Coupling Simulation Driven Fire Risk Analysis in 3D (FRI3D) with Probabilistic Safety Analysis using RiskSpectrum PSA

Ramprasad Sampath(*)[a], Steven Prescott[b]
[a]Centroid LAB, Torrance, USA
[b]Idaho National Laboratory, Idaho Falls, USA

Abstract: Current fire modeling practices require many manual steps and processes to transfer fire scenario information and data between fire logic databases, analytical methods such as Fire Dynamic Tools (FDT), zone model tools such as the Consolidated Model of Fire and Smoke Transport (CFAST), computational fluid dynamics tools like Fire Dynamics Simulator (FDS) and Probabilistic Safety Analysis tools software such as RiskSpectrum PSA (RSPSA). The Fire Risk Investigation in 3D (FRI3D) software was developed to help minimize these manual steps by automating as many steps as possible and linking the 3D spatial information with the PSA logic. RiskSpectrum PSA software is used by nuclear plants worldwide for performing various PSA tasks. However, for Fire PSA, external tools had to be used as a process involving manual integration of results. Initially, FRI3D was coupled directly with the existing fire logic input data to perform fire analysis. This paper presents a cost-effective and timely solution by providing seamless integration of 3D computational simulation-driven fire analysis using FRI3D into the RiskSpectrum PSA toolkit, where event/fault trees are updated with fire simulation-driven results simultaneously, providing advanced visualization capabilities by means of an example of a fire scenario being added into RiskSpectrum PSA for evaluation based on a generic compartment from a generic facility.

Keywords: PSA, Risk Spectrum, Fire PRA, Fire PSA.

1. INTRODUCTION

Fire Risk Investigation in 3D (FRI3D) is a software that implements industry approved methods to simplify and automate many tasks required for nuclear power plant (NPP) fire modeling. To that extent, FRI3D was designed with the ability to couple the most commonly used tools and methods used by the NPP industry such as RiskSpectrum Inc's (RS) RiskSpectrum PSA (RSPSA) software [1].

RiskSpectrum PSA is used to construct and calculate NPP risk models, typically for regulatory use. More recent updates to these models have included a standard process for fire modeling aspects. FRI3D automates the Fire PSA process to create and calculate its scenarios in RiskSpectrum PSA. This paper outlines the RiskSpectrum fire modeling process and how it is automated using FRI3D, which drastically reduces costs for development and maintenance at applicable facilities using fire Probabilistic Risk Analysis(PRA) or Probabilistic Safety Analysis(PSA) models. In this paper the terms PRA and PSA have been used interchangeably.

2. FRI3D OVERVIEW

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 a single easy-to-use platform. This enables users to easily perform advanced fire modeling as well as compartment screening and several other steps outlined in NUREG/CR-6850 [2].

2.1. Fire Modeling Components

There are several aspects of a fire model that FRI3D maintains and links together. The software can import a plant's existing fire-PSA logic model and plant equipment databases in certain formats such as FRANX and Plant Data Model System (PDMS). FRI3D currently couples with Consolidated Model of Fire and Smoke Transport (CFAST) [3] as well as Fire Dynamic Simulator (FDS) [4] with an open ended architecture enabling coupling to various other fire modeling and PSA codes. The interactions between tools are shown in Figure 1. For more information on the specific processes involved, please refer to [5].

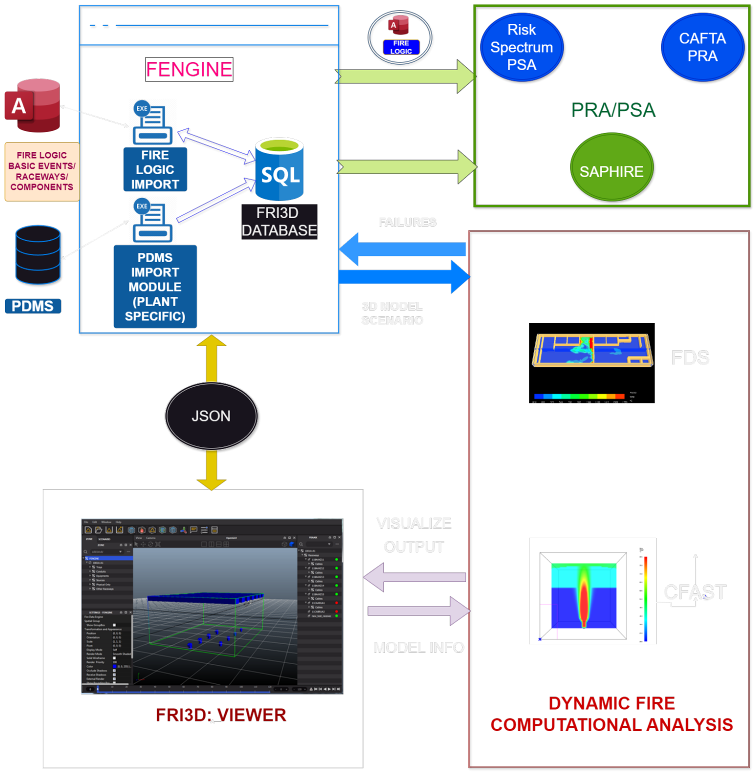

Figure 1. Integration of FRI3D Components

The user-friendly interface of FRI3D enables users to import, setup, configure and run the fire scenarios needed and the failures resulting from these scenarios are automatically linked with their associated fire logic. The, simulation results, scenarios, 3D data, and PRA/PSA links are all stored in an internal sequential database thereby enabling post processing and statistics.

2.2. User Interface

FRI3D provides a graphical user interface that includes a Computer Aided Design (CAD) based modeling tool, view different compartments and associated scenarios, then assign or modify the spatial information in the center 3D area. Detailed fire modelling of nuclear power plants (NPPs) requires many steps, tools, and calculations. By combining 3D visualization directly with the PRA/PSA data and fire calculations, FRI3D provides a single interface for developing and analyzing fire models, while automating many steps. Figure 2 shows the User Interface (GUI) which has five primary areas:

- Compartment/Scenario Editor (top left) – Displays all the items in the current compartment/scenario;
- Properties Editor (bottom left) – Shows the properties for the selected item and allows the user to edit;
- 3D View (center) – Allows for modelling and viewing the spatial relationships, along with fire simulation results;
- Fire Logic View (right side) – Shows the logical mapping of raceways, cables, components, and PRA basic events;
- Timeline – Displays the timing results from fire simulation and failure calculations (i.e., when items fail).

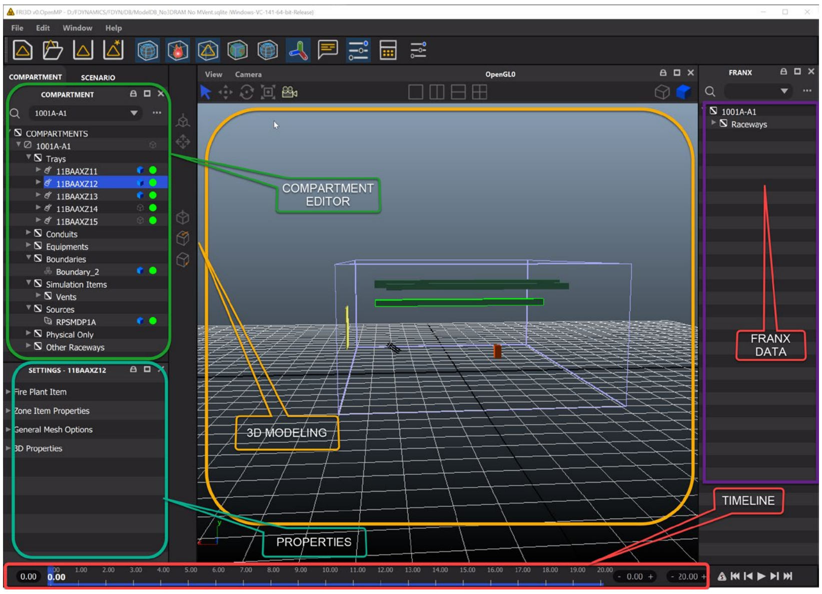

Figure 2. User Interface

2.3. Fire Scenarios

Fire scenarios can be created by hand, or automatically, by running a fire simulation. This eliminates the need for the various stages of hand calculations and manually assigned failed components. The following steps are used to auto-generate a scenario.

1. Construct CFAST/FDS models from FRI3D's model, which includes 3D data and properties.
2. Simulate CFAST/FDS using specified heat release rates (HRRs).
3. Determine if there are any secondary combustibles using CFAST results and the FLASH-CAT [6] Method. If so, calculate a new HRR and go back to step 2.
4. Use simulation results to determine additional cable failures using the Thermally-Induced Electrical Failure THIEF [7] method if cable data exists. If cable data doesn't exist, use heat soak method [8]. Also, use simulation data to determine direct component failures for the compartment.
5. Use the fire logic mapping to determine subsequent components that failed due to cable failures.
6. Save failures, timing, and other data as a scenario for the compartment.

Scenarios generated can then be evaluated or modified by the user and sent to the PRA/PSA model for a conditional core damage frequency and other PSA calculation.

3. FIRE MODELING IN RISKSPECTRUM PSA

There are multiple ways to incorporate fire scenarios into a PSA/PRA model, such as adding them directly into fault trees and generating fire event trees sequences or modify initiating events in the existing event tree. Scenarios can be incorporated directly into existing internal event analysis. There are different types of PRA/PSA modeling software such as CAFTA, SAPHIRE and RiskSpectrum PSA. Each of them has different features and methods for the creation of fire scenarios and subsequently ways to incorporate the FRI3D results into them. The following sections are not intended for exact instructions on fire modeling but general processes and descriptions of the main pieces. It is assumed that the reader has an understanding of the RiskSpectrum PSA and the modeling process, including event trees, fault trees, and boundary conditions, etc. For more information on RiskSpectrum PSA modeling, refer to the RiskSpectrum PSA User's Guide [1] or training information.

A fire model consists of a set of "Full room burnup" scenarios or all the fire sources as scenarios for each compartment/area in a facility. A fire scenario is an initiating event with the frequency of the combined fields fire initiating event frequency, severity factor, non-suppression probability. This is used to quantify event tree sequences where all the basic events associated with components that failed in the fire which are set to a 1.0.

After adding all the fire scenarios, the fire scenarios are quantified and the difference in the CDF from vs the normal initiating event CDF gives the increased risk due to fire.

3.1. Model Preparation

A few pre-requisites are needed before fire modeling can be performed. To simplify calculations, Risk Spectrum allows you to create an analysis case group. A new group needs to be created to put all the individual analysis cases under, so they can all be solved at the same time as shown in Figure 3. A fire basic event also needs to be added with the frequency of 1.0. This event will be substituted for all the failed basic events for a scenario, likely causing an increased probability for the cut sets using those events when the fire scenario is quantified.

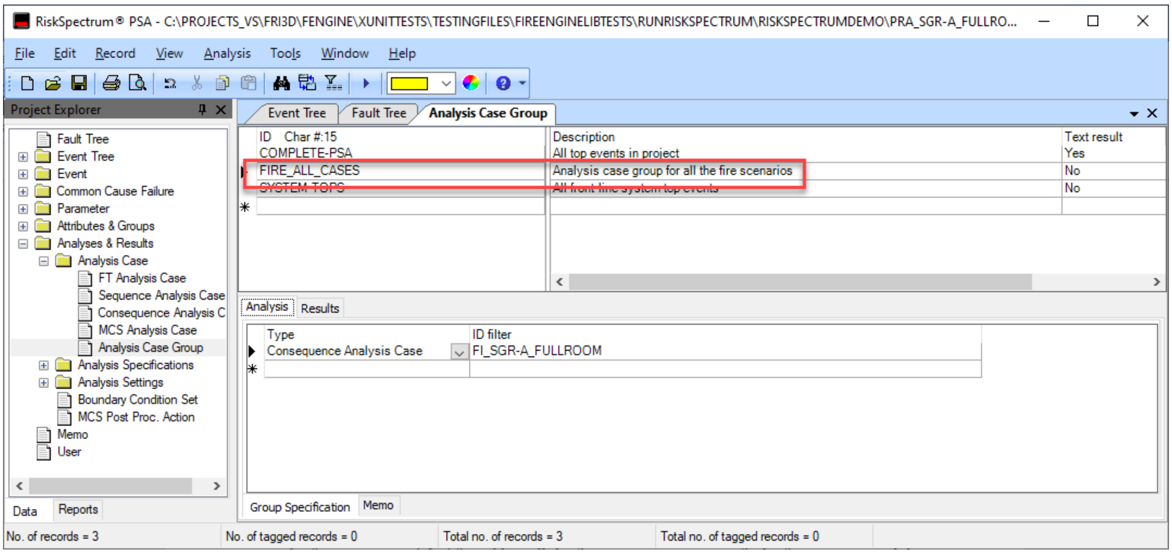

Figure 3. Analysis case group in RiskSpectrum for all the fire scenarios

3.2. Adding Fire Scenarios

For each fire scenario whether a full room burnup or single sources, the process is the same. Create a new house event, an event without a probability that must evaluate to a True or False, for the scenario. Perform a fire analysis to determine all the failed components and associated PRA basic event for the scenario. The house event just created is linked to a Boundary Condition (BC) with the basic events of the scenario. This substitutes the fire basic event value of 1.0 to those basic events.

Make a new fire scenario analysis case by copying the main analysis case for an event tree such as the loss of offsite power (LOOP) and set the BC set to this new analysis case, as shown in Figure 4.

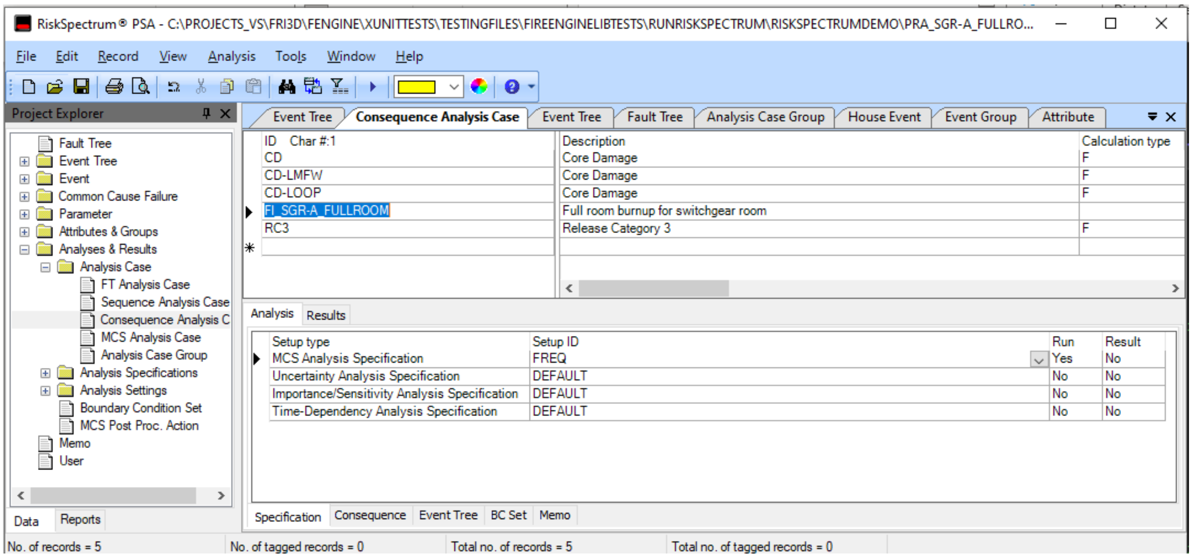

Figure 4. New fire scenario analysis case in RiskSpectrum

3.3. Cut Sets & Quantification of Fire Scenarios

Minimal Cut Set (MCS) generation and Quantification is the last part of fire modeling. Once all the fire scenarios have been identified, the event trees developed, event sets created and linked to the fire scenario accident sequences, minimal cut sets can be generated. Minimal cut sets represent those combinations that lead to the failure of accident sequence.

The fire code damage (CD) can now be quantified to all of them together to obtain the overall fire core damage frequency (CDF). The quantification process of these cut sets can utilize different options. The default option utilized by most PSA software programs is the minimal cut set upper-bound approximation, 1-Product(1-cut set(i)) i = 1 to n. This grouped end state of fire scenario cut sets can then be separated into the individual fire scenarios to obtain the individual fire scenario CDF and its percent contribution to the overall fire CDF. Comparisons of the fire CDF to the internal events CDF can also be obtained.

4. RISKSPECTRUM PSA COUPLING

RiskSpectrum PSA has a robust interactive graphical user interface to allow users to add basic events, house events, fault trees, event trees, and other information like analysis cases to create and update their PRA/PSA models. The software can load various types of data through its Excel sheet based Input capability as well. Figure 5 is an example excel sheet generated by FRI3D that indicates the house events from FRI3D output into Risk Spectrum. The input fire logic to FRI3D is specified within a standard table within this Excel spreadsheet or can be optionally imported from a standardized databases such as Microsoft Access or SQL. Customizations specific to the database format can be easily accomplished via the modular interface to FRI3D.

	A	B	C
1	HE ID	Description	
2	IEALOOP-PTMODE	Loss Of Offsite Power Post-Trip Mode	
3	LMFW	Loss of main feedwater	
4	LOCA	Large Loss Of Coolant Accident	
5	LOOP	Loss Of Offsite Power	
6	MFW-ISOL1	Main Feed Water System isolation valve 1 opened	
7	MFW-ISOL2	Main Feed Water System isolation valve 2 opened	
8	MFW-P1	Main Feed Water System pump 1 in operation	
9	MFW-P2	Main Feed Water System pump 2 in operation	
10	MFW-P3	Main Feed Water System pump 3 in operation	
11	P-TRANS	Transient at power	
12	S-TRANS	Transient when in shut down	
13	SUMMER	Summer conditions	
14	WINTER	Winter conditions	
15	FI_SGR-A_FULLROOM	FRI3D House event for fire scenario SGR-A_FULLROOM	
16	FI_FSOURCE_1_CFAST	FRI3D House event for fire scenario FSOURCE_1_CFAST	

Figure 5. RiskSpectrum House Events from FRI3D

4.1. FRI3D & RiskSpectrum Macros

RiskSpectrum PSA provides a method for exporting and importing a project through a Microsoft Excel spreadsheet and a script based interface that can run RiskSpectrum PSA routines. RiskSpectrum PSA Macro enables writing scripts that execute operations in RiskSpectrum PSA, such as adding and deleting records, editing relations between records, etc. RiskSpectrum PSA Macro provides an Application Programming Interface (API) for RiskSpectrum PSA. It makes use of the "PowerShell" script engine. An embedded command-line shell available in Windows. This provides an entry point for seamless integration into RiskSpectrum PSA thereby further automating the fire PSA process.
This also enables transferring data from the fire model to the PSA model and furthermore into documentation thereby keeping documentation and reporting up to date for regulators.

FRI3D uses these calls to load or extract data files that define the PSA database and add fire scenarios to the project. These scripts are programmatically injected to add to or modify the PSA model pieces. For this project the RiskSpectrum PSA macros were constructed by FRI3D, described in Section 5. The script calls and field descriptions are provided in RiskSpectrum PSA reference manual [1].

Using RiskSpectrum Model Compare the results pre and post fire analysis using FRI3D could also be shown. The following script demonstrates a sequence of steps performed using the RiskSpectrum Macro language.

```
#   set variables
$psa_script = ".\RiskSpectrum.RS32.Scripting.dll"
$psa_exe "C:\ProgramFiles\RiskSpectrum\PSA160loud\RiskSpectrum.PSA.exe"
$model_dir = "C:\temp\playwright"
$model_path = "C:\temp\playwright\test.rpp"
$model_name = "TEST"
$user_name = "sa"
$pwd = "sa"
$excel_data_path = "C:\temp\playwright\test.xls"
$analysis_group = "COMPLETE-PSA"

# Allow dlls to be loaded
Get-ChildItem | Unblock-File

# import commands
Import-Module $psa_script

# Get list of attached models
Get-PsaModels

# mount model
Mount-PsaModel -Name $model_name -FilePath $model_path -UserName $user_name -Pwd $pwd

# import Excel file
Import-PsaModel -Model $model_name -Format Excel -FilePath $excel_data_path -Type Overwrite
-IncludeTables All

# dismount model to allow it to be accessed by RiskSpectrum PSA
Dismount-PsaModel -Name $model_name -UserName $user_name -Pwd $pwd

# Run analysis
Start-Process -NoNewWindow -Wait -WorkingDirectory $model_dir -FilePath $psa_exe -
ArgumentList "/U=$user_name /W=$pwd /P=$model_path /A=$analysis_group"

# mount model again
Mount-PsaModel -Name $model_name -FilePath $model_path -UserName $user_name -Pwd $pwd

# Get list of results
Get-PsaObject -Model $model_name -Type ConsequenceAnalysisCase | Format-Table -Property
Type,ID,Text,Mean

# dismount model to allow it to be accessed by RiskSpectrum PSA
Dismount-PsaModel -Name $model_name -UserName $user_name -Pwd $pwd
```

Algorithm 1. Sequence of RiskSpectrum Macros invoked by FRI3D

4.2. FRI3D Scenarios to RiskSpectrum

The FRI3D software has a project library specifically set up for linking to different PRA/PSA software platforms as shown in Figure 6. The first link was done for CAFTA, using the FRANX interface, then a SAPHIRE module was added and the most current interface is RiskSpectrum.

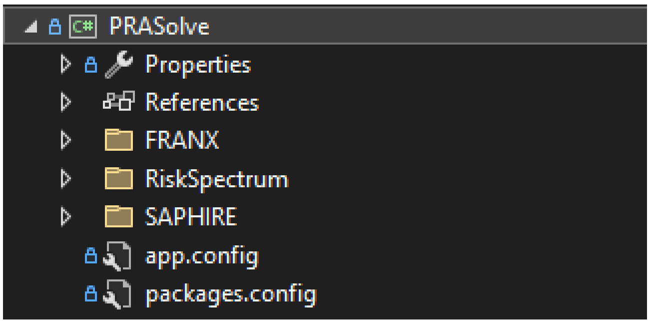

Figure 6. FRI3D software library for linking to PRA software tools

To create or add scenarios from FRI3D to the RiskSpectrum model the following steps are performed:

1. Use the Risk Spectrum Macro commands to export the base project that the user has specified links to the FRI3D model to a temporary work location using the excel output feature in Risk Spectrum.
2. Add the fire exchange event to substitute for the basic events that fail due to fire.
3. Create a fire analysis case group so that all the fire scenarios can easily be calculated.
4. For each FRI3D fire scenario the user wants to calculate do the following:
    a. Create a house event for the scenario.
    b. Link the house event and the fire exchange event for each basic event in the scenario.
    c. Copy the analysis case this fire scenario is based upon as a new fire analysis case.
    d. Add the fire analysis case to the fire analysis case group
    e. Create a boundary condition to include this fire scenario
5. Save the modified Excel sheets
6. Run the Risk Spectrum Macro commands to import the modified PRA Excel sheets
7. Open RiskSpectrum to solve and execute the fire analysis case group

4.3. FRI3D Setup for Risk Spectrum PSA

Appropriate modifications to the FRI3D interface was made to accommodate Risk Spectrum output, these included specification of the Risk Spectrum master PSA file, the user credentials , analysis case and the initiating event. Figure 7 displays the user specified model parameters which are passed on to RiskSpectrum by the FRI3D interface.

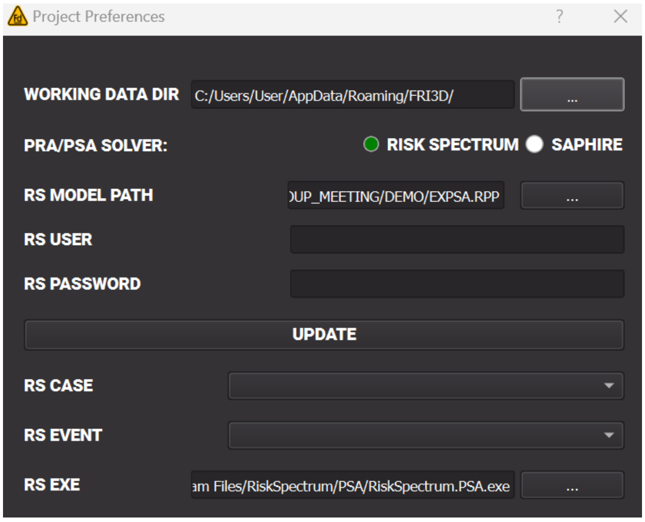

Figure 7. RiskSpectrum Settings in FRI3D

5. GENERIC MODEL EXAMPLE

An example FRI3D model was created using the demo model provided in the RiskSpectrum software. This model is of a simple switchgear room with a few components and raceways. Raceways link to cables, to components, and finally to the basic events specified in RiskSpectrum.

5.1. FRI3D Model

First, a hypothetical layout for a switch gear room was made. A basic fire logic mapping was also constructed to import into a new FRI3D model to begin modeling. The switch gear room consists of power cabinets for the A train of the following RiskSpectrum components: 4KV, 480V, CCW, RHR, SIS, AFW, and DCP[1]. Raceways connect the different cabinets with a hypothetical configuration of cables running from 4KV to the other power cabinets, and power cables from the cabinets to their components. , Figure 8 shows the 3D model constructed in FRI3D with the cabinets labeled as well as the result of a CFAST run. The "Basic Events" to components mapping is also indicated in the figure.

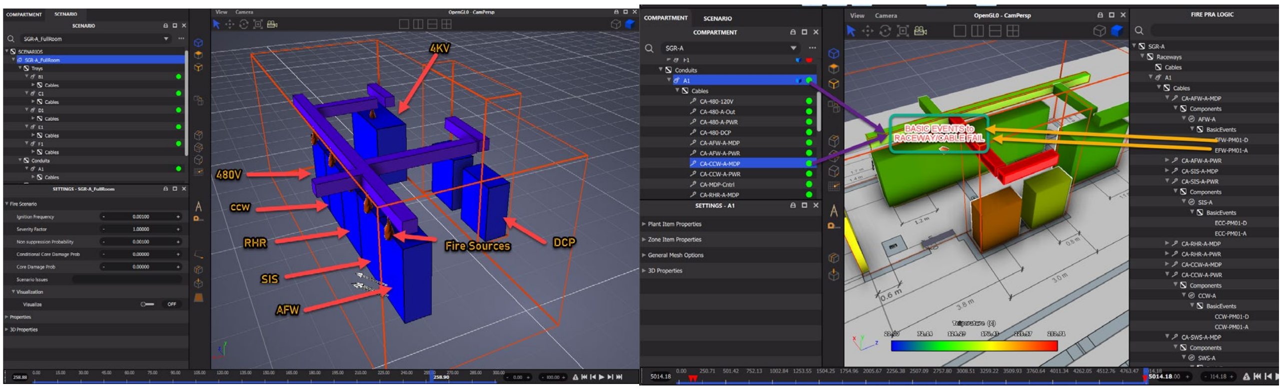

Figure 8. FRI3D for the Generic SG PWR run with CFAST and Basic Event mapping

5.2. Scenarios & RiskSpectrum

A fire source for each of the cabinets was added using a medium T-Squared HRR curve. Scenarios were auto-generated using CFAST results. A mapping of basic events to components in the FRI3D model was made using data from the exported RiskSpectrum Excel sheets. A mapping of basic events to components in the FRI3D model was made using data from the exported RiskSpectrum Excel sheets. This was used by FRI3D to link any failures to the basic events specific to the Risk Spectrum Model.

Appropriate RiskSpectrum preferences were set in FRI3D including the location of the master risk spectrum database, username and password. The other entries which were set, included the RiskSpectrum Analysis case (for example: Core Damage/CD), as well as the initiating event. After selecting the calculate button, the selected scenarios were used to generate the Excel files to update the base RiskSpectrum model.

When a CFAST or an FDS simulation is run via FRI3D, the interface visualizes the failures after a run with a red outline as shown in in Figure 7 which also displays the mapping between the cables to their corresponding basic events. In this specific case two scenarios, one of which included a full room burnout (default if nothing is modeled) and the other with an initiating fire from the AFW cabinet, were simulated in CFAST. The PRA/PSA calculations from these two scenarios were exported as shown inFigure 9.

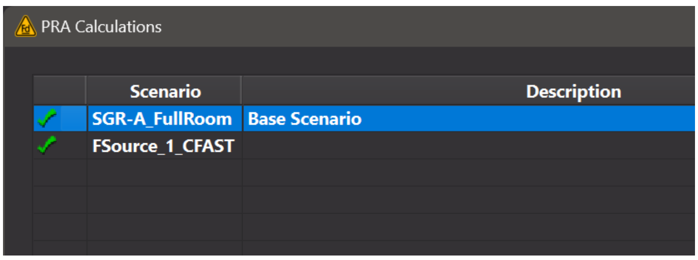

Figure 9. Scenarios Generated from the FRI3D Simulation to be Sent to RiskSpectrum for a Conditional CDF Calculation

6 RISKSPECTRUM PSA Model

[1] See component naming descriptions at the end of the document.

In Risk Spectrum PSA, all the fire related events corresponding to FRI3D are created with a prefix FI and in this specific case since we had run the analysis for only one fire scenario apart from the full room burnout, the house events FI_FSOURCE_1_CFAST and FI_SGR-A_FULLROOM are created which are exchanged with the corresponding basic events. In this case as indicated in Figure 6 the cable(s) under raceway A1 fail one of which is CA-CCW-A-MDP which in the Risk Spectrum model was linked to the basic event(s) EFW-PM01-A and EFW-PM01-D (Emergency Feed Water System pump train 1 fail to start and Emergency Feed Water System pump train 1 stops operating). The house events from the scenario are exchanged with these basic events via Exchange Events in RiskSpectrum.

7. CONCLUSION

The methods for performing fire modeling in RiskSpectrum was successfully added to FRI3D. This was demonstrated with a sample RiskSpectrum PSA model for a generic simplistic switch gear room, by adding fire scenarios and solving for a conditional Core Damage Probability (CDP). This work demonstrated a seamless integration into the RiskSpectrum PSA workflow. Previous demonstration cases have shown how FRI3D can simplify and reduce many of the costs associated with fire modeling. Previous work has estimated a 50% reduction in scenario development time using FRI3D over traditional methods for new fire scenario development [5]. A case study previously performed for a plant modification using a 3rd party fire consulting company to do their analysis with their current methods and also with FRI3D to provide data in estimating potential cost savings of FRI3D these findings were presented to the PWR and CANDU owners group and at the FSEP 2023 conference **[9]**. Results as shown in **Figure 10** conclude that for fire compartments never modeled in FRI3D, would have a 0–30% time-savings (middle column), depending on how many raceways are in the room vs. the current processes. For any subsequent changes or fire evaluations in the same compartment the time would be cut by 80% (right column).

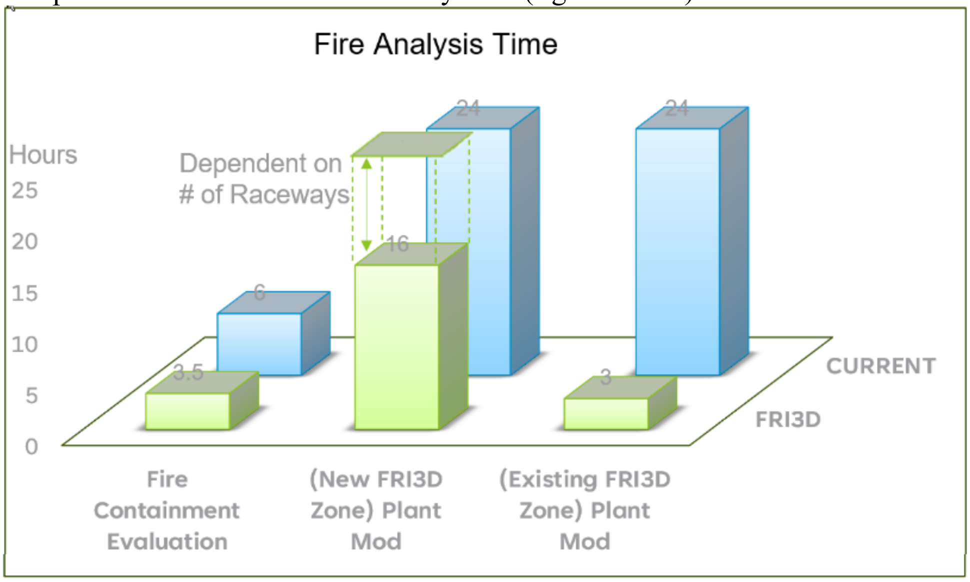

Figure 10. Case study results.

This case study was done using CAFTA for the PRA solving, but a similar outcome is expected for RiskSpectrum. The modular design of FRI3D made it easy to include RiskSpectrum PSA for quantification, and now FRI3D can be used for by almost all existing and currently being designed nuclear power facilities with significant time and cost savings, even if prior fire analysis already exists.

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***Component Naming Descriptions**
4KV – 4,000 volt main power cabinet feeding the plant, going to the system cabinets.
480V – General 480 volt supply
CCW – Component Cooling Water
RHR – Residual Heat Removal
SIS – Safety Injection System
AFW – Auxiliary Feedwater
DCP – DC Power