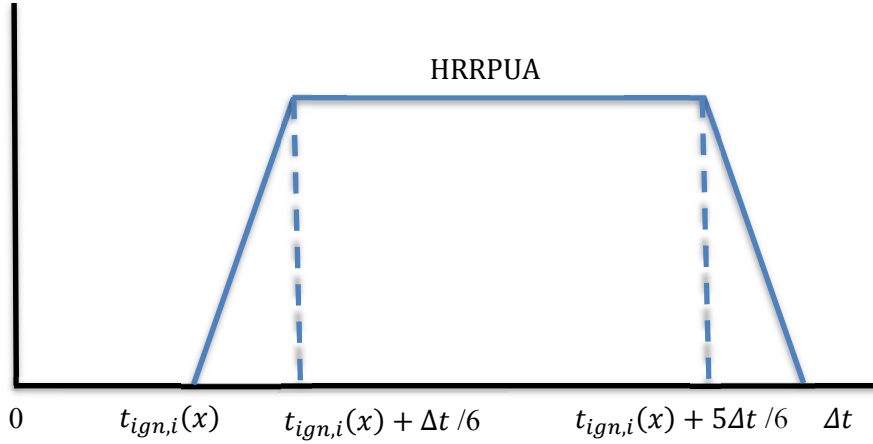
Figure 5. Time history of the local HRRPUA for each raceway grid.

Once all the HRRPUA profiles for each raceway grid have been calculated, the total HRR of the secondary combustible is calculated by summing all the local HRRPUA profiles from all raceways as follows:

$$\dot{Q}(t) = \dot{Q}_{fire} + W \sum_{i=1}^{N_{trays}} \left[\int_{x_0}^{x_j} \dot{q}''\left(t - t_{ign,i}(x)\right) dx \right] \tag{5}$$

Where $\dot{Q}(t)$ is the total secondary combustible's HRR, $\dot{Q}_{fire}$ is the HRR of the initial fire, W is the raceway's width, $\dot{q}''$ is the local HRRPUA, and t is the discrete observation time.

The process to initiate FLASH-CAT in our work is as follows:

1. Model the compartment, fire source(s), vent(s), cables, and raceways in FRI3D.

2. Run the initial CFAST simulation.

3. Get CFAST output of actual HRR, fire area, heat flux, and temperature at each raceway.

4. Iterate through each raceway. Check raceway geometrical coordinate if it is located above the fire source. (If a raceway is above it is conservatively included vs. the 0.45 m spacing requirement).

5. If raceway is on top of a fire source, calculate the initial length of cable that combusts. Iterate on each cable in the raceway. Check if the maximum temperature or heat flux at the raceway exceeds the cable's combustion threshold. If it does, check the cable material properties. If the properties are not defined by the modeler in FRI3D, the default material properties are used for the cable, typically thermoplastic unless changed by the user (see Appendix B).

6. Create a one-dimensional spatial mesh along the cable's length (dx) and calculate which mesh segments are burning at certain times (dt) by taking into account the horizontal fire spread rate.

7. Integrate the spatio-temporal heat release rate over the cable's length to obtain the time-dependent HRR for that cable.

8. Sum the time-dependent HRR for all the cables within the raceway.

9. Repeat Step 5 until Step 7 for other raceways in the vertical stack.

10. Add the cable HRR to the initial fire's HRR, update the CFAST input file with the new HRR, and re-run CFAST simulation.

11. Use the new CFAST results to get the temperature and heat flux at the next raceway in the iteration. Repeat from Step 4.

12. After all raceways have been evaluated, get the temperature and heat flux from the last CFAST simulation to estimate component failures.

2.3.2 Data from the 3D Model

When modeling raceways, a single raceway is typically broken up into sections wherever a cable enters or exits, which enables simple linking to the FRANX style of logic modeling. However, to calculate FLASH-CAT, the entire tray data and all cables need to be used. To enable this, each raceway has links to other raceway pieces. When the simulation indicates a particular raceway section will have secondary combustibles, the data from all linked raceways is used in the FLASH-CAT calculation. FRI3D automatically adds the links to raceways if they are touching and distinguishes between horizontal and up or down connections. Currently only horizontal connections are calculated for secondary combustion. The linking of local raceways described above is the solution chosen to ensure FLASH-CAT fire can propagate along the whole physical raceway. From the initial fire source, data for each route or path away from the fire is gathered, branches in the raceway cause additional fire propagation paths.

The raceways sections that are linked programmatically typically each contain different cables than adjacent raceways. For more realism, these differences should be accounted for to calculate the FLASH-CAT HRR. However, in the current version, a conservative simplified approach is used. Instead of calculating the HRR contribution for each raceway section, the conservative method uses the section with the largest combustible mass and HRR per unit area for the entire raceway. This could be updated in a future revision but was done currently to reduce code complexity and computation time. The combustible mass is calculated for each local raceway following Equation (2). The maximum value among all local raceways is taken as the combustible mass for all pieces of raceway in the FLASH-CAT calculation. This value is then used to calculate the burning period Δt following Equation (3). Therefore, the burning period for each raceway grid is conservatively longer than what is expected. These local HRRPUA profiles are then summed following Equation (5) to form the overall HRR profile. As a result, the HRR profile has conservative higher gradient and the fire burns longer.

2.4   Failure Calculations

Users are able to specify data used in failure calculations; if no data is provided, then default parameters are used. The default parameters outlined in Appendix B are initially assigned to conservative NRC specified values, but they can be altered for plant specific needs. These sections go over the implementation of the methods implemented in FRI3D.

2.4.1   Cables

Two methods to estimate cable failures are adopted in this work, namely the heat-soak method [4] and the THIEF method [5]. The heat-soak method is the simplest out of the two. It uses a lookup table for time-to-damage as a function of constant exposure. It determines failure in a generic manner based on whether the cable is a thermoset or a thermoplastic one. For that reason, this method is selected by default when detailed data of the cable is not provided by the modeler in the FRI3D model. The method calculates a variable called the damage integral based on the time-dependent reaction rate. Damage occurs when this damage integral is greater than or equal to 1. This method can be applied using temperature or heat flux data using the lookup table to determine failure listed in Appendix B. The time of the cable failure is determined if/when the time the cable tray is above a given temperature or flux of passes the time specified in the table.

The THIEF calculation is more detailed compared to the heat-soak method. It uses the cable's dimension and thermal data to calculate the temperature inside the cable. Assuming the heat transfer on a cable is largely in the radial direction, it calculates the one-dimensional radial conductive heat transfer with the surface boundary conditions taken as the temperature or heat flux calculated by CFAST. Cable is damaged when the internal cable temperature, after thermal attenuation from the cable's jacket, exceeds a specific threshold for thermoplastic or thermoset. This method is more realistic compared to the heat-soak method; however, it takes more computation time and data. The method is selected when the modeler provides the cable's data in the FRI3D model. Circled area 2 in Figure 3 shows the application of either the THIEF or heat-soak method in the scenario generation flow.

The THIEF methodology is based on several assumptions as follows:

1. The dominant heat transfer along the cable is in the radial direction, thereby the axial heat transfer can be omitted to simplify the calculation

2. The cable's composition is homogenous

3. The thermal properties of the cable are independent of temperature

4. There is no physical decomposition within the cable during heating, ignition and burning

5. Cable fails electrically when the temperature inside the cable's jacket reaches a threshold value.

To perform the THIEF calculation, a CFAST simulation is run to obtain the surface temperature and incident flux at a raceway. The surface temperature is then used as the boundary condition to solve the following transient conductive heat transfer equation:

$$\rho c \frac{dT}{dt} = \frac{1}{r} \frac{d}{dr} k \, r \frac{dT}{dr} \qquad (6)$$

Where ρ, c, and k are effective density, specific heat, and thermal conductivity respectively. The equation is solved by the finite difference method. The cable's radius R is divided into N uniformly spaced radial grids of length dr. A time step constraint dt is selected based on the value of dr as a criterion of numerical stability:

$$dt = \frac{c\rho \, dr^2}{2k} \qquad (7)$$

The finite difference solution to Equation (6) is given by:

$$\rho c \frac{T_i^{n+1} - T_i^n}{dt} = \frac{2k}{(r_{i+1} + r_i)} \frac{1}{2\,dr} \left[r_i \frac{T_{i+1}^n - T_i^n}{dr} - r_{i-1} \frac{T_i^n - T_{i-1}^n}{dr} + r_i \frac{T_{i+1}^{n+1} - T_i^{n+1}}{dr} \right. \tag{8}$$
$$\left. - r_{i-1} \frac{T_i^{n+1} - T_{i-1}^{n+1}}{dr} \right]$$

The boundary condition for this solution is given by:

$$k \frac{T_{N+1}^n - T_N^n}{dr} = \dot{q}^n(t^n) \tag{9}$$

Where $\dot{q}^n(t^n)$ is the net heat flux at the surface due to the heat convection with the surrounding gas as follows:

$$\dot{q}^n(t^n) = \varepsilon\sigma\left(T_g(t^n)^4 - (T_s^n)^4\right) + h\left(T_g(t^n) - T_s^n\right) \tag{10}$$

Where ε is the emissivity of the cable surface (assumed to be 0.95 in THIEF methodology), σ is the Stefan-Boltzmann constant, h is the convective heart transfer coefficient (assumed to be 10 W/m2/K), and $T_g(t^n)$ is the effective gas temperature at the n-th time step. The effective gas temperature may be approximated by the cable's surface temperature obtained from the preliminary CFAST simulation if the radial grid is reasonably small. The cable is assumed to fail when the internal cable temperature exceeds 400°C and 200°C for thermoplast and thermoset cables respectively. The failure timing is taken when that threshold is exceeded.

2.4.2   Components

Failure of active components can be determined by assuming the component is limited by the vulnerability of its power supply unit, control system, and/or electrical cables which support the operation of that component [2 Passive components such as pipes, water tanks constructed of ferrous metal, and valves are considered invulnerable to fire. Specific recommendations are given for solid-state control components, where the failure criteria are 3 kW/m² and 65ºC. If a component can directly fail due to fire, it can be assigned specific failure criteria, or use the default recommended value in the FRI3D UI. The failure criteria are checked by evaluating the component's heat flux and temperature as calculated by CFAST, and if it fails, the time and component info is added to the scenario. Ar in Figure 3 shows the application of FLASH-CAT in the scenario generation flow. (The "Apply Shielding if any" step is a placeholder for a possible option.)

2.5   PRA Model Integration

All failed cables and components described in the Section 2.4 are used to generate a new scenario internal to FRI3D. However, if the user has imported a FRANX model then the new scenarios can be added or modified once altered in the linked model. To solve, the user must also assign an exit-in CAFTA model, if this has been done, when they select solve for the current scenario, FRI3D opens the associated FRANX model makes the modifications, then opens the CAFTA application with the modified FRANX file. From here, the user can use CAFTA as usual to view or analyze the results.

3.   INDUSTRY LEVEL MODELS

3.1   NUREG-1934 Appendix A

NUREG-1934 Appendix A [6] emulates a cabinet fire in the master control room. The room itself is non-cuboidal in shape; however, it is made up of sub-compartments cuboidal in shape, and the total cuboidal shape of the room is approximated with the total volume conserved. Although the specific goal of this appendix is to approximate the time for which the room remains habitable for our purpose, it is to compare the zone temperatures to serve as validation for FRI3D. The room is depicted by the screenshot shown in Figure 6, along with its measurements. The model also depicts how floor plan specs can be imported into FRI3D. The model has the following venting constraints. There are two return vents and six supply vents (mechanical) positioned at

appropriate locations. The room also has a leakage under the compartment which can be specified by another vent (natural vent).
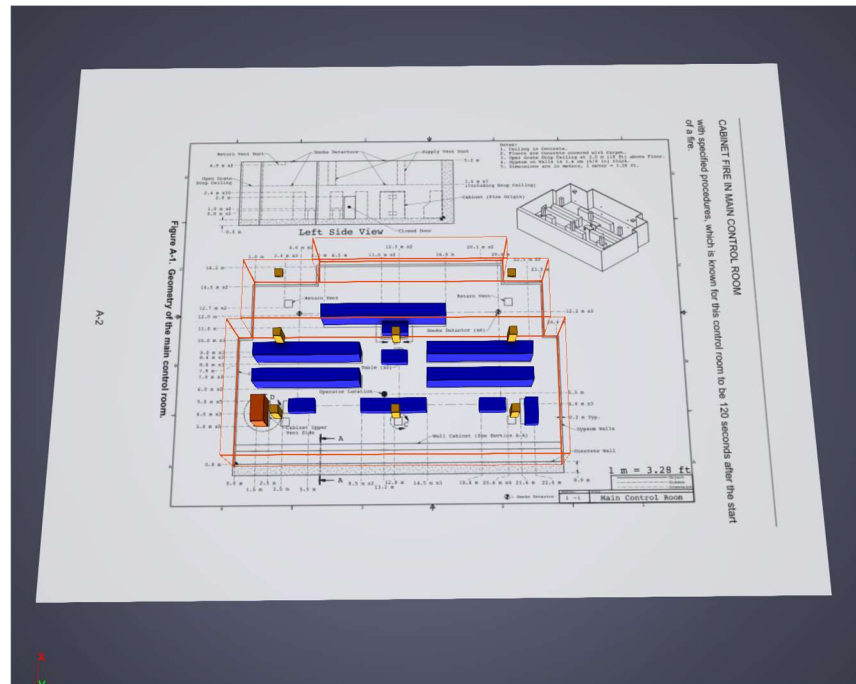
Figure 6. NUREG-1934 Appendix A modeled in FRI3D using the imported 2D architectural drawing.

3.1.1 Modeling Insights

The total time for modeling this room in FRI3D was about 45 minutes after the drawings had been examined. There are various tools in FRI3D which enable this modeling process to be simple. One of the features which was instrumental in this case is the measurement tool, which computes and displays distances between items. An illustration of this is indicated in Figure 7. As the user selects and moves the object, the measurements are updated dynamically. Other tools which aided this process are the Snap feature and the Incremental Translation.; These features facilitated the placement of objects at discrete distances from each other. Using this process, the model indicated in NUREG-1934 Appendix A was completed in less than an hour.
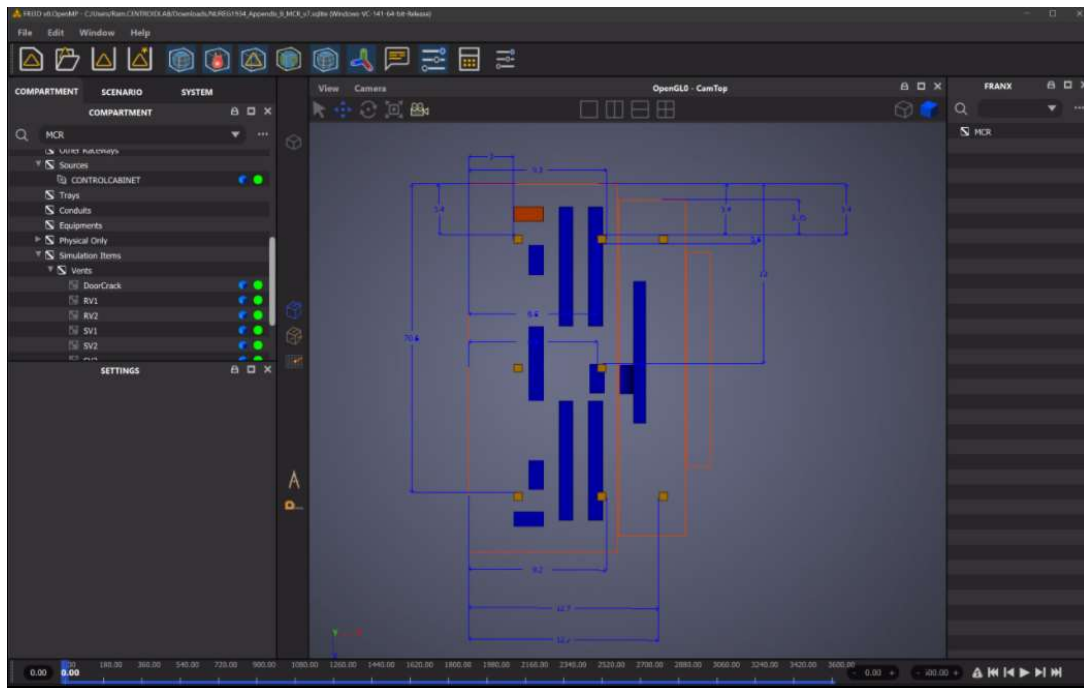
Figure 7. Top view showing measurement option in FRI3D.

3.1.2 Verification

To verify the correctness of FRI3D simulation, the fire scenario described in the Appendix A of NUREG-1934 was modeled in FRI3D [6]. The resulting CFAST input file from this model is compared against the CFAST input file for the same scenario as modeled by the NRC. The CFAST input file is comprised of several input tabs. In this report, only the tabs that have differences are shown. The compartment tab is shown in Table 3-1, the data for wall vents are shown in Table 3-2, and data for fire sources are given in Table 3-3. The differences between the two models are written in italics. The difference in compartment dimensions is due to the difference in constraints. NRC used two constraints to calculate the compartment size: the conservation of volume and conservation of boundary surface area. Meanwhile, FRI3D uses the same first constraint (i.e. the conservation of volume), but its second constraint is based on preserving the respective proportions of the length, width, and height. The difference in floor leak ratios between the two models are caused by rounding-off error, a known technical limitation in FRI3D. This limitation will be resolved in the near future.

Table 3-1. Compartments input data.

Compartments	NRC model	FRI3D-generated model
Geometry		
Width	27.1	24.03593
Depth	13.8	15.82854
Height	5.2	5.080766
Position X	0	0
Position Y	0	0
Position Z	0	0
Advanced		
Flow characteristics	Normal	Normal
Wall leak area ratio	0.00017	0.00017
Floor leak area ratio	5.20E-05	5.00E-05

Differences in the sill, soffit, width, and offset of the wall vent as highlighted in Table 3-2 are minor and may be caused by the way the vent is modeled in FRI3D. Despite this, the vent scales (width, height and area) are the same.

Table 3-2. Wall vents input data.

Wall vents	NRC model	FRI3D-generated model
First Compartment	MCR	MCR
Second compartment	Outside	Outside
Sill	0	0
Soffit	0.013	0.013
Width	0.91	0.9099
Offset	7	6.859
Face	Left	Left
Open/Close criterion	Time	Time
Time	-	0
Fraction	-	1

The fire source is located slightly different between the NRC and FRI3D model. Since positions are specified to CFAST with respect to a compartment corner, this discrepancy can be explained by the difference in compartment dimensions. As previously stated, it is scheduled to be resolved in the near future.

Table 3-3: Fires Input Data.

Fires	NRC model	FRI3D-generated model	Fires
Compartment	MCR	MCR	Compartment
x	2	2.352015	x
y	4	4.832551	y
Ignition criterion	Time	Time	Ignition criterion
set point	0	0	set point
C	3	3	C
H	4.5	4.5	H
O	0	0	O
N	0	0	N
Cl	0.5	0.5	Cl
Heat of combustion	10300	10300	Heat of combustion
Radiative fraction	0.53	0.53	Radiative fraction
HRR	Follows curve	Follows curve	HRR
Height	1.2	1.2	Height
Area	0.12	0.12	Area
CO Yield	0.082	0.082	CO Yield
Soot yield	0.175	0.175	Soot yield
HCN yield	0	0	HCN yield
TS yield	0	0	TS yield
Fires	NRC model	FRI3D-generated model	Fires

After simulating the input files in CFAST, the output data of both models are compared. Several sample figures of result comparison are shown below. The layer temperatures are displayed in Figure 8. There is only a negligible difference between the NRC's model and the FRI3D-generated model. The layer height is displayed in Figure 9. The figure shows the upper layer height starts from the compartment's height (i.e. 5.2 meters for the NRC model and 5.08 meters for the FRI3D model). This layer height converged at around t=120 seconds when the ventilation's purge mode was activated. The compartment pressure is displayed in Figure 10 which shows the pressure between the two model is similar.
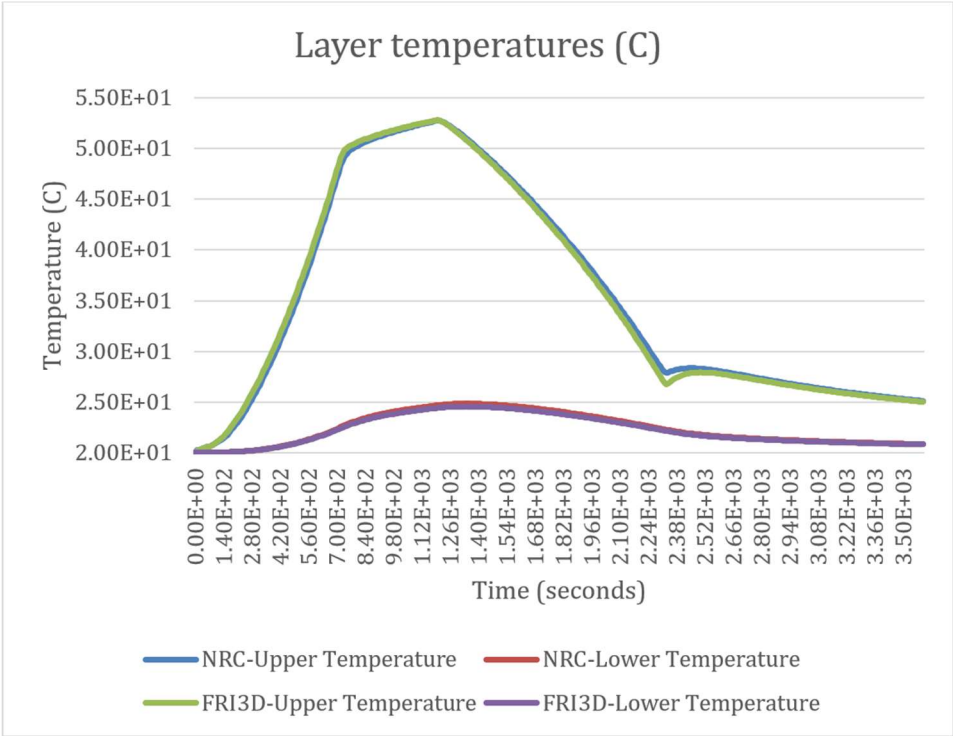
Figure 8. Layer temperature.
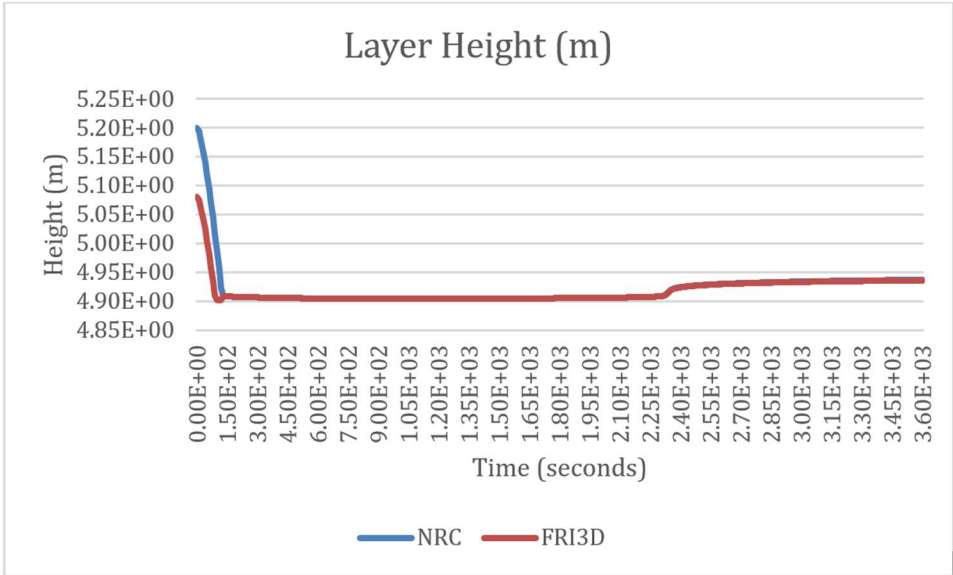
Figure 9. Layer height.

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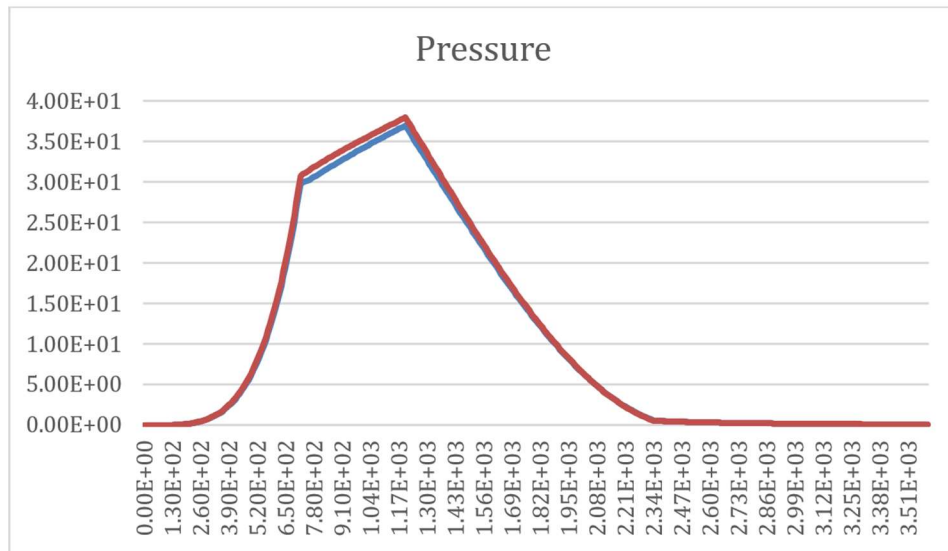
Figure 10. Compartment pressure.

Another comparison was done on the fire model of Appendix B of NUREG-1934 [6]. The layout of this model is shown in Figure 11. There are three raceways on top of the cabinet fire. Therefore, a secondary combustible fire is expected to arise from this scenario. Parameters of the NRC and FRI3D compartment models are compared in Table 3-4. The compartment's volume and surface area are the same; however, the width and length are inverted. This difference does not affect the CFAST simulation.
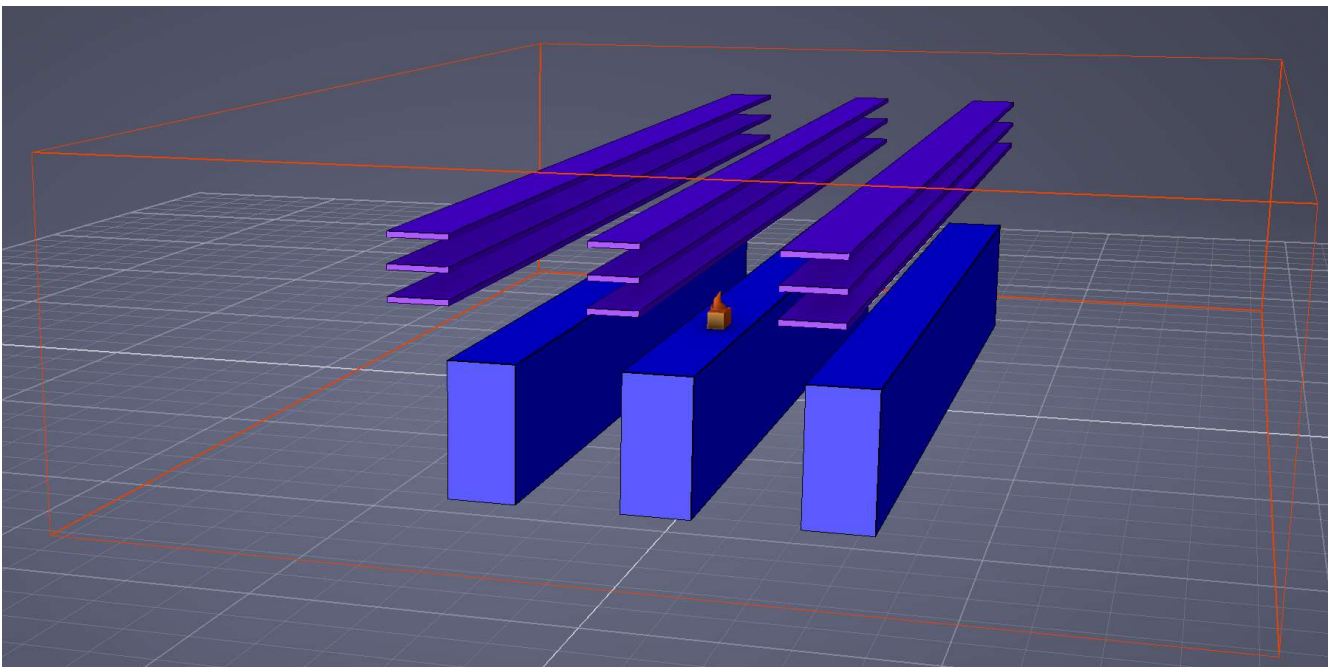
Figure 11. Appendix B NUREG-1934.

Table 3-4. Compartments input data.

Compartments	NRC model	FRI3D-generated model
Geometry		
Width	26.5 m	18.5 m
Depth	18.5 m	26.5 m
Height	6.1 m	6.1 m
Position X	0	0
Position Y	0	0
Position Z	0	0
Advanced		
Flow characteristics	Normal	Normal
Wall leak area ratio	0.00017	0.00017
Floor leak area ratio	5.20E-05	5.20E-05

The fire source is located slightly different between the NRC and FRI3D model. Since positions are specified to CFAST with respect to a compartment corner, this discrepancy can be explained by the difference in compartment dimensions. It is scheduled to be resolved in the near future. Furthermore, the primary and secondary fires in the NRC model are separated; meanwhile, FRI3D combines the two into a single fire.

Table 3-5. Fires input data.

Fires	NRC model	FRI3D-generated model
Compartment	MCR	MCR
x	8.3	8.95
y	9.5	8.3
Ignition criterion	Time	Time
set point	0	0
C	2	2
H	3.5	3.5
O	0	0
N	0	0
Cl	0.5	0.5
Heat of combustion	20900	20900
Radiative fraction	0.49	0.49
HRR	Follows curve	Follows curve
Height	2.4	2.4
Area	0.18 & 1	0.18
CO yield	0.147	0.147
Soot yield	0.136	0.136
HCN yield	0	0
TS yield	0	0

The comparison between the fire's total HRR between NRC's model and FRI3D's model is shown in Figure 12. The HRR profiles are quite similar overall. The minor variations are perhaps caused by the difference in size of raceway grids and the difference in sample timings.
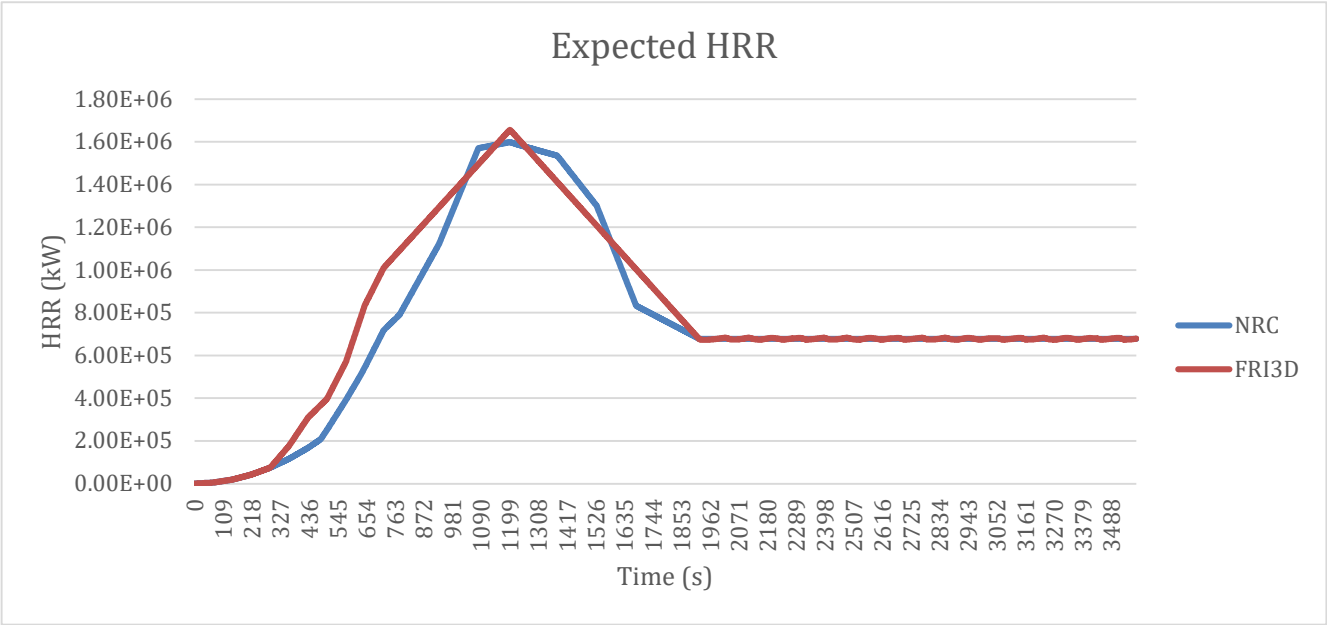
Figure 12. Total HRR in NRC and FRI3D models.

The other comparison made is about the layer heights between the two models as shown in Figure 13. It shows the layer heights are slightly different around the 10 minutes to 30 minutes mark. This height difference might be caused by how the secondary fire was modeled. In the NRC model, it is modeled separately from the initial fire at a different height; meanwhile, it is combined with the primary fire in the FRI3D model. This layer height difference may explain the difference in the upper layer temperatures between the two models as shown in Figure 14.
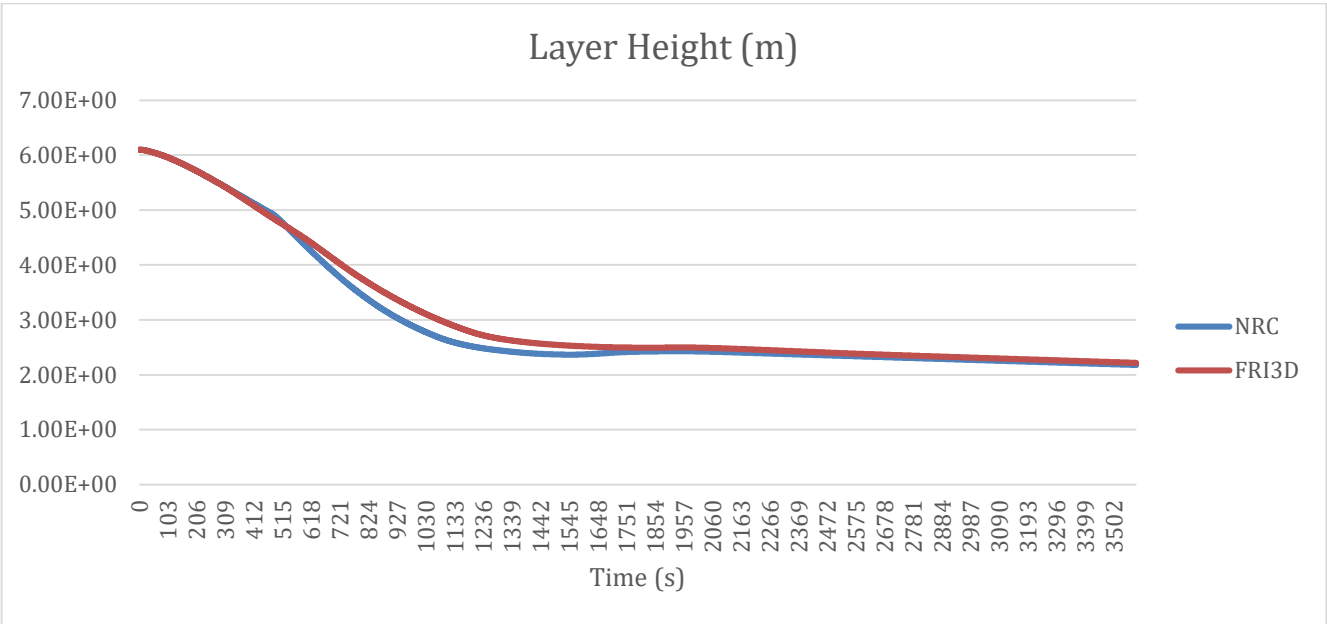
Figure 13. Layer heights in NRC and FRI3D models.
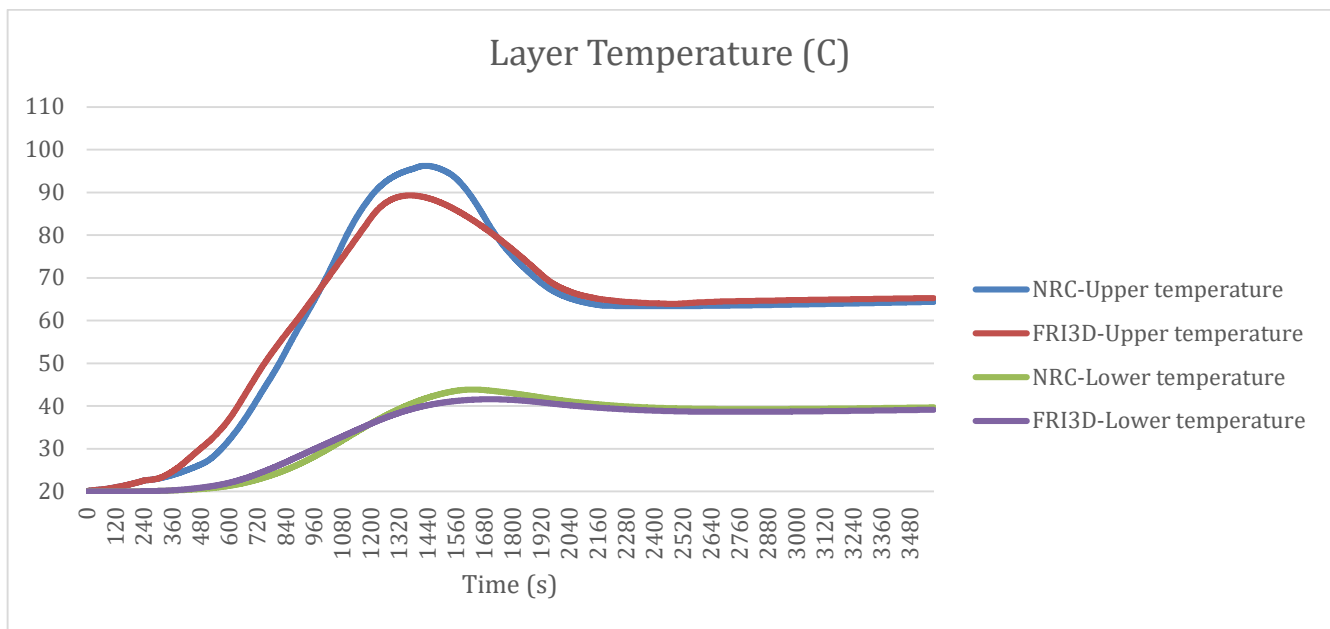
Figure 14. Layer temperatures in NRC and FRI3D models.

3.2   Industry Switchgear Room

Another test model was developed, in collaboration with an industry partner, for an actual nuclear power plant (NPP) switchgear room. An existing FRANX and PDMS databases were imported into FRI3D. These were used along with architectural drawings and the plant fire analysis report, were used to perform the 3D modeling and scenario tests of the switchgear room in FRI3D. The initial goal of this task was to evaluate FRI3D modeling features and the scenario generation process using a large industry model. Section 3.2.1 relates the process and experience of a modeler who was new to using FRI3D and the facility being modeled.

3.2.1   Modeling Insights

Modeling in FRI3D can start out as an empty project or data can be imported from a FRANX file, PDMS facility database. For this evaluation the FRANX file and the architectural drawings were useful starting points but FRI3D had some limitations in using that data. The FRANX import had all the cabinets as raceways and a single source for all cabinet fires. This meant additional sources had to be crated manually and linked to the components. The drawings provided had many useful notations and measurements, but without any set scale, this made it too difficult to import as a floor plan into FRI3D to do the modeling on top as shown in Figure 6. Consequentially, the drawing upload feature was not used for this project. Supporting documentation including the tray and conduit drawings were used to identify raceways listed, determine distances and locations when modeling.

The first operation of modeling in FRI3D is to set the boundaries. This was straightforward given it is a box of the dimensions in the drawings. Multiple boxes are snapped into place to create rooms that are, when combined, not rectangular in shape. There is not a current ability to model a boundary with curved walls in FRI3D.

The second operation of modeling in FRI3D is to populate the room with the various components. Modeling was started with the cabinet sources, then the trays, raceways and conduits. At the time of this modeling, conduits could only be modeled as single strait pieces.

Typical switchgear rooms have multiple cabinets side-by-side, similar to the fictitious example shown in Figure 15. For the plant model, dimensions and positioning were entered as interpreted from the drawings and pictures provided. A copy and paste action, along with a snap-to-object function, provided within FRI3D was used to accomplish this easily after the first one was modeled. In addition, exact X, Y, and Z coordinates are

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listed and can be modified for scale and position as shown in Figure 16. To run scenarios in FRI3D sources were added in each cabinet 1'from the top, under the raceways.
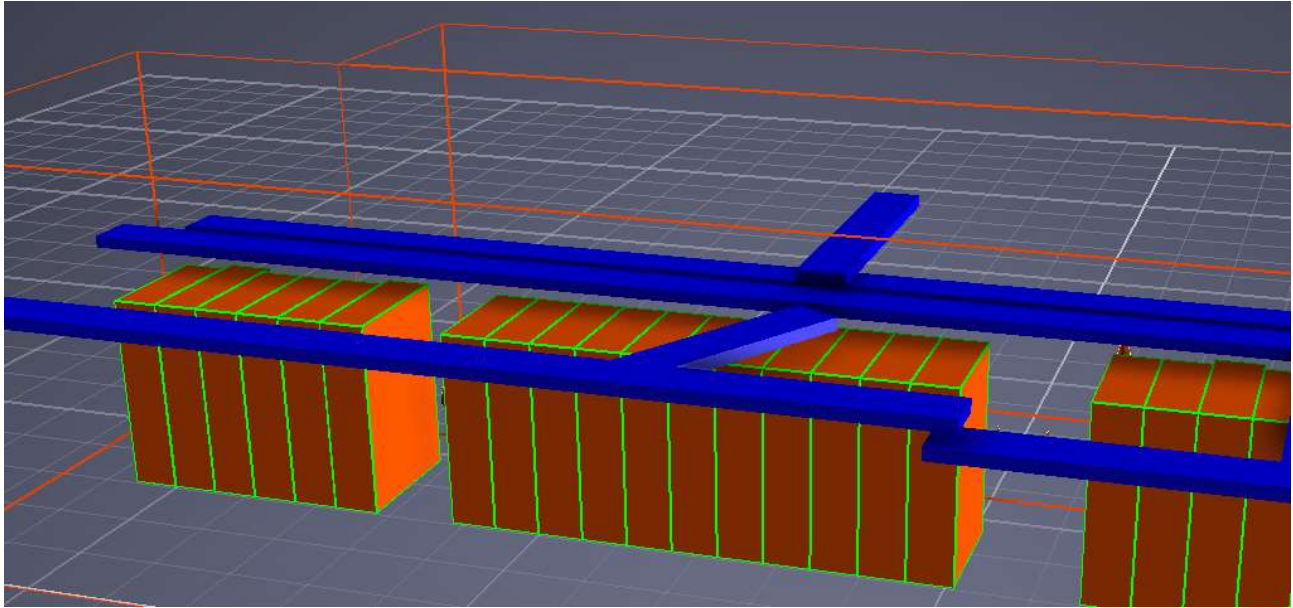
Figure 15. Example of stacked cabinets for modeling a switchgear room.
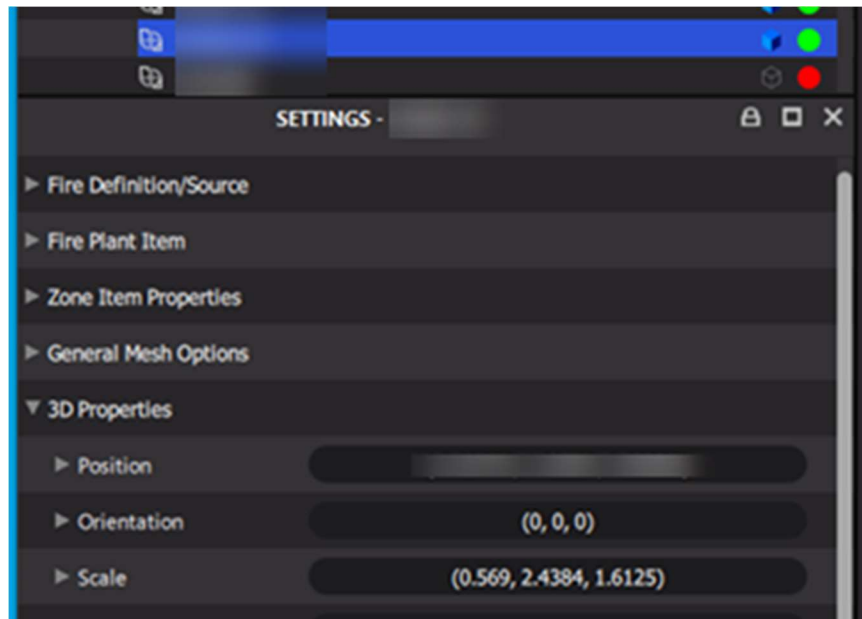
Figure 16. Properties section allowing user to manually set 3D location and size of the item and other properties.

Most, but not all trays and conduits, were modeled, due to time constraints in locating items only using architectural drawing, the modeler not being familiar with the plant and having limited pictures. Having LiDAR scans with tools for measurements and "Street View" visualization for reading labels, would simplify many aspects of this modeling. The "four view" perspective tool, was useful to both visualize and model the room, a generic example is shown in Figure 17.
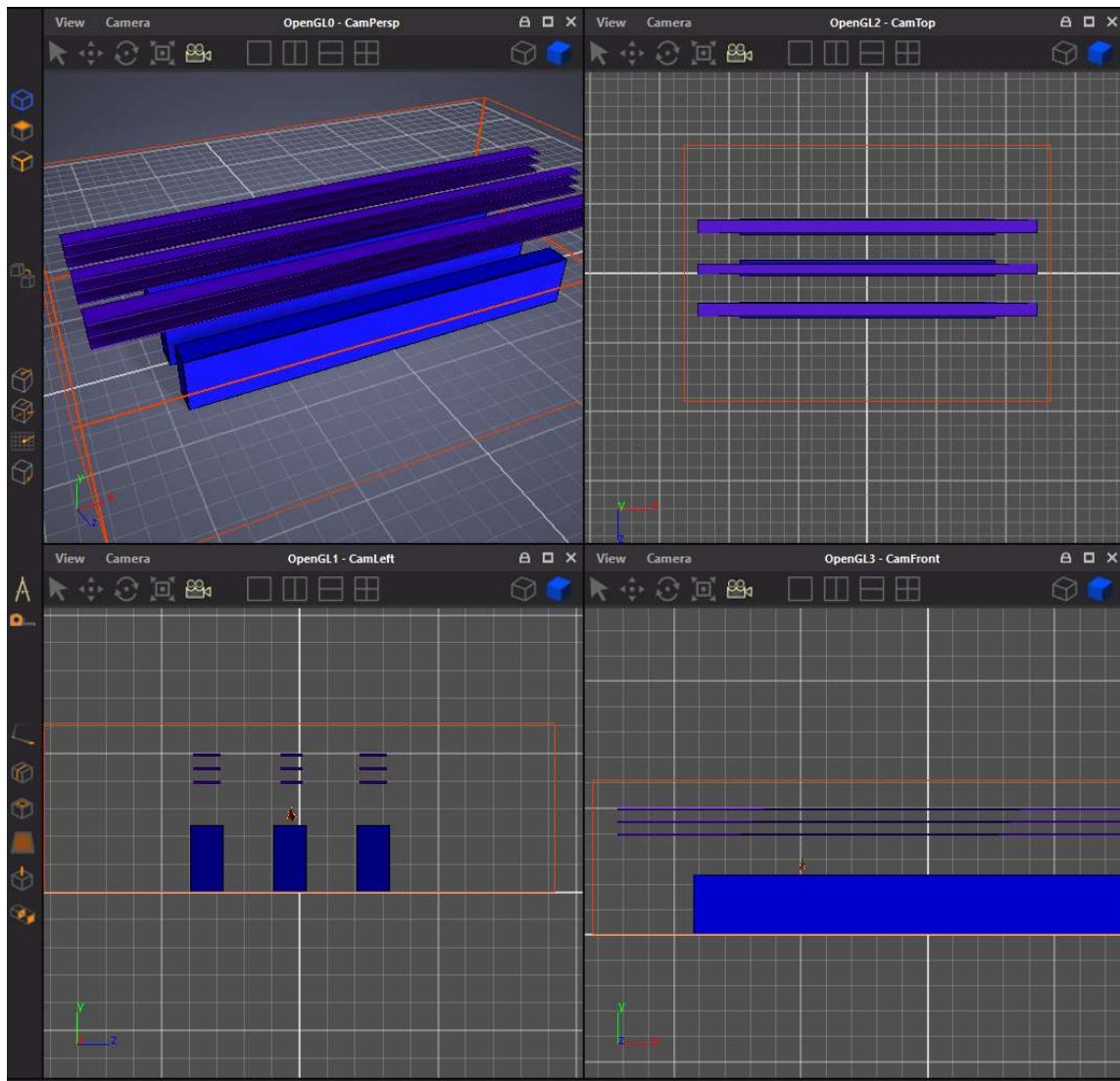
Figure 17. An example of the four view perspectives available in the modeling area of FRI3D.

Beyond the 3D modeling, the properties of each component, such as materials for cables and heat profiles for sources, were entered in a menu based format on sub-levels of the component profile menu. The properties of these features are not contained in FRANX or from known databases and so had to be entered manually.

There were a few issues encountered in modeling using FRI3D, most of which were fixed in development patches while we progressed through the modeling process. The developed improvements include eliminating extensive loading times, adding a snap-to-object function, measurements, copying and pasting 3D information, and more. By the end of the project, the needed features were functional, and most of the time spent creating the model was in researching the placement, dimensions, and materials, instead of modeling the components correctly in 3D area and entering the data. When modeling, it was noted a method to import the HRR data, if available, would be useful as a future improvement. Currently, conservative NRC recommendations are used if the property it is set to Null, which is the default value. One particular point of interest in suggested improvements of the 3D model is to provide curved sections or automated connections. As can be seen in Figure 18, only straight-line segments can be modeled. When two segments of trays lead up to a curve, they must be modeled without a corner unless one is longer than it is in real life, and the other is butted up against it in a corner. A curved portion would be able to connect the two, fill in a little more 3D space for modeling, and

be more aesthetically pleasing and closer to the actual representation. However, this will not affect calculation results using CFAST.
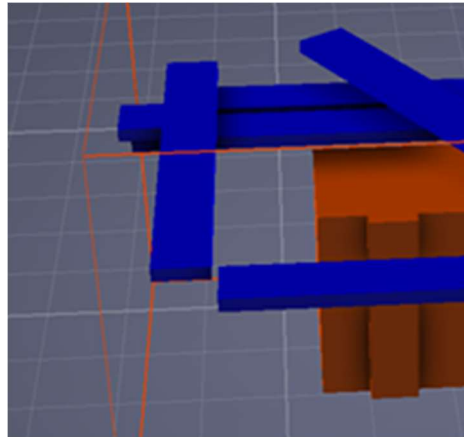
Figure 18. No curved section for trays.

3.2.2 Scenario Generation

After initial modeling of the switchgear room was just completed 6 cabinet fire scenarios from the string of cabinets, were chosen that had different core damage frequencies for the plant or a change in layout. For each of these, the source was used to generate a scenario in FRI3D. The following Table 3-1, compares the failed items of the scenario for the given model vs. FRI3D.

Table 3-6. Scenario results comparison

	Original Failures		FRI3D Failures		% Delta CDF
	Raceways	Cabinets	Raceways	Cabinets	
1	14	3	4	1	76%
2	14	3	2	1	90%
3	14	3	3	1	90%
4	14	3	2	1	90%
5	8	2	2	1	91%
6	11	3	3	1	91%

The existing scenarios were developed using generic fire model treatments where a zone of influence conservatively determines failures. This zone of influence fails all items in a given boundary around the fire depending on an HRR. The differences in the test scenarios are attributed to the more accurate modeling and simulation methods used. CFAST was not used in the initial scenario development because when combining the ignition frequency, severity factor, and suppression probability, the risk increase from these scenarios was considered within acceptable bounds. Using FRI3D to perform more detailed modeling for all key areas could significantly increase margin and more accurately represent the fire contribution to the overall risk of the plant.

4. DYNAMIC FIRE MODELING ASPECTS

One of the drawbacks of traditional PRA modeling is its inability to easily capture changes over time in the model. Estimates are made, and general bins are used to capture large categories of conditions, but this causes large conservatisms in the model. There are several areas in fire modeling such as manual suppression times or crediting component failure times, that could benefit from dynamic modeling.

4.1   Scenario Refinement Using FRI3D

A typical approach for fire scenario selection is iterative. Analysts often start with a very conservative scenario selection and refine scenarios that contribute the most to the overall plant's risk (i.e., fire PRA core damage frequency [CDF] and large early release frequency [LERF]). A very conservative scenario assumes a full room burnout—all the equipment and cables in the same fire zone as the source are failed due to fire with no credit taken for fire suppression. If the risk contribution from this overly conservative scenario is insignificant, then no refinement is needed. For fire zones where the initial overly conservative approach results in a fire risk that is too large, refinements are made where multiple fire scenarios are defined depending on fire severity using the approach described in NUREG/CR-6850, Appendix E [2]. The components are placed in the fire scenarios, or bins, according to the fire with significant enough HRR to fail those components. Multiple fire scenarios can be defined; each scenario characterized by a specific Target Set, HRR, severity factors, and non-suppression probability. However, it is rare when more than three fire scenarios are defined.

Fire scenario definition is not a trivial task since it requires knowledge and experience from the fire engineer to identify which equipment in the zone can be damaged by a fire with certain HRR. This is where FRI3D becomes a valuable tool since it allows a quick simulation of multiple fire bins (i.e., fire scenarios). Each fire bin scenario run will demonstrate equipment that is failed or not failed due to the postulated fire. This quick (matter of minutes) exercise would allow the fire engineer to select the number of fire bins for a given fire zone; each bin associated with a set of equipment (i.e., Target Set) affected by each scenario.

Let's use a hypothetical switchgear room fire zone as an example. The switchgear room has multiple vertical cabinets, all with qualified cables and a set of cable trays at different distances from the cabinets. In a typical fire PRA, two scenarios would be identified in a risk-significant fire zone such as switchgear room per ignition source:

1. **Scenario 1**, where a relatively small fire that fails the cabinet where fire initiated (i.e., fire source) and equipment immediately next to it, and

2. **Scenario 2**, with a larger fire that fail all other targets within the zone of influence for the scenario.

In this hypothetical example, the HRR peak and distribution rates from NUREG/CR-6850 are used for the discussion purpose since severity factors are readily available from the tables in Appendix E. In practice, for fire scenarios where an electrical cabinet is an ignition source, a fire engineer would use HRR peak and distribution rates from NUREG/CR-2178 Tables 4-1 and 4-2 [4], to calculate severity factors. The fire scenario guidance did not change from NUREG/CR-6850 to NUREG/CR-2178. NUREG/CR-2178 provides refined (i.e., more realistic, less conservative) HRR peak and distribution rates for select ignition sources. Specifically, HRR distribution rates were refined for main control boards, battery chargers, and electrical cabinets. To simplify the discussion, values from NUREG/CR-6850 are used to describe the approach for scenario refinement which would remain the same if used HRR values from NUREG/CR-2178.

From Table E-3 in [2] presented as Figure 19, severity factors would be SF_1=0.506 and SF_2=0.494 for Scenario 1 and Scenario 2, respectively.

Table E-3
Discretized Distribution for Case 2 Heat Release Rate (Vertical Cabinets with Qualified Cable, Fire in more than One Cable Bundle)

Bin	Heat Release Rate – kW (Btu/s)			Severity Factor (P_i)
	Lower	Upper	Point Value	
1	0 (0)	90 (85)	34 (32.7)	0.506
2	90 (85)	179 (170)	130 (123)	0.202
3	179 (170)	269 (255)	221 (209)	0.113
4	269 (255)	359 (340)	310 (294)	0.067
5	359 (340)	448 (425)	400 (379)	0.041
6	448 (425)	538 (510)	490 (464)	0.026
7	538 (510)	628 (595)	579 (549)	0.016
8	628 (595)	717 (680)	669 (634)	0.010
9	717 (680)	807 (765)	759 (719)	0.006
10	807 (765)	897 (850)	848 (804)	0.004
11	897 (850)	986 (935)	938 (889)	0.003
12	986 (935)	1076 (1020)	1028 (974)	0.002
13	1076 (1020)	1166 (1105)	1118 (1060)	0.001
14	1166 (1105)	1255 (1190)	1208 (1145)	0.001
15	1255 (1190)	Infinity	1462 (1386)	0.001

$SF_1 = 0.506$
$SF_{R1} = 0.506$
$SF_2 = 0.494$
$SF_{R2} = 0.489$
$SF_{R3} = 0.005$

Figure 19. NUREG/CR-6850, Table E-3.

Let's postulate a fire in one of the switchgear room cabinets, Ignition Source in Figure 20. Let's also postulate the switchgear room houses equipment that supports critical SSCs (e.g., reactor heat removal [RHR] pump, emergency feedwater [EFW] pump), Target Set C in Figure 20. Failure of Target Set C would clearly result in a significant contribution to risk. Since Target Set C would fail due to a larger fire compared to a smaller fire capable of failing Target Set A, it may be desirable to create an additional scenario for this fire zone.
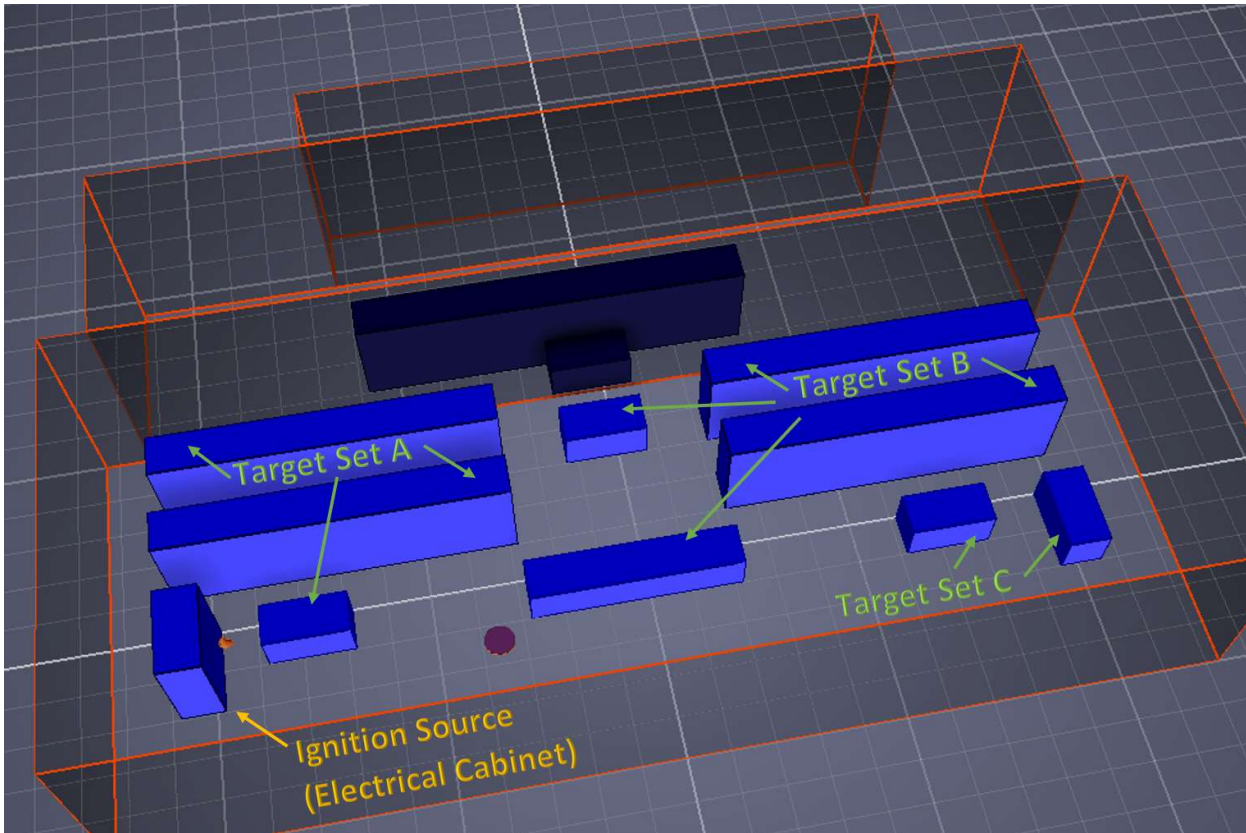
Figure 20. Hypothetical Switchgear Room Layout.

Using FRI3D, the fire engineer would quickly run fire simulations with various HRRs from Table E-3 in [2] to find out, for example, the fire with a HRR of 1076 kW (a conservative upper HRR value) corresponding to Bin #12 fails Target Set C, but none of smaller HRR fires would. In this case, three scenarios with three severity factors (SF_{Ri}, *R for Refined*) are warranted: Scenario 1 with SF_{R1}=0.506, Scenario 2 with SR_{R2}=0.489, and Scenario 3 with SF_{R3}=0.05. Scenario 3 is dedicated to equipment with high-risk significance. This allowed, in this example, to lower the probability of Target Set C equipment failure due to a fire initiated in the Ignition Source by two orders of magnitude by reducing the severity factor from 0.494 to 0.005.

This fire scenario refinement is achievable using traditional fire modeling approaches, but it is a time-consuming and labor-intensive task. However, the same task would only take minutes to accomplish using FRI3D.

4.2 Failure Timing

Time is an important parameter in fire analyses, but it is not always credited or properly accounted for in typically conservative fire PRA models. FRI3D has a feature to show the time-dependent temperature and failure timing of components in the model, as shown in Figure 21. The figure shows failed components as highlighted with red borderlines. Meanwhile the bottom part of the figure is a timeline measured in seconds, showing the time when each component fails.
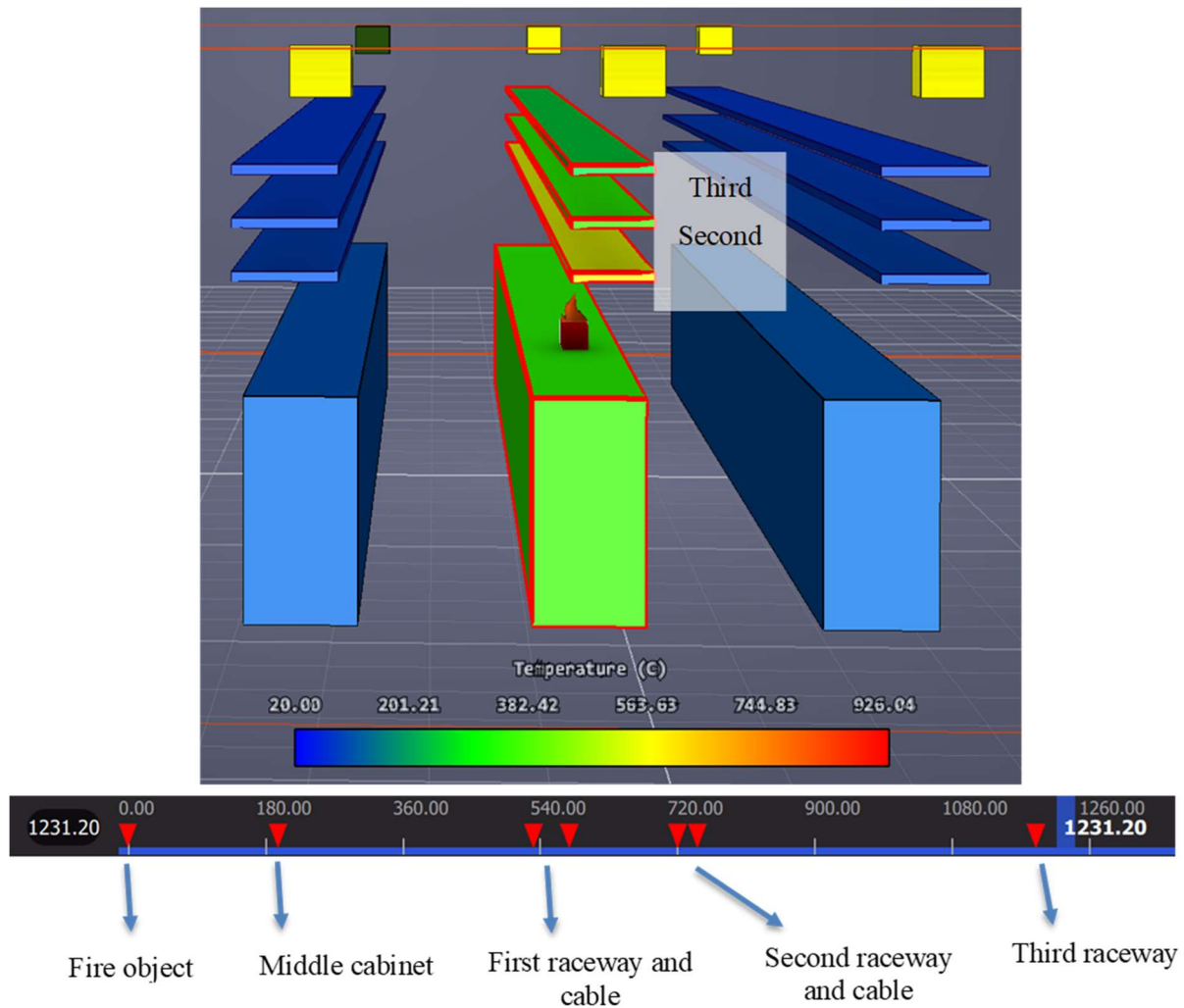
Figure 21. Time-dependent temperature and failures in FRI3D.

Two areas where fire scenario timing is important are discussed in the subsections below.

4.2.1 Fire Non-Suppression Probability Determination

In a typical fire PRA, fire suppression is not always credited because determination of fire non-suppression probabilities requires additional analyses and advanced fire modeling. The two essential parameters required to calculate fire non-suppression probability are time for smoke detection and time to target damage. Simulations in FRI3D provide the necessary timing parameters, and these time values are linked to the visualization module of fire scenario progressing. This, for example, allows the user to quickly identify potential benefits of refinement of fire scenarios to take advantage of decreased non-suppression probability associate with given target sets.

The time for detection is time for the operators to recognize presence of fire and initiate fire procedures which start with deployment of a plant operator to verify the alarm. Upon alarm verification and confirmation, actions are taken for fire suppression, such as manual actuation of fire suppression system and/or fire brigade deployment. Success of fire suppression is directly dependent on time available before postulated fire damages the Target Set (e.g., a cable supporting risk-significant equipment). The benefit of FRI3D is it includes necessary advanced fire simulation modeling and required timing parameters are available for each fire scenario simulation.

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To obtain a realistic fire non-suppression probability, a dynamic simulation of operator actions to recognize the presence of fire and implement fire suppression given specific fire scenario progression parameters can be performed. This can be accomplished by using dynamic PRA modeling tool Event Modeling Risk Assessment using Linked Diagrams (EMRALD) which uses state diagrams to represent fire progression, plant states, operator actions, and their relations. In this case, fire engineer would use more plant-specific and scenario-specific inputs to calculate non-suppression probability instead of reliance on the generic industry-wide non-suppression probability distribution function. The dynamic simulation approach offers a justified basis for the selection of a more realistic non-suppression probability value for a given scenario of interest—an option not readily available if generic industry values are used.

Taking credit of fire suppression allows to further reduce risk from a given fire scenario and, consequently, lower overall fire hazard risk metrics for the entire plant.

4.2.2   Correlation of Target Set Failure Time and Affected Operator Actions

Another area of conservatism related to timing is an assumption that operator actions with reliance on indicators that may be affected by fire are guaranteed to fail. However, there may be a case an operator action may still be successful because fire damage to a cable supplying power to the associated indicator occurs after the operator action is expected to take place. For example, operator action is to start a standby train of a system when recognizing the primary train is inoperable. If the cable supporting equipment providing indication of the primary train operability is postulated to be damaged by a fire scenario, probability of failure of the operator action to start the standby train is set to 1.0 (i.e., operator action is considered not feasible, and credit is not taken for the fire scenario).

This is where a dynamic risk analysis can be applied to determine probability of operator action failure due to a loss of indication caused by fire damage. In this case, operator action failure probability would not have to be set to 1.0. Instead, probability of operator action failure would be determined based on time required to accomplish the action and time to indicators being damaged due to fire.

5.   OUTCOMES

5.1   Summary

The features and methods implemented in FRI3D can assist with most of the fire modeling steps and automate many manual areas. Modeling both the NUREG 1934 Appendix A example and an industry switchgear room tested the FRI3D software features for industry needs. Several modeling capabilities and evaluation gaps were discovered and fixed. Testing of the 3D modeling tools and features in FRI3D estimate a reduction in modeling and integration into fire PRA by 50%, time saving for plant modifications would be more significant but still need comparison cases for evaluation.

To reduce costs, early fire modeling only modeled to a level of detail where the CDF risk combined with the ignition frequency; severity factor was considered within acceptable bounds. While these may be currently within bounds, overall fire contributions unrealistically dominate risk calculations and may not provide enough margin for small changes or corrections to the model. While there may be many small features that still need developed for direct industry use, it has been shown FRI3D can provide an economical way to do detailed modeling and help bring about the anticipated benefits from the NFPA 805 fire PRA methodology.

Verification of generating and running of the fire simulation code was done using NUREG Appendix A and B test cases. By using validated tools and methods, a strong verification process is all that is needed for use by industry. The industry example model will be used for further research activities primarily the dynamic modeling scenarios outlined in Section 4 are planned to be implemented directly into the software.

5.2   Additional Capabilities Needed

Some features that were not critical to this switchgear room modeling or were identified and are listed below:

- Bulk cable additions – The ability to add multiple cables that are not part of the safety systems or in the FRANX model for inclusion in secondary combustibles.

- Tray duplication – The ability to duplicate tray items with contained cables. This feature will assist in the development of more detailed models, making it easier to model tray path changes or start with a simple model and making it more detailed by adding additional sections.

- Obstructed temperatures – CFAST currently does not include new elements to reduce conservatisms including calculate obstructed plume temperatures specified in NUREG-2178 Vol. 1 [7], obstructed radiation in NUREG-2178 Vol. 2, and fire location factor in NUREG -2178 Vol. 2 [4].

- Tools verification check – Include a check to verify the output and execution of CFAST is setup correctly upon install of software.

In this work, other items were identified that were missing or considered key for industry use; they are outlined in the subsections of 5.2.

5.2.1 Vertical FLASH-CAT

The FLASH-CAT methodology was initially designed for horizontal cables. Several additions to FLASH-CAT methodology will be incorporated as future works as follows:

1. Including FLASH-CAT for vertical cables, which is done by adjusting the flame spread rate to 50 m/h.

2. Adding a "flashover" scenario which burns the cable at its full length instead of gradually as in FLASH-CAT methodology. This is done when the gas layer temperature exceeds the cable's ignition point. Further details are needed to incorporate this scenario, which includes the period of burning and the HRR time profile.

3. Adding a checkbox in FRI3D for raceways/cables to be included/excluded from FLASH-CAT calculation. This feature is needed because FLASH-CAT methodology is derived with several technical assumptions that may not be fully determined from the model but requires engineering judgment from the modeler.

5.2.2 Transient Location Identification

Transients scenarios have a likelihood of occurring at any open location within the compartment; however, some locations are more significant than others. The current process takes some engineering judgment to identify the most significant spot in order to conservatively model that scenario instead of evaluating all possible scenarios of the open floor space. FRI3D could determine a "Area of Influence" for the transient types and do spatial calculations to identify where there are possible failure change sections in the open floor space. Each of these sections can then be calculated using the current FRI3D scenario process to determine the most significant location. This would provide an automated method to determine transient locations without expert judgment being required and removing the risk of human errors.

5.1 Industry Access

An Alpha version of FRI3D can be made available for evaluation by industry and can support most aspects needed for fire modeling. The software backend and user interface were developed for Light Water Reactor Sustainability (LWRS) Program's research and as part of a Department of Energy technology transfer with Centroid Lab. For access to the software, contact Steven.Prescott@inl.gov or Ram@centroidlab.com.

6. REFERENCES

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Appendix A

Comparison on NUREG-1934 Appendix A Results from NRC's and FRI3D Models

Appendix A
Comparison on NUREG-1934 Appendix A Results from NRC's and FRI3D Models

Several variables from Table A-1 which have significant percentage difference are plotted in Figure A-1 for further investigation. The figure shows the maximum recorded deviations in HRR upper actual and plume entrainment rate can be dismissed as outliers. Further scrutiny of the data confirmed the variation was in the order of 1E–12 which is negligible. It might have originated from round-off errors in the software. The upper layer volume variation was rather consistent. It might have been caused by the difference in compartment dimensions including its height. This geometrical factor seems to be the underlying issue on the variation of the hot gas layer's properties including optical density and concentration of gaseous particles (CO, CO_2, and HCL).

Table A-1. Maximum difference between NRC and FRI3D outputs on NUREG-1934 Appendix A.

Variable	Maximum difference (%)
Upper Layer Temperature	4.01%
Lower Layer Temperature	1.14%
Layer Height	2.29%
Upper Layer Volume	44.00%
Pressure	6.01%
N_2 Upper Layer	0.15%
O2 Upper Layer	0.61%
CO_2 Upper Layer	23.82%
CO Upper Layer	23.82%
HCN Upper Layer	0.00%
HCl Upper Layer	23.82%
Unburned Fuel Upper Layer	0.00%
H_2O Upper Layer	4.28%
Optical Density Upper Layer	23.80%
OD from Flaming Upper Layer	23.80%
OD from Smoldering Upper Layer	0.00%
N_2 Lower Layer	0.01%
O2 Lower Layer	0.03%
CO_2 Lower Layer	0.00%
CO Lower Layer	0.00%
HCN Lower Layer	0.00%
HCl Lower Layer	0.00%
Unburned Fuel Lower Layer	0.00%
H_2O Lower Layer	0.03%
Optical Density Lower Layer	0.00%
OD from Flaming Lower Layer	0.00%
OD from Smoldering Lower Layer	0.00%
Ignition	0.00%

Variable	Maximum difference (%)
Plume Entrainment Rate	21.45%
Pyrolysis Rate	0.00%
HRR Expected	0.00%
HRR Actual	0.00%
HRR Convective Actual	0.00%
HRR Lower Actual	0.00%
HRR Upper Actual	100.00%
Flame Height	0.00%
HRR Door Jet Fires	0.00%
HRR Door Jet Fires	0.00%
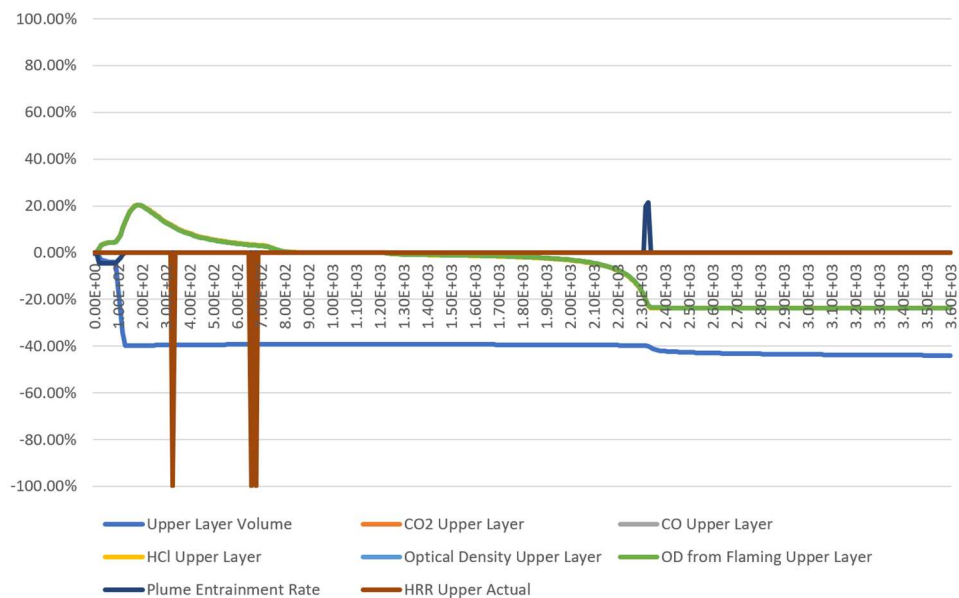
Figure A-1. Variations of selected outputs from Table A-1.

Table A-2 shows the maximum difference for the vents' outputs between the two models. It shows there were no significant differences. The discrepancy in wall and floor leakage values may be caused by the difference in compartment dimensions.

Table A-2. Maximum difference between NRC and FRI3D vent outputs on NUREG-1934 Appendix A.

Variable	Description	Maximum difference (%)
W_1_Outside_1	Net Inflow	2.98%
WF_Outside_1_1	Opening Fraction	0.00%
M_1_Outside_1	Net Inflow	0.17%
M_TRACE__1_Outside_1	Trace Species Flow	0.00%
M_FILTERED_1_Outside_1	Trace Species Filtered	0.00%
MF_Outside_1_1	Opening Fraction	0.00%
M_1_Outside_2	Net Inflow	0.17%

Variable	Description	Maximum difference (%)
M_TRACE__1_Outside_2	Trace Species Flow	0.00%
M_FILTERED_1_Outside_2	Trace Species Filtered	0.00%
MF_Outside_1_2	Opening Fraction	0.00%
M_Outside_1_3	Net Inflow	0.00%
M_TRACE__Outside_1_3	Trace Species Flow	0.00%
M_FILTERED_Outside_1_3	Trace Species Filtered	0.00%
MF_1_Outside_3	Opening Fraction	0.00%
M_Outside_1_4	Net Inflow	0.00%
M_TRACE__Outside_1_4	Trace Species Flow	0.00%
M_FILTERED_Outside_1_4	Trace Species Filtered	0.00%
MF_1_Outside_4	Opening Fraction	0.00%
M_Outside_1_5	Net Inflow	0.00%
M_TRACE__Outside_1_5	Trace Species Flow	0.00%
M_FILTERED_Outside_1_5	Trace Species Filtered	0.00%
MF_1_Outside_5	Opening Fraction	0.00%
M_Outside_1_6	Net Inflow	0.00%
M_TRACE__Outside_1_6	Trace Species Flow	0.00%
M_FILTERED_Outside_1_6	Trace Species Filtered	0.00%
MF_1_Outside_6	Opening Fraction	0.00%
M_Outside_1_7	Net Inflow	0.00%
M_TRACE__Outside_1_7	Trace Species Flow	0.00%
M_FILTERED_Outside_1_7	Trace Species Filtered	0.00%
MF_1_Outside_7	Opening Fraction	0.00%
M_Outside_1_8	Net Inflow	0.00%
M_TRACE__Outside_1_8	Trace Species Flow	0.00%
M_FILTERED_Outside_1_8	Trace Species Filtered	0.00%
MF_1_Outside_8	Opening Fraction	0.00%
Wall Leak	Net Inflow	6.81%
Floor Leak	Net Inflow	4.75%

Table A-3 shows the maximum difference between the two models, specifically on the particulate concentrations on the upper and lower layers. Most of these differences originate in the upper layer, which might be caused by the discrepancy in compartment's height between the two models. Some of these variables are plotted in Figure A-2.

Table A-3. Maximum Difference Between NRC and FRI3D Particulate Concentration on NUREG-1934 Appendix A.

| Particulate Concentration	Maximum Difference (%)
N_2 Upper Layer Mass	43.95%
O_2 Upper Layer Mass	43.68%
CO_2 Upper Layer Mass	57.33%
CO Upper Layer Mass	57.33%
HCN Upper Layer Mass	0.00%
HCl Upper Layer Mass	57.33%
Unburned Fuel Upper Layer Mass	0.00%
H_2O Upper Layer Mass	46.39%
Soot Upper Layer Mass	57.33%
Soot from Flaming Upper Layer Mass	57.33%
Soot from Smoldering Upper Layer Mass	0.00%
Trace Species Upper Layer Mass	0.00%
N_2 Lower Layer Mass	1.83%
O_2 Lower Layer Mass	1.83%
CO_2 Lower Layer Mass	0.00%
CO Lower Layer Mass	0.00%
HCN Lower Layer Mass	0.00%
HCl Lower Layer Mass	0.00%
Unburned Fuel Lower Layer Mass	0.00%
H_2O Lower Layer Mass	1.83%
Soot Lower Layer Mass	0.00%
Soot from Flaming Lower Layer Mass	0.00%
Soot from Smoldering Lower Layer Mass	0.00%
Trace Species Lower Layer Mass	0.00%
Total Pyrolysate Released	0.09%
Total Trace Species Released	0.00%
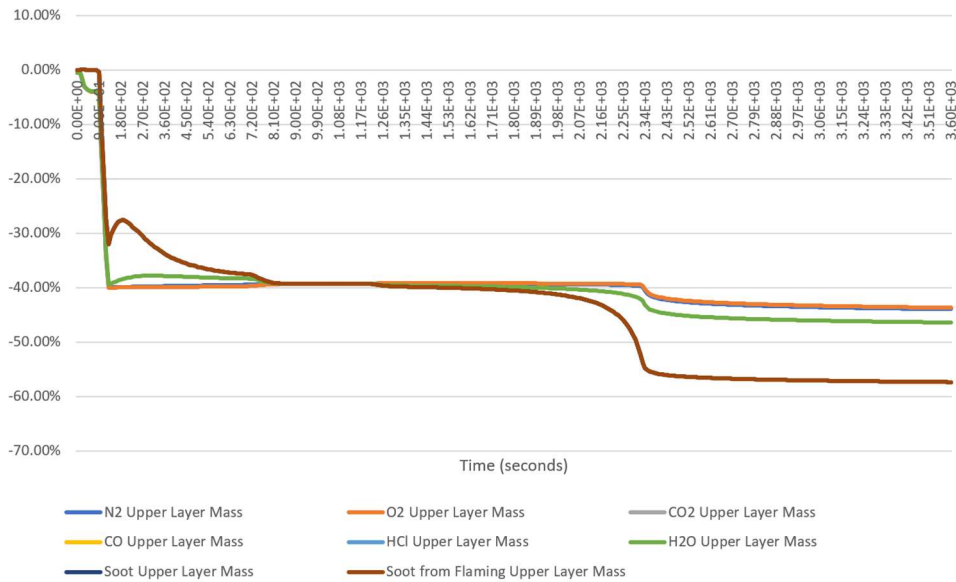
Figure A-2. Variations of selected variables from Table A-3.

Table A-4 shows the maximum difference of compartment wall temperature between the two models of NUREG-1934 Appendix A. There was not a significant difference observed in this case.

Table A-4. Maximum difference between NRC and FRI3D wall temperature on NUREG-1934 Appendix A.

Variable	Maximum Difference (%)
Ceiling Temperature	0.95%
Upper Wall Temperature	1.53%
Lower Wall Temperature	3.48%
Floor Temperature	0.46%

Smokeview is a compact visualization tool that comes bundled with CFAST installer. It allows the CFAST output to be displayed visually in a three-dimensional layout. The Smokeview visual of NRC model on NUREG-1934 Appendix A is shown in figure A-3; meanwhile, the visual of FRI3D output of the same model is in figure A-4. The figures show the layers' temperatures are similar; however, the hot gas layer in FRI3D model was thinner than the one in the NRC model. This might be caused by the difference in compartment dimensions between the two models. This spatial discrepancy also caused the difference on the location of the mid-compartment slice. The NRC model puts all the mechanical vents in the same horizontal location. This approach is acceptable because vent horizontal location does not affect CFAST simulation which is based on zone-modeling methodology. Meanwhile FRI3D modeled all vents in their respective horizontal coordinates to give a better visual output to the user.
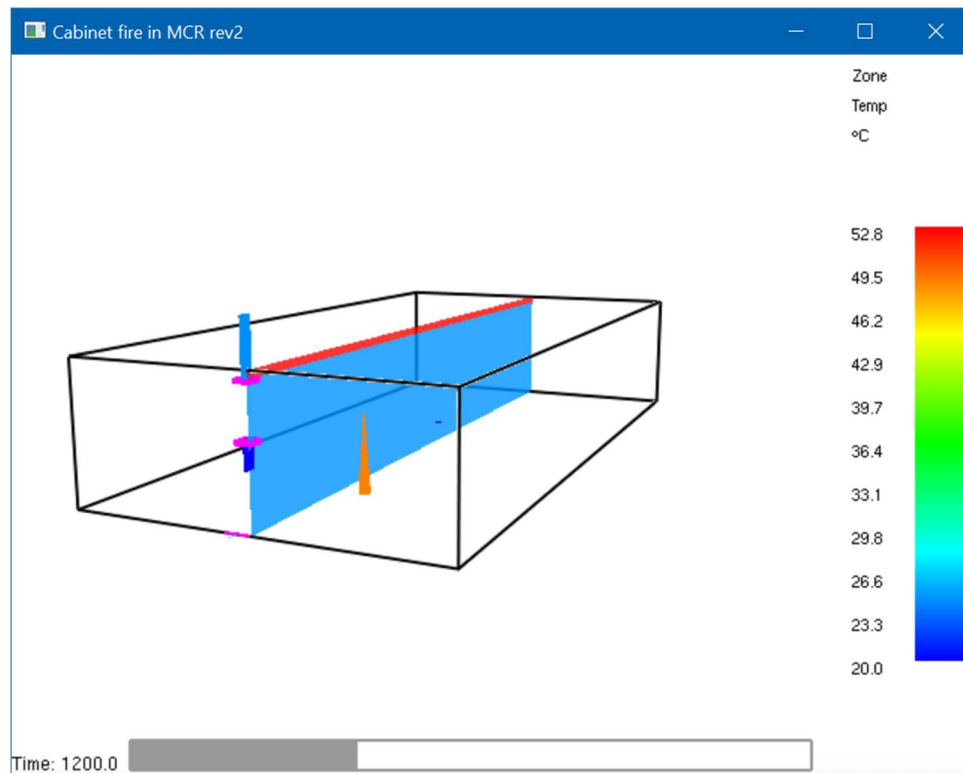
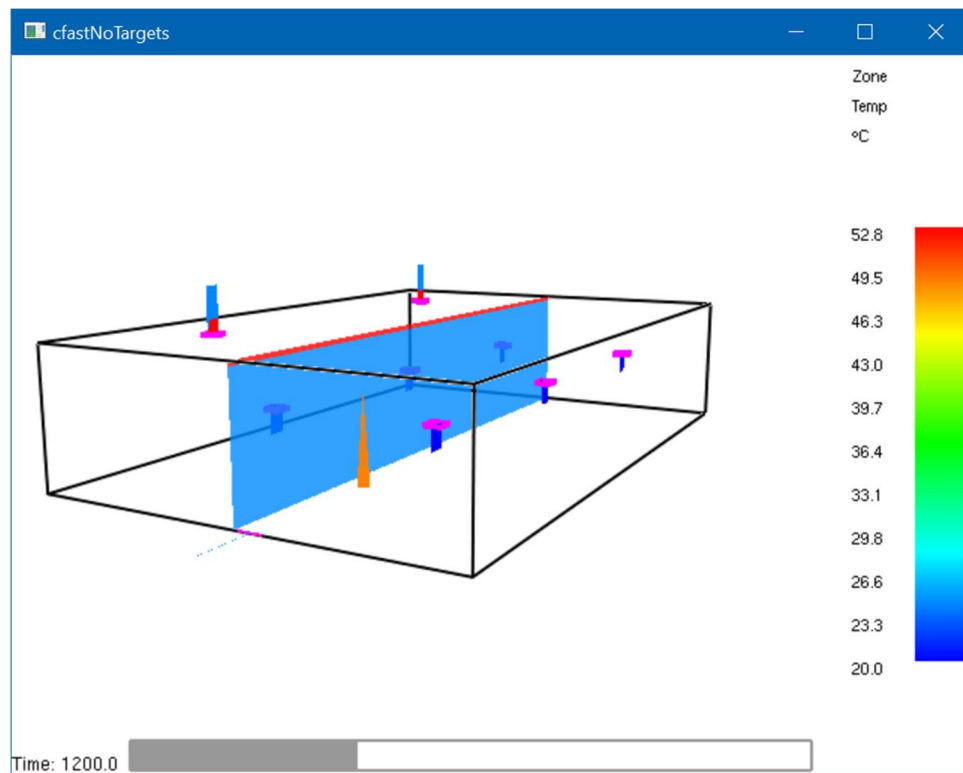Figure A-3. Smokeview output of NUREG-1934 Appendix A NRC model.

Figure A-4. Smokeview output of NUREG-1934 Appendix A FRI3D model.

Appendix B

Comparison on NUREG-1934 Appendix B Results from NRC's and FRI3D Models

Appendix B
Comparison on NUREG-1934 Appendix B results from NRC's and FRI3D Models

Several parameters in Table B-1 below have significant percentage differences. These large differences were caused by a dividing them with a small value that is close to zero to form a percentage. Therefore, even a slight difference between the two variables become significant when expressed in the percentage format.

Table B-1. Maximum difference between NRC and FRI3D outputs on NUREG-1934 Appendix A.

Variable	Maximum difference (%)
Upper Layer Temperature	16%
Lower Layer Temperature	7%
Layer Height	12%
Upper Layer Volume	11%
Pressure	40%
N_2 Upper Layer	1%
O_2 Upper Layer	4%
CO_2 Upper Layer	71%
CO Upper Layer	55%
HCN Upper Layer	0%
HCl Upper Layer	71%
Unburned Fuel Upper Layer	0%
H_2O Upper Layer	19%
Optical Density Upper Layer	68%
OD from Flaming Upper Layer	68%
OD from Smoldering Upper Layer	0%
N_2 Lower Layer	0%
O_2 Lower Layer	0%
CO_2 Lower Layer	0%
CO Lower Layer	0%
HCN Lower Layer	0%
HCl Lower Layer	0%
Unburned Fuel Lower Layer	0%
H_2O Lower Layer	0%
Optical Density Lower Layer	0%
OD from Flaming Lower Layer	0%
OD from Smoldering Lower Layer	0%
Ignition	0%
Plume Entrainment Rate	71%
Pyrolysis Rate	0%
HRR Expected	85%
HRR Actual	85%

Variable	Maximum difference (%)
HRR Convective Actual	85%
HRR Lower Actual	100%
HRR Upper Actual	100%
Flame Height	38%
HRR Door Jet Fires – Switchgear Room	0%
HRR Door Jet Fires - Outside	0%

Appendix C

Lookup and Default Values

Appendix C
Lookup and Default Values

Conservative default values have been used in several areas of the model. The user can increase the fidelity of the model by determining the correct value or modeling those features. The following are the areas and values used:

The following areas still need methods for adding default values:

- Venting – If vents are not added to the 3D model then a conservative vent sized for flow, using Q* (Fire Froude Number) for fire diameter, should be added. This makes sure the fire is not limited from lack of oxygen.

The following JSON file is used to look up most default values used if the user does not specify a value:

"defaultSimInfo": {

  "simulation time": 900,

  "pressure": 101325,

  "humidity": 50,

  "interior temperature": 20,

  "exterior temperature": 20,

  "default component Fail Temp": 205,

  "cfast props": {

    "text output interval": 50,

    "spreadsheet output interval": 10,

    "dfltCableType": "thermoplastic",

    "smokeview output interval": 10,

    "maximum time step": 2,

    "lower oxygen limit": 0.15,

    "adiabatic surfaces": "false",

    "default material": "Concrete 8in"

  },

  "fds props": []

},

"defaultFlashCat": {

  "number of cables": 32,

  "tray spacing": 0.3,

  "tray length": 2.4,

  "tray width": 0.45,

  "mass per length": 253,

  "plastic mass fraction": 0.69,

"char yield thermoset": 0.25,

"char yield thermoplast": 0,

"hrrpua thermoset": 150000,

"hrrpua thermoplast": 250000,

"spread rate thermoset": 0.000305556,

"spread rate thermoplast": 0.000888889,

"heat of combustion": 16000,

"ignition flux thermoset": 11000,

"ignition flux thermoplast": 6000,

"ignition temp thermoset": 625,

"ignition temp thermoplast": 400,

"fire diameter": 0.3
},
"defaultCriterian": {
  "cfast": {
    "type": "time",
    "value": [0],
    "percent": [1]
  },
  "fds props": []
}
}

The following values from a JSON file are used for determining failure times of cables for the "heat soak" method and is derived from NUREG 2187 [4]:

"heatSoakTable": {
  "thermoset": {
    "temps": [330, 335, 340, 345, 350, 360, 370, 380, 390, 400, 410, 430, 450, 470, 490, 99999],
    "failTimes": [28, 28, 24, 20, 16, 13, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1]
  },
  "thermoplastic": {
    "temps": [205, 220, 240, 245, 260, 275, 290, 300, 315, 330, 345, 355, 370, 99999],
    "failTimes": [30, 25, 20, 15, 10, 8, 7, 6, 5, 4, 3, 2, 1, 0]
  }
},
"heatSoakHFTable": {

```
"thermoset": {
  "temps": [ 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 14, 16, 18, 99999 ],
  "failTimes": [ 209, 209, 104.5, 69.66, 52.25, 41.8, 34.8, 29.85, 25.8, 32.2, 20.9, 19, 12, 6, 1 ]
},
"thermoplastic": {
  "temps": [ 1, 2, 3, 4, 5, 6, 8, 10, 11, 14, 16, 99999 ],
  "failTimes": [ 114, 114, 57, 38, 28.5, 28.8, 19, 10, 6, 4, 2, 1 ]
}
```