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Light Water Reactor Sustainability Program

FRI3D Industry Adoption and Verification Tasks

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ABSTRACT

The Fire Risk Investigation in 3D (FRI3D) software was developed at the Idaho National Laboratory under the Risk-Informed System Analysis pathway under the Light Water Reactor Sustainability Program. This software combines multiple tools used by industry for fire modeling with plant risk analysis and 3D spatial information. This report outlines several updates and additions that were made to help meet industry needs before it can be fully transferred to an industry partner for commercial use. Examples include software verification features and a library of commercially used fire sources. This report also goes over work for industry adoption, including a fire analysis pilot study done for a nuclear power plant modification. This pilot study showed a time comparison between using FRI3D and current methods used by fire analysis experts and an evaluation from the experts on the potential for use by industry.

ACKNOWLEDGMENTS

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CONTENTS

ABSTRACT iii
ACKNOWLEDGMENTS iv
1. FRI3D BACKGROUND 1
  1.1 Early Development 1
  1.2 Feasibility and Case Study 2
  1.3 Commercial Transfer 2
2. FIRE DYNAMIC SIMULATION OPTIONS 2
  2.1 Secondary Fires 3
  2.2 Adaptive Meshing 6
  2.3 Fire Sources and Vents 6
  2.4 Chemical Reactions 7
  2.5 Temperature Visualization 8
  2.6 Smoke Visualization 9
3. FIRE MATERIAL LIBRARY 10
  3.1 Source Documents 10
  3.2 Library Compilation 11
  3.3 FRI3D Fire Material Library GUI 11
4. VERIFICATION TASKS 13
  4.1 Testing Setup 13
  4.2 CFAST Verification Tests 13
5. INDUSTRY COLLABORATION TASKS 16
  5.1 Plant Modification Pilot 16
    5.1.1 Existing Model and Evaluation 16
    5.1.2 Plant Data Import 16
    5.1.3 Internal Model Testing 17
    5.1.4 EPM Modeling 17
    5.1.5 Pilot Comparison 17
    5.1.6 Generalized Results 18
    5.1.7 Feedback and Industry Comments 19
    5.1.8 Items Not Considered 20
  5.2 Full Plant Fire PRA 20
    5.2.1 Risk Spectrum 20
6. CONCLUSION 21
7. REFERENCES 21

FIGURES

Figure 1. The FRI3D user interface developed to integrate existing plant date, 3D spatial information, and fire simulation results. 1

Figure 2. Adaptive meshing example. 6

Figure 3. Venting example in FRI3D (left) and FDS (right). 7

Figure 4. Fire source example between FRI3D (left) and FDS (right). 7

Figure 5. Temperature visualization from an FDS simulation results in FRI3D. 9

Figure 6. Smoke visualization in FRI3D from FDS results. 10

Figure 7. FRI3D form showing the fire material properties with the library of solid fuels. 12

Figure 8. FRI3D form showing the liquid fire materials from the library. 12

Figure 9. Functional testing calls in the FRI3D source code using the XUnit test package. 13

Figure 10. CFAST/CEdit “Detection/Suppression” tab (left) and FRI3D “Scenario” tab (right). 15

Figure 11. FRI3D “3D Window” (left) and SmokeView (right). 15

TABLES

Table 1-1. CDF reduction from original NPP fire scenarios vs. FRI3D results. 2

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ACRONYMS

API	Application Programming Interface
CAFTA	Computer Aided Fault Tree Analysis System
CDF	Core Damage Frequency
CFAST	Consolidated Model of Fire Growth and Smoke Transport
CFD	Computational Fluid Dynamics
DOE	Department of Energy
EPM	Engineering Planning and Management, Inc.
EPRI	Electric Power Research Institute
FDS	Fire Dynamic Simulation
FDT	Fire Dynamics Tool
FRI3D	Fire Risk Investigation in 3D
FY	Fiscal year
GUI	Graphical User Interface
HRR	Heat Release Rate
INL	Idaho National Laboratory
LWRS	Light Water Reactor Sustainability Project
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PRA	Probabilistic Risk Analysis
PWROG	Pressurized-water reactor owners group
RISA	Risk-Informed Safety Analysis
SAPHIRE	Systems Analysis Program for Hands-On Integrated Reliability Evaluations
SBIR	Small Business Innovation Research
SFPE	Society of Fire Protection Engineers
STTR	Small Business Technology Transfer
TCCL	Transient Combustible Control Location
UI	User Interface
ZOI	Zone of Influence

FRI3D Industry Adoption and Verification Tasks

1. FRI3D BACKGROUND

Fire Risk Investigation in 3D (FRI3D) software tool was originally conceived 5 years ago as a research task under the Light Water Reactor Sustainability (LWRS) project's Risk-Informed Safety Analysis (RISA) pathway to assist the nuclear industry with their fire analysis. The main research and development tasks of this project under RISA have been wrapping up over the last 2 years, with this year focusing on the few development tasks described in Sections 2–4 and shifting the project over to a commercial partner by working with industry collaborators to help in the successful use of the tool.

1.1 Early Development

In a RISA working group meeting, Idaho National Laboratory (INL) presented some exploratory research on options for fire analysis using existing plant data and automation and simulation to evaluate advanced fire scenarios. The nuclear power plant (NPP) representatives asked if we could simply add a user interface (UI), as shown in Figure 1, allowing the analyst to drive the conditions but automate many of the tasks and generate fire scenarios. Current methods for developing fire scenarios consisted of many disconnected parts that were used to perform calculations and then added to their fire probabilistic risk assessment (PRA) model.

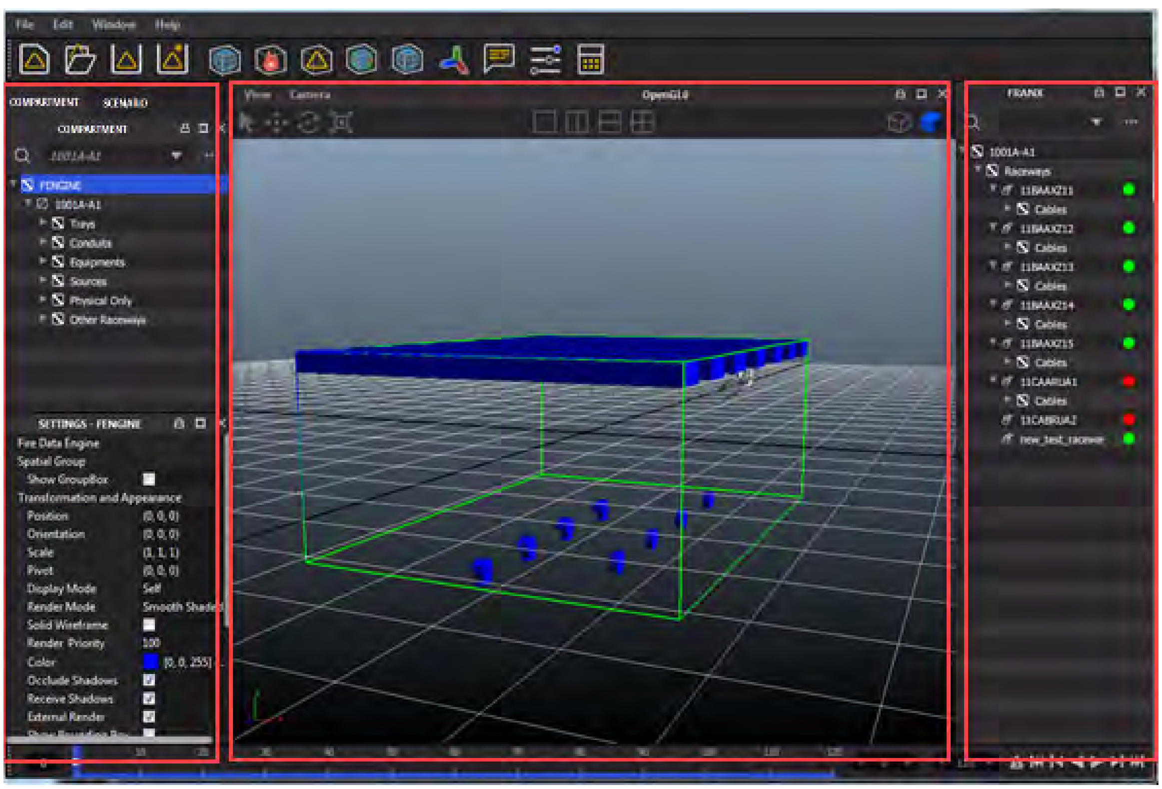

Figure 1. The FRI3D user interface developed to integrate existing plant date, 3D spatial information, and fire simulation results.

Work was done with an NPP's fire modelers to import existing plant data and develop an intuitive UI that coupled the plant PRA, 3D modeling, and existing industry fire simulation tools to make a fully coupled tool for fire PRA modeling. Work was also performed with Jensen Hughes, who are commonly contracted to perform fire analysis for NPPs, to assist in the methods and common practices. Our goal was to use existing validated tools and methods to make FRI3D easy to use for the nuclear industry and minimize regulatory concerns. Refer to the reports *Fire Modeling Enhancement Tools and Methods* [1] and *Fire Risk Investigation in 3D (FRI3D) Software and Process for Integrated Fire Modeling* [2].

1.2 Feasibility and Case Study

The tool showed great promise to simplify fire modeling, eliminate user errors, require less expert training, and dramatically improve knowledge transfer. The next step was to do a case study to evaluate using FRI3D on actual plant data and determine the potential for industry level use. Our collaborating NPP provided plant data for a switchgear scenario to be modeled. We used someone not initially on the project to test the modeling and use of the software to build the model. This was then compared to the actual plant scenarios to ensure consistency and to determine benefits of using FRI3D vs doing analyses in a traditional way (i.e., using a set of fire analyses methods, spreadsheets, and sets of reports). Verification was also done against nuclear regulatory commission (NRC) example cases.

Results estimated that the use of FRI3D could reduce fire scenario modeling time by 50% depending on how many ignition sources needed to be analyzed and the complexity of the room. Once a room is modeled, additional scenarios or plant modification analysis would have even larger reductions. The comparison of existing scenario results showed that using FRI3D also supported a significant reduction in conservatisms typically imbedded in fire analyses resulting in less conservative core damage frequency (CDF), see Table 1-1. The reduction in CDF is accomplished by using optimal fire analysis methods that are typically avoided because of the associated significant increase in required time and labor. For more information, see *Industry Level Integrated Fire Modeling Using Fire Risk Investigation in 3D (FRI3D)* [3].

Table 1-1. CDF reduction from original NPP fire scenarios vs. FRI3D results.

	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%

1.3 Commercial Transfer

With the potential to have a significant benefit to industry, the Department of Energy (DOE) put out a Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR) call for someone to explore the commercialization of FRI3D [4]. This call was won by Centroid Lab, and they evaluated the commercial viability of FRI3D and developed a business plan as part of the Phase 1 STTR. They presented a strong case and received very positive feedback. A subsequent phase II was not awarded due to limited funding from DOE. They still see a potential commercial path forward although slower without phase II support. A preliminary license agreement for FRI3D has been made between INL and Centroid Lab.

2. FIRE DYNAMIC SIMULATION OPTIONS

Most detailed fire analysis done by industry requiring a fire simulation code uses the consolidated model of fire growth and smoke transport (CFAST) code as it is faster and simpler to set up compared to other alternatives. FRI3D focused on also using CFAST for fire simulation results but was designed in a way to be able to incorporate other fire simulation codes. Feedback from industry emphasized the need for a full computational fluid dynamics (CFD) tool such as Fire Dynamic Simulation (FDS) for some scenarios. A task was started near the end of fiscal year (FY) 2022 to evaluate the feasibility and start incorporating FDS into FRI3D [5].] A large portion of the work was done during the feasibility evaluation before completion of the task in January 2023. FRI3D could convert its 3D model into a basic FDS model. A few tasks were also identified as key capabilities or features for realistic use within FRI3D. These tasks are listed in this section and were finished in FY 2023.

2.1 Secondary Fires

The approach to model secondary fires in FDS differs from the approach used in CFAST. This difference is because FDS can simulate the spread of secondary fires while CFAST cannot. The following procedure steps were used to model secondary fires in FDS from FRI3D:

1. Determine if there are cable raceways above the initial fire following the FLASHCAT geometry.
2. If there are, sort the raceways according to their distance from the fire.
3. Assign the fire spread rate to each raceway according to their cable type. 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 a raceway, use the most conservative (the fastest) fire spread rate.
4. Assign the ignition time for each raceway according to raceway ignition times (Table 2-1).

Table 2-1. Raceway ignition times.

Raceway’s order of closest distance to initial fire	Ignition Time
1	t_1 = as calculated by FDS using the THIEF method
2	$t_2 = t_1$ + 4 minutes
3	$t_3 = t_2$ + 3 minutes
4	$t_4 = t_3$ + 2 minutes
5	$t_5 = t_4$ + 1 minute
6	$t_6 = t_5$
7 and above	$t_7 = t_8 = \ldots = t_6$

5. Assign the initial ignition length for each raceway using Equation (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.

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

6. Calculate the plastic combustible mass in each raceway, m_c”, using Equation (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

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

7. Calculate for how long the secondary fire burns using Equation (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

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

8. Determine the HRR profile for each cell of secondary fires following Figure 3, where Δt is obtained from Equation (3) and $t_{ign,i}(x)$ is the time when a mesh cell ignites which is computed by FDS.

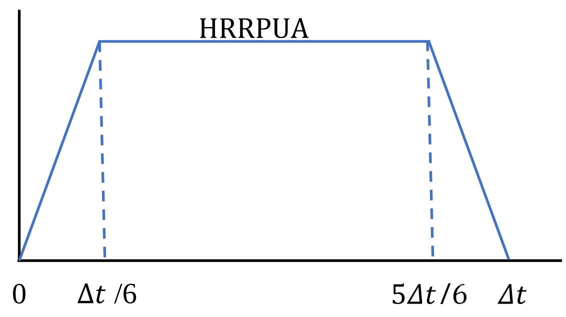

Figure 2. HRR profile for secondary fires

9. Divide the raceways into the initial fire region and the lateral fire-spread regions as illustrated in Figure 3. FRI3D then informs FDS of the parameters calculated in step 1-8 above and allows FDS to simulate the secondary fire progression.

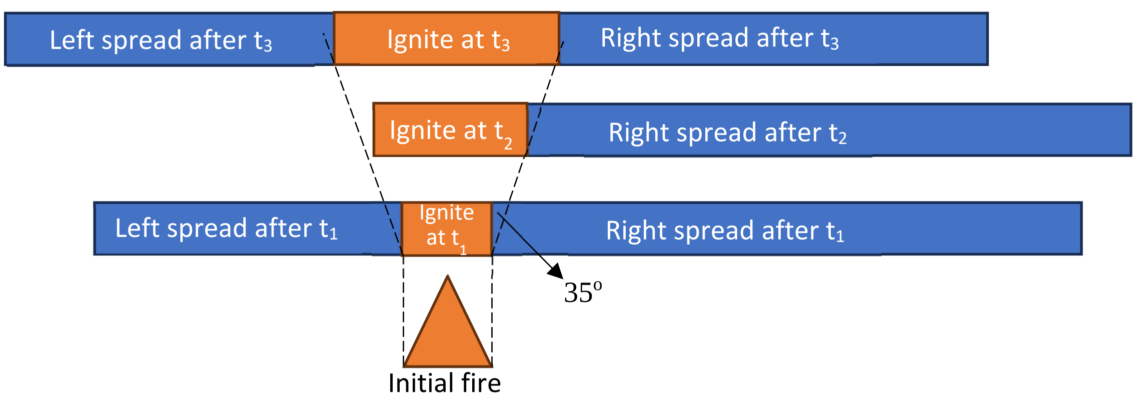

Figure 3. Raceway divisions

An example is given in Figure 4 in which a cabinet fire occurs in an electrical room where there are three raceways above the fire.

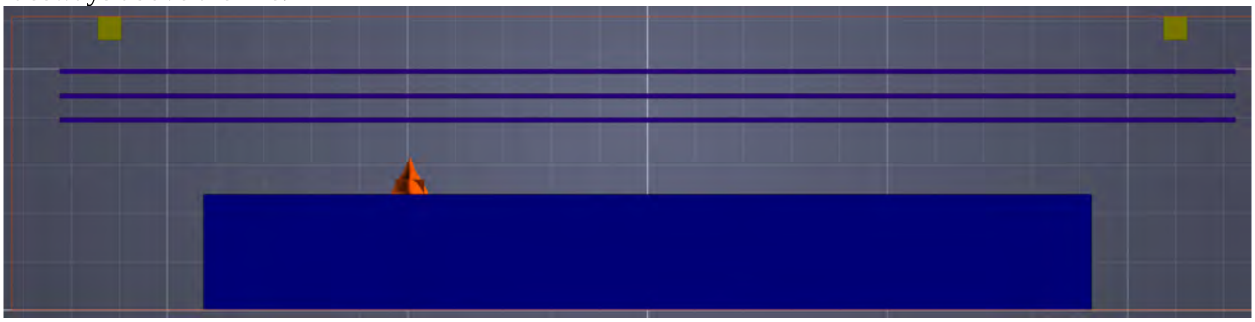

Figure 4. Secondary fire example

For this example, FRI3D creates the following FDS input lines to assign material properties to the cables inside the three raceways:

```
&MATL ID='THIEF cable material 0', DENSITY=2855.4, CONDUCTIVITY=0.2, SPECIFIC_HEAT=1.5 /
&MATL ID='THIEF cable material 1', DENSITY=2662.4, CONDUCTIVITY=0.2, SPECIFIC_HEAT=1.5 /
&MATL ID='THIEF cable material 2', DENSITY=2631.2, CONDUCTIVITY=0.2, SPECIFIC_HEAT=1.5 /
```

And writes the following lines to assign the conduit's thickness:

```
&SURF ID='THIEF cable surface 0', THICKNESS=0.0127635, LENGTH=0.1, MATL_ID='THIEF cable material
0', GEOMETRY='CYLINDRICAL' /
&SURF ID='THIEF cable surface 1', THICKNESS=0.011176, LENGTH=0.1, MATL_ID='THIEF cable material
1', GEOMETRY='CYLINDRICAL' /
&SURF ID='THIEF cable surface 2', THICKNESS=0.0090805, LENGTH=0.1, MATL_ID='THIEF cable material
2', GEOMETRY='CYLINDRICAL' /
```

The following lines set up a temperature sensor for each raceway:

```
&PART ID='THIEF cable segment 0', SURF_ID='THIEF cable surface 0', ORIENTATION=0,0,-1,
STATIC=.TRUE., PROP_ID='THIEF cable picture' /
&PART ID='THIEF cable segment 1', SURF_ID='THIEF cable surface 1', ORIENTATION=0,0,-1,
STATIC=.TRUE., PROP_ID='THIEF cable picture' /
&PART ID='THIEF cable segment 2', SURF_ID='THIEF cable surface 2', ORIENTATION=0,0,-1,
STATIC=.TRUE., PROP_ID='THIEF cable picture' /
&INIT ID='THIEF cable position 0', XYZ=7.1, 9.6, 3.9, N_PARTICLES=1, PART_ID='THIEF cable segment
0' /
&INIT ID='THIEF cable position 1', XYZ=7.1, 9.6, 4.4, N_PARTICLES=1, PART_ID='THIEF cable segment
1' /
&INIT ID='THIEF cable position 2', XYZ=7.1, 9.6, 4.9, N_PARTICLES=1, PART_ID='THIEF cable segment
2' /
```

This line assigns the ignition criteria at 400 C for the lowest raceway:

```
&DEVC ID='RacewayGroup_0', INIT_ID='THIEF cable position 0', QUANTITY='INSIDE WALL TEMPERATURE',
DEPTH=0.002, SETPOINT=400 /
```

These lines assign the HRRPUA and color for the three raceways:

```
&SURF ID = 'BURNING CABLE 0'
    COLOR = 'BLACK'
    HRRPUA = 250
    RAMP_Q = 'cable fire ramp 0' /
&SURF ID = 'BURNING CABLE 1'
    COLOR = 'BLACK'
    HRRPUA = 250
    RAMP_Q = 'cable fire ramp 1' /
&SURF ID = 'BURNING CABLE 2'
    COLOR = 'BLACK'
    HRRPUA = 250
    RAMP_Q = 'cable fire ramp 2' /
```

These lines set the HRR profile for each cell of the raceway:

```
&RAMP ID = 'cable fire ramp 0', T=0, F=0 /
&RAMP ID = 'cable fire ramp 0', T=16.134, F=1 /
&RAMP ID = 'cable fire ramp 0', T=80.668, F=1 /
&RAMP ID = 'cable fire ramp 0', T=96.802, F=0 /
&RAMP ID = 'cable fire ramp 1', T=0, F=0 /
&RAMP ID = 'cable fire ramp 1', T=11.533, F=1 /
&RAMP ID = 'cable fire ramp 1', T=57.667, F=1 /
&RAMP ID = 'cable fire ramp 1', T=69.2, F=0 /
&RAMP ID = 'cable fire ramp 2', T=0, F=0 /
&RAMP ID = 'cable fire ramp 2', T=7.525, F=1 /
&RAMP ID = 'cable fire ramp 2', T=37.623, F=1 /
&RAMP ID = 'cable fire ramp 2', T=45.148, F=0 /
```

These input lines set the geometry of the bottom-most raceway, including the first ignition region and the regions where fire spreads to:

```
&VENT XB= 6.8, 7.4, 9.2, 10.0, 4.0, 4.0, SURF_ID = 'BURNING CABLE 0', DEVC_ID='RacewayGroup_0' /
&VENT XB= 1.0, 6.8, 9.2, 10.0, 4.0, 4.0, SURF_ID = 'BURNING CABLE 0', DEVC_ID='RacewayGroup_0',
SPREAD_RATE=0.000888889, XYZ=6.8, 9.6, 4.0 /
```

```
&VENT XB= 7.4, 25.5, 9.2, 10.0, 4.0, 4.0, SURF_ID = 'BURNING CABLE 0', DEVC_ID='RacewayGroup_0',
SPREAD_RATE=0.000888889, XYZ=7.4, 9.6, 4.0 /
```

Meanwhile, these lines set the geometry for the second and third raceways. Note that unlike the bottom-most raceway, these raceways use CTRL_ID to delay the ignition following Table *2-1*.

```
&VENT XB= 6.5, 7.8, 9.2, 10.0, 4.5, 4.5, SURF_ID = 'BURNING CABLE 1', CTRL_ID='CableDelay_1' /
&VENT XB= 1.0, 6.5, 9.2, 10.0, 4.5, 4.5, SURF_ID = 'BURNING CABLE 1', CTRL_ID='CableDelay_1',
SPREAD_RATE=0.000888889, XYZ=6.5, 9.6, 4.5 /
&VENT XB= 7.8, 25.5, 9.2, 10.0, 4.5, 4.5, SURF_ID = 'BURNING CABLE 1', CTRL_ID='CableDelay_1',
SPREAD_RATE=0.000888889, XYZ=7.8, 9.6, 4.5 /
&VENT XB= 6.1, 8.1, 9.2, 10.0, 5.0, 5.0, SURF_ID = 'BURNING CABLE 2', CTRL_ID='CableDelay_2' /
&VENT XB= 1.0, 6.1, 9.2, 10.0, 5.0, 5.0, SURF_ID = 'BURNING CABLE 2', CTRL_ID='CableDelay_2',
SPREAD_RATE=0.000888889, XYZ=6.1, 9.6, 5.0 /
&VENT XB= 8.1, 25.5, 9.2, 10.0, 5.0, 5.0, SURF_ID = 'BURNING CABLE 2', CTRL_ID='CableDelay_2',
SPREAD_RATE=0.000888889, XYZ=8.1, 9.6, 5.0 /
```

Lastly, the CTRL_ID is explained in these lines. It informs that the second raceway burns 4 minutes after the first raceway, and the third raceway burns 7 minutes after the first raceway.

```
&CTRL ID='CableDelay_1', FUNCTION_TYPE='TIME_DELAY', INPUT_ID='RacewayGroup_0', DELAY=240 /
&CTRL ID='CableDelay_2', FUNCTION_TYPE='TIME_DELAY', INPUT_ID='RacewayGroup_0', DELAY=420 /
```

2.2 Adaptive Meshing

The grid cells which define the computational mesh in FDS can be adaptive to be more refined or coarse depending upon some user-specified criteria. The specific criteria used in this case is the region around the source of primary fire since more detail may be needed in that area. Adaptive grid (see Figure 5) is optional and is specified in the simulation options.

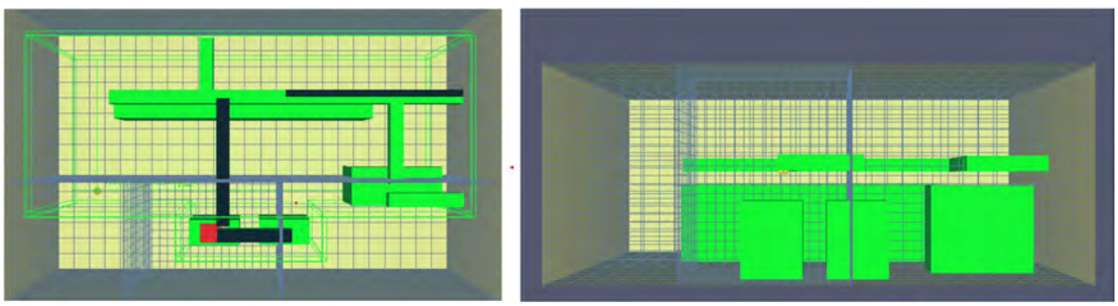

Figure 5. Adaptive meshing example.

2.3 Fire Sources and Vents

Fire sources and vents in FDS are specified as boundary conditions. The ventilation system of individual compartments within a building is described using velocity boundary conditions. For example, fresh air can be blown into and smoke can be drawn from a compartment by specifying a velocity in the normal direction to a solid surface.

The directives generated by FRI3D are VENT primitives, and VENTS in FDS are boundary conditions which are associated with obstacles (OBST). Therefore, the implementation had to consider the intersection of the source object (fire) as depicted with the appropriate planes of intersection with the obstacle primitives as defined by the user in the 3D interface. Figure 6 shows the fire source in FRI3D on the left with the FDS vent equivalent on the right.

```
&VENT XB=2.75, 3.3, -1.13, -0.67, 1.5, 1.5, SURF_ID='New Fire Material 1_FSource_1'  /
```

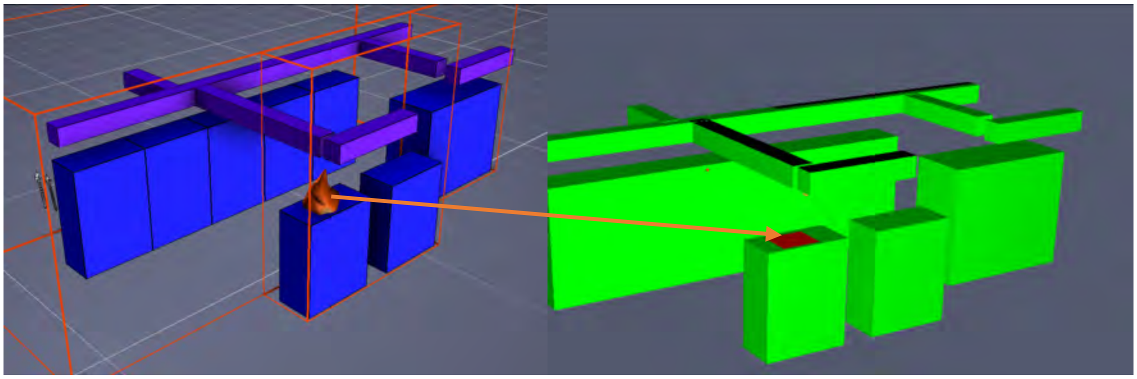

Figure 6. Venting example in FRI3D (left) and FDS (right).

If the fire source geometry as indicated by the flame icon intersects with multiple faces of the obstacles, then multiple fire sources are output to FDS by means of VENT specifications as indicated by the following directives and images.

```
&VENT XB=2.75, 3.3, -1.19, -1.19, 1.24, 1.5, SURF_ID='New Fire Material 1_FSource_1'  /


&SLCF PBX=3.02, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBY=-1.19, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
!! Fire Source Specifications


&VENT XB=2.75, 3.3, -1.19, -0.94, 1.5, 1.5, SURF_ID='New Fire Material 1_FSource_1'  /
```

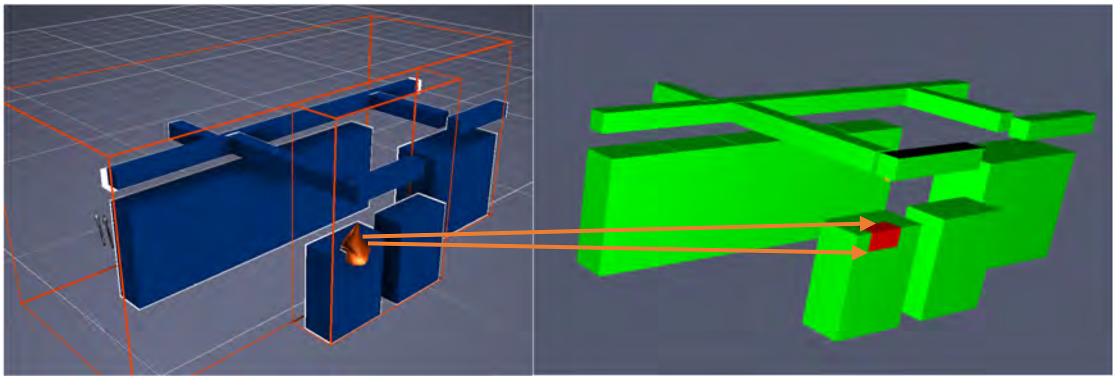

Figure 7. Fire source example between FRI3D (left) and FDS (right).

Vents follow a similar principle in which the area of intersection of the vent as specified in the interface with a boundary wall is output as a VENT primitive. This holds well for both powered vents and windows/doors.

2.4 Chemical Reactions

FDS implements the following chemical reaction as the combustion reaction. The various stoichiometric coefficients are converted into their respective volume fractions to be output as FDS directives.

$$C_xH_yO_zN_v + \nu_{O_2}O_2 \rightarrow \nu_{H_2O}H_2O + \nu_{CO}CO + \nu_s soot + \nu_{N_2}N_2$$

The volume fractions of the chemical constituents which represent the combustion reaction are calculated and specified as directives indicated as follows. This is based on the fire specification entered by the user, details of which is explained in Section 3.

```
&SPEC ID = 'PE/PVC', FORMULA = 'C2H3.5Cl0.5' /
&SPEC ID = 'OXYGEN',            LUMPED_COMPONENT_ONLY = .TRUE. /
&SPEC ID = 'NITROGEN',          LUMPED_COMPONENT_ONLY = .TRUE. /
&SPEC ID = 'HYDROGEN CHLORIDE', LUMPED_COMPONENT_ONLY = .TRUE. /
&SPEC ID = 'WATER VAPOR',       LUMPED_COMPONENT_ONLY = .TRUE. /
&SPEC ID = 'CARBON MONOXIDE',   LUMPED_COMPONENT_ONLY = .TRUE. /
&SPEC ID = 'CARBON DIOXIDE',    LUMPED_COMPONENT_ONLY = .TRUE. /
&SPEC ID = 'SOOT',              LUMPED_COMPONENT_ONLY = .TRUE.,FORMULA='C1' /


&SPEC ID='AIR', BACKGROUND=.TRUE., SPEC_ID(1)='OXYGEN',
VOLUME_FRACTION(1)=0.21, SPEC_ID(2)='NITROGEN', VOLUME_FRACTION(2)=0.79 /
&SPEC ID='PRODUCTS',SPEC_ID(1)='HYDROGEN CHLORIDE', VOLUME_FRACTION(1)=0.5,
SPEC_ID(2)='WATER VAPOR', VOLUME_FRACTION(2)=1.5,
SPEC_ID(3)='CARBON MONOXIDE',   VOLUME_FRACTION(3)=0.2376,
SPEC_ID(4)='CARBON DIOXIDE',    VOLUME_FRACTION(4)=1.2496,
SPEC_ID(5)='SOOT',              VOLUME_FRACTION(5)=0.5128,
SPEC_ID(6)='NITROGEN',    VOLUME_FRACTION(6)=7.9692 /
&REAC ID='PE/PVC', HEAT_OF_COMBUSTION = 20900.,
SPEC_ID_NU='PE/PVC','AIR','PRODUCTS', NU=-1,-10.0876,1, RADIATIVE_FRACTION =
0.49 /
```

2.5 Temperature Visualization

Temperature information from the grid cells is read from the output generated from PLT3D files which are in the PLOT3D file format specification. There is a per time output of quantity files with a .q extension and the zonal information as indicated in another file with an .xyz extension. Both of these file formats are documented in the FDS User Guide. Rendering using graphics processing units (GPUs) with the nVIDIA-architecture-supported CUDA programming language was implemented. Volume rendering techniques were used to render the volumetric voxel information specified into the grid cells.

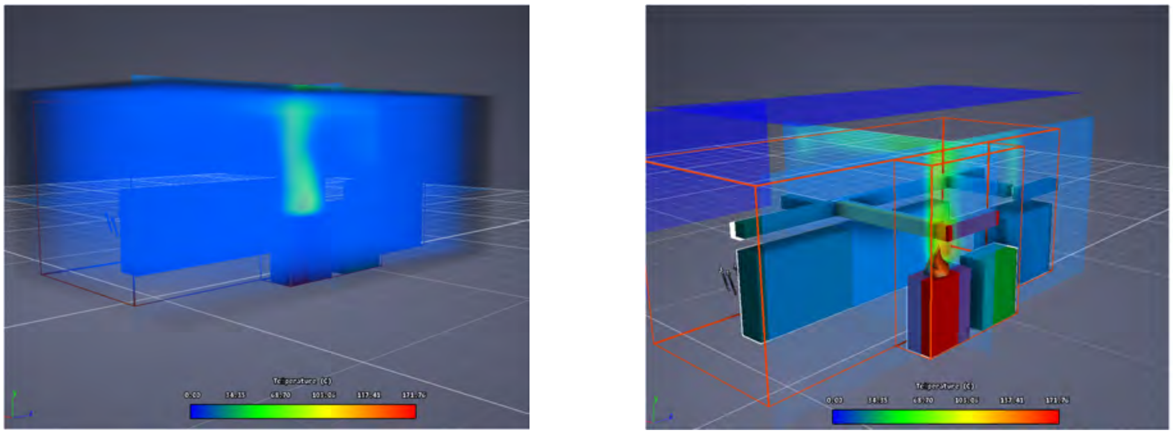

Figure 8. Temperature visualization from an FDS simulation results in FRI3D.

2.6 Smoke Visualization

FDS outputs smoke quantities like the amount of soot, temperature, and heat flux into a file with .s3d extension. This file format is documented in the *Fire Dynamics Simulator User's Guide* [6]. FDS output is generated by specifying the directive to output *.s3d.sz files—this text file contains the time specification of quantities in a run length encoded compressed format. Code was written to post process and read these files and render them volumetrically using the principles mentioned in the previous section.

```
0.000000          22599         267      0
15.01001            22599         1657   6.650605
25.00000            22599         2328   11.02572
dummy
fTime1 buffer_length_in_char buffer_length_compressed maxVal
fTime2 ...
fTime3 ...
```

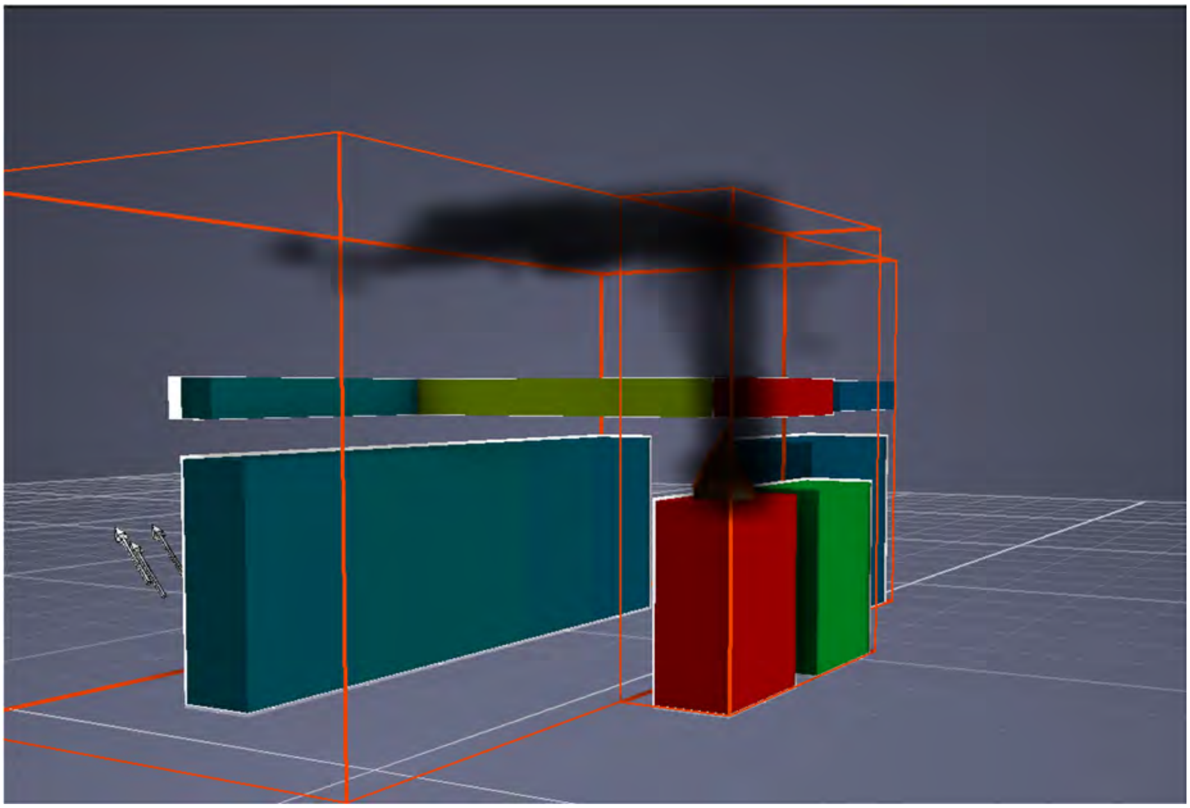

Figure 9. Smoke visualization in FRI3D from FDS results.

3. FIRE MATERIAL LIBRARY

For detailed fire modeling, each item identified as a potential fire source under the fire analysis needs to have relevant data such as ignition frequency and a heat release rate (HRR). The fire simulation code uses the HRR for the fire growth and to perform the simulation analysis. There could be an innumerable amount of different fire source HRRs, so NRC performed different studies to help categorize and bin items into different accepted data groups. The data for these are spread out over several documents. Manually finding appropriate HRRs and adding the data points is a tedious process. To make it easier for the user to model, the industry-developed information was gathered and imported into FRI3D as different types of fire material. When the user creates a new fire source, they assign a specific fire material from a list. The following sections describe the sources of data and how they are accessed in FRI3D as fire materials.

3.1 Source Documents

There were several sources for the fire source material data, some of which have been updated or replaced with better data. The information concerning liquid fire data, bin grouping, and ignition frequency was collected from the text, *SFPE Handbook of Fire Protection Engineering, 3rd Edition* [7] from 2016. The rest of the source information on solid fire material data was gathered from a series of NUREG reports released by the Electric Power Research Institute (EPRI). NUREG/CR-6850, Volumes 1 and 2 [8] both released in 2005, provided HRR and timing profile data for electrical cabinets, pumps, motors, and transient combustibles. Additionally, these documents contained liquid fuel and ignition frequency data, but this was not collected as it was superseded by the 2010 release of an updated report supplement to NUREG/CR-6850 [9]. Next, NUREG-2169 [10] was published containing ignition frequencies, but this data was not collected as it was later updated. In 2016 and 2019, EPRI released two more reports, Volume 1 and Volume 2 of NUREG-2178 [11, 12]. These reports contained improved data on HRRs, fire sizes, timing profiles, heat of combustions, and fire elevations for electrical motors, transformers, and electrical enclosures. Also in 2019, NUREG-2232 [13] was released with HRR, heat of combustion, yield, fire size, and fire elevation data as well as revised timing profiles for the HRR curves to be used in fire source simulations. Most recently, the report NUREG-2233 [14] was released in 2020 containing further data pertaining to transient and transient combustible control location (TCCL) fires.

3.2 Library Compilation

From the NUREG reports and *Society of Fire Protection Engineers (SFPE) Handbook* [7] discussed previously, the data was collected and organized into three main spreadsheets: one for solid fire materials, one for liquid fire materials, and one for ignition frequencies and the corresponding bin groupings. Many other spreadsheets were kept to track the documentation, the relations between NUREG reports, and notes required to make sense of the data. To import the data into the FRI3D tool and utilize the compiled libraries of data, calculations needed to be performed on the current data so that it would be useful in FRI3D. In many of the NUREG reports, mainly NUREG-2232, timing profile data was provided to model fire behavior. Peak HRR, fire growth, plateau, and decay periods, as well as growth and decay exponents, are data that make up a fire source's timing profile. The following equations from NUREG-2232 were used to generate curves for every fire material, where sufficient data was found:

$$q(t) = \begin{cases} q_{peak}\left(\frac{t}{t_g}\right)^{n_1} & t \leq t_p \\ q_{peak} & t_g < t \leq t_g + t_p \\ q_{peak}\left(1 - \left(\frac{t - t_g - t_p}{t_d}\right)^{n_2}\right) & t_g + t_p < t \leq t_g + t_p + t_d \end{cases} \quad (4)$$

where t is the time in seconds, $q(t)$ is the HRR at time t, q_{peak} is the peak HRR, t_g is the growth period in seconds, t_p is the plateau period in seconds, t_d is the decay period in seconds, n_1 is the growth constant, and n_2 is the decay constant. With the compiled libraries of data and many calculations needed to fully have an imported library already set up in FRI3D for end-users, a tool was developed to take the three main spreadsheets of data in comma delimited form and generate the necessary fire curves as well as import the data into the FRI3D database. This enabled a user-friendly interface to be implemented in FRI3D. Additionally, FRI3D has the functionality to add and update the database with more fire material data with ease. This allows the "built-in" library of fire source data to stay up to date as fire PRA data is published to update the data and add to it as more source materials are tested and observed.

3.3 FRI3D Fire Material Library GUI

Previously, FRI3D listed solid fire materials that the user defined but could be used repeatedly for multiple fire sources and across different models. This graphical user interface (GUI) was used but slightly modified to handle both solid and liquid fire materials. The ability to handle a large number of fire materials, categories and sub-categories was added for sorting and to make it easier for the user to find the correct fire material when assigning it to a simulation source.

The fire database entries are loaded into the user interface. Figure 10 depicts the solid fires and Figure 11 shows the liquid fire entries from the database. The fire presets can be duplicated, and properties customized according to plant specifications.

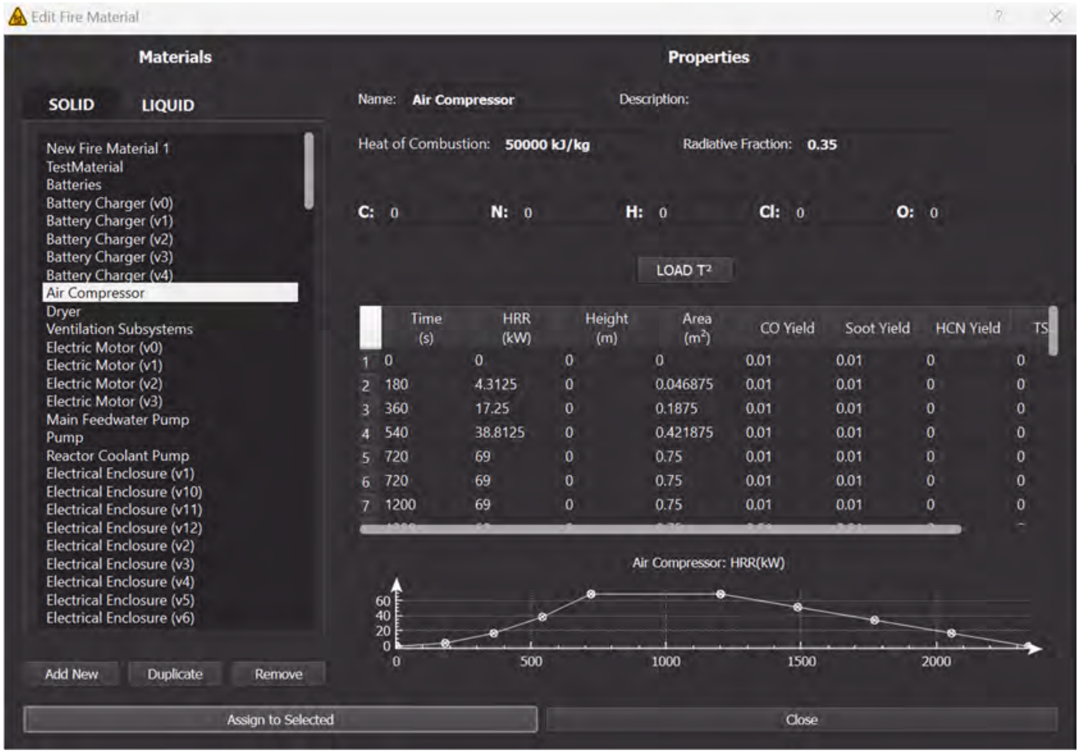

Figure 10. FRI3D form showing the fire material properties with the library of solid fuels.

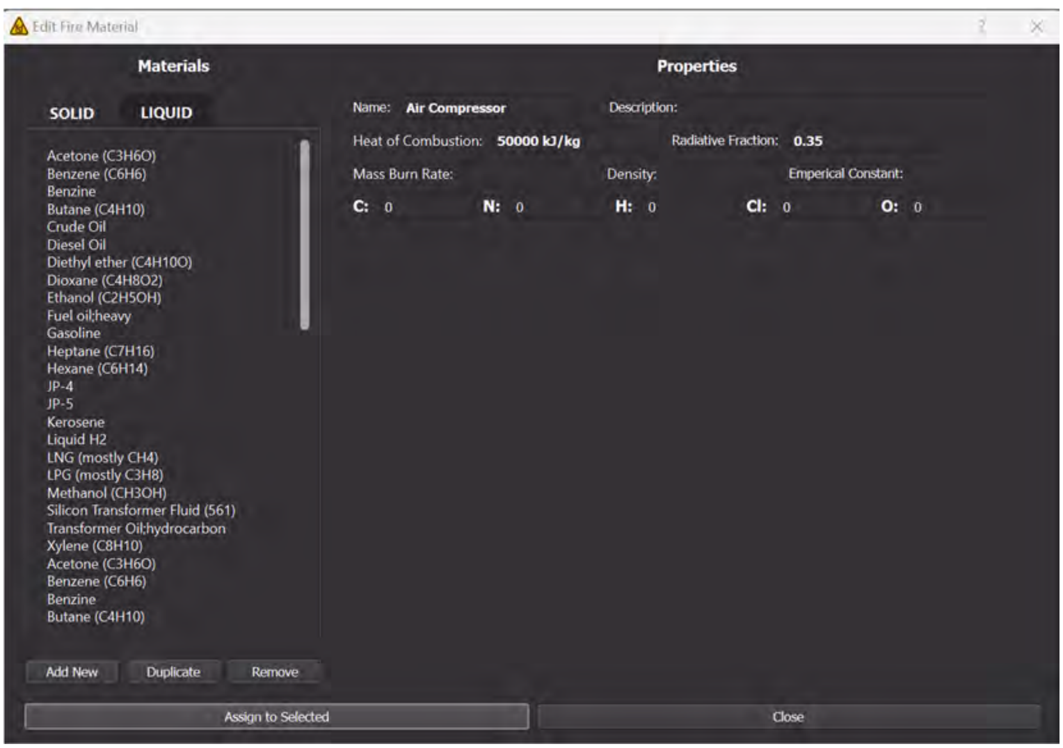

Figure 11. FRI3D form showing the liquid fire materials from the library.

4. VERIFICATION TASKS

FRI3D uses exiting validated tools and methods currently used by industry. Early testing verified results from FRI3D were equivalent to cases presented in NRC NUREG reports [3]. The last report [5], covered a test added to FRI3D to verify that none of the known CFAST modeling limitations were present in the user's 3D model and notified them if it did. Given that CFAST is already validated, and the model was checked for violations, there is no further validation of CFAST needed for FRI3D. However, verification that the correct data and execution of the tools and methods is needed and should be done in a repeatable process for the software quality assurance. The FRI3D application programming interface (API) source has a built-in unit and functional testing platform to automate checking that code changes do not cause other errors. This testing platform can also be used to host the verification testing. This section goes over the testing architecture and the verification tests added.

4.1 Testing Setup

The back end of FRI3D has two types of testing built into the source code using the XUnit testing package. The first is unit testing, and the second is functional testing. The unit testing verifies individual software calls work as designed for given parameters. Functional testing verifies that scenarios or the behavior of larger model aspects function as expected. Functional testing has been used to setup and run different FRI3D model validation cases. These tests are run after modifications are made to see if the changes affected any other areas of code and before a release is made, as shown in Figure 12.

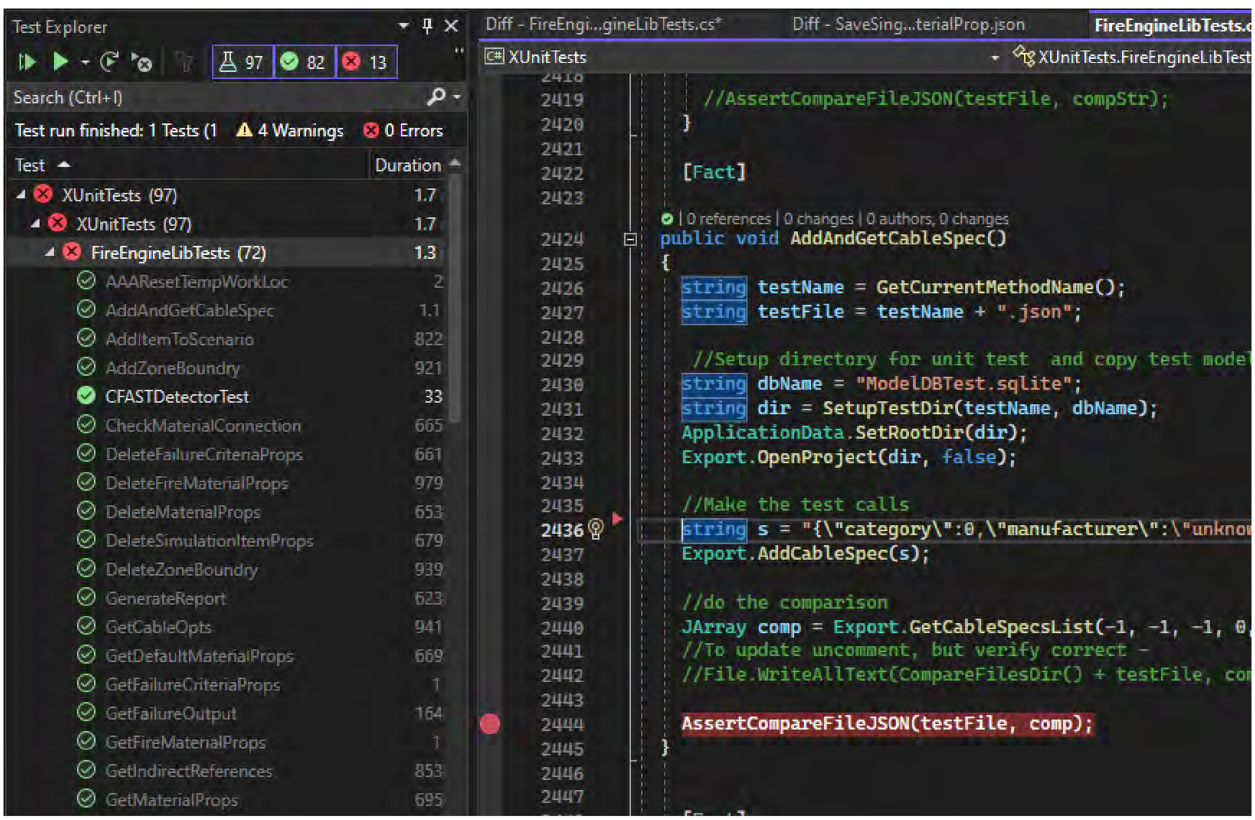

Figure 12. Functional testing calls in the FRI3D source code using the XUnit test package.

4.2 CFAST Verification Tests

FRI3D uses CFAST to perform the fire simulation, as it has already been validated and approved for fire simulation analysis by the NRC. However, as part of software quality assurance, it must be shown that FRI3D generates the correct CFAST model from its internal 3D model. The following tests were created to confirm the library import functionality was working correctly, and data is available for use in CFAST. The tests are run, which call the library import function and confirm successful import of the data by checking that the number of entries imported matches that of the library. Two tests were created for this verification, one test for the fire materials library and one test for the frequency library as follows:

- TestFireMaterialsLibrary: tests if the fire materials library is imported with all entries.
- TestFrequencyLibrary: tests if the frequency library is imported with all entries.

The subsequent set of tests aimed to validate the transfer of data and object parameters from FRI3D to the CFAST environment. To achieve this, unique scenarios were constructed within FRI3D using its built-in 3D environment and libraries. The use of unique scenarios allowed the isolation of particular aspects of FRI3D functionality making it easier to identify any potential issues when running the tests. The testing method involved simulating a scenario or fire source within FRI3D, resulting in the generation of output files from FRI3D, as well as input files for CFAST and SmokeView. Subsequently, an initial numerical comparison between FRI3D and CFAST, as well as an initial analytical check between FRI3D and SmokeView, were conducted to ensure that all inputs and the 3D environment match accurately as follows:

- TestFireSourceProperties: Tests fire source properties
- TestTrayProperties: Tests tray and other raceway properties
- TestVentProperties: Tests vent properties
- TestAlarmProperties: Tests heat alarm, smoke alarm, and sprinkler properties
- TestTwoBoundaryTwoSources: Tests geometry and properties of model with two boundaries and a source in each
- TestMotorFireProperties: Tests environment with multiple components

The entirety of these tests is meant to verify the integration of CFAST into FRI3D. An example of an initial check between FRI3D and CFAST is shown below in Figure 13 where the focus is on the inputs between the two windows. An example of an initial check between FRI3D and CFAST is shown below in Figure 13 where the focus is on the inputs between the two windows. The results in Figure 13 are a match and accepted as a validation case. The results in Figure 13 are a match and accepted as a validation case. In cases where the values did not match, the errors were tracked down and fixed then tested again.

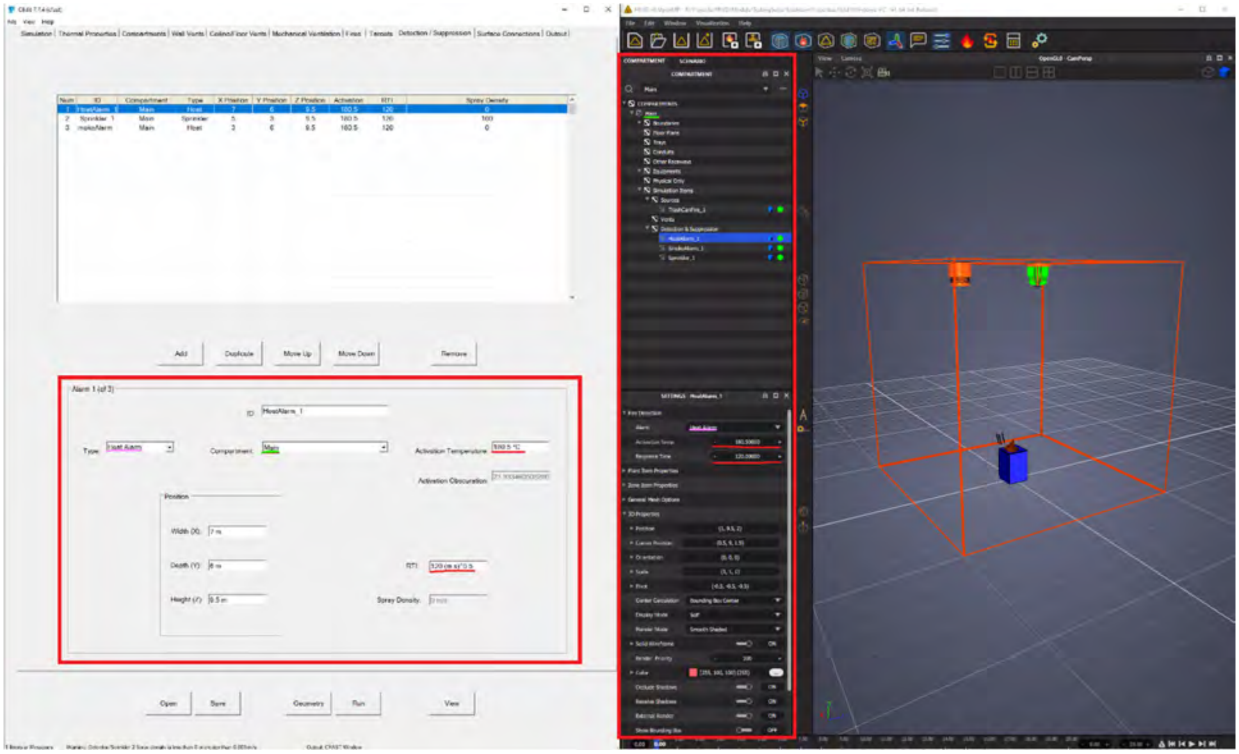

Figure 13. CFAST/CEdit “Detection/Suppression” tab (left) and FRI3D “Scenario” tab (right).

Once the inputs are confirmed to be matching or as intended, the same scenario is taken into SmokeView to compare the visual 3D environment with that of FRI3D, as shown in Figure 14. This visual verification provides a quick, and the fields in the CFAST and FRI3D model provide exact verification. It was assumed after checking one model with exact numerical validation that a visual verification would suffice for like components. The results of the simulations are also validated with a visual comparison made between SmokeView rendering and FRI3D rendering.

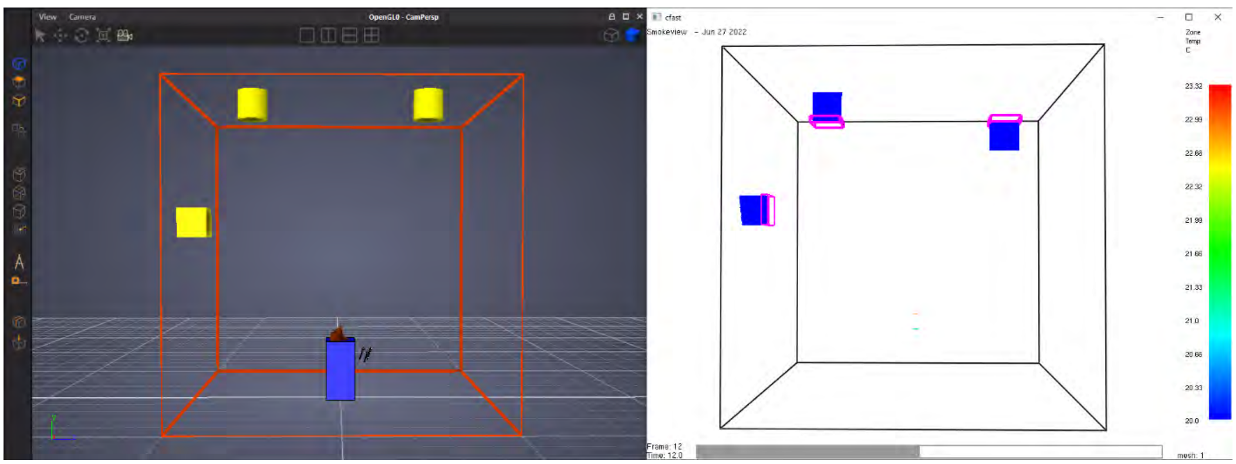

Figure 14. FRI3D “3D Window” (left) and SmokeView (right).

5. INDUSTRY COLLABORATION TASKS

This research project is in the final stages; one of the main tasks this year is to assist in industry use or collaboration efforts. Demonstration of actual use by a facility and presenting those results to the industry is key for adoption by the nuclear industry.

5.1 Plant Modification Pilot

In collaboration with the pressurized-water reactor owners group (PWROG), initial findings of the work were presented, and we asked for a volunteer who would be willing to use FRI3D to evaluate a plant modification and evaluate against their current process. We had a volunteer and worked with Engineering Planning and Management, Inc. (EPM) [15] on a plant modification that was upgrading and moving plant equipment. The following sections outline this ongoing work.

5.1.1 Existing Model and Evaluation

As part of the evaluation, EPM performed an impact review of the plant modification as they typically would for the facility. In this modification, a newer version of oil containing equipment would be replacing an old one and placed in a new location. This would mean the new equipment and the oil within the new equipment would serve as new potential fire sources and would replace fire scenarios originating from the old equipment. The new pieces of equipment had a different volume of oil and were closer to the fire zone boundary.

Instead of using CFAST to perform the fire scenario analysis, EPM used their own fire modeling tools that are based on NRC's Fire Dynamics Tools (FDTs) to evaluate the zone of influence (ZOI). The ZOI model provides conservative estimations for the properties of the fire given the user inputs. For example, a ZOI is used to determine PRA targets (i.e., cables and components) within a certain distance of the source. These tools are faster to use than building a CFAST model, running it, and using the data to determine failures.

Initially, there were eight different fire scenarios associated with the two pieces of equipment being moved. While analyzing the equipment fires, it was determined that it would be appropriate to use a full room burnup for the two 100% oil spill fire scenarios. Since these would be a full room burn up, and the smaller oil fires were easily modeled with the existing fire modeling tools, main analysis was to evaluate design options to limit the maximum 100% oil spill size from affecting PRA target items beyond the originating fire zone. There were three options to minimize the effect of the 100% oil spill: using curbing in the new area, incorporating an oil confinement system around the equipment, or crediting the existing plant drains near the equipment to limit the spill area. Using these calculations, EPM was able to risk-inform the decision process and present the options to the plant operators, who then selected using the floor drains. Not counting all the research and utility discussions, this process took between 4–8 hours.

Since all the scenarios were not run in the modification analysis, this is not a perfect comparison for evaluating against FRI3D which uses CFAST to determine the failures vs. the FDTs equations. However, it does provide a good time comparison for the initial zone boundary evaluation, and the old scenarios can be used as a basis for scenarios to be modeled in FRI3D.

5.1.2 Plant Data Import

FRI3D was developed to import existing fire model data and scenarios from a specific type of database file developed by EPRI called FRANX. The FRANX file and format was developed and is used by EPRI for external hazards modeling in their Computer Aided Fault Tree Analysis System (CAFTA) risk analysis software. To import EPM's plant models, slight modifications were needed for the import tool to handle some slight differences in the EPM's FRANX files needed for their inhouse tools. With just a couple of days of work, we were able to successfully import the plants fire model. This showed that even with model variation, it was still a minimal effort to setup the initial FRI3D model. This model had all of the compartments, raceways, components, cables, and existing scenarios for the NPP. It was provided to EPM as a starting point for spatial or 3D modeling and the case study.

5.1.3 Internal Model Testing

Before EPM started the case study modeling, Centroid Lab tested development of the 3D model for the compartment. This was done to get a feel for what information the analysts would have and the likely steps they would take so they could more easily answer questions and make sure there were no software issues that would likely be encountered. This process also prompted the evaluation to identify that a full room burnup was better for two of the scenarios.

The plant schematics including the floor plans of the appropriate zone to be modeled were provided by EPM and information was gathered from EPM engineers with regards to the specifics of the floor plan as well as what items needed to be modeled in regard to the relevant analysis to be performed. Since engineers at Centroid LAB were considered to be quite knowledgeable to the workflow of FRI3D, the modeling process metrics gathered, would set a good estimate on the time taken to model a plant from scratch if FRI3D proficient modeler would model a plant.

5.1.4 EPM Modeling

In FRI3D, EPM staff modeled the compartment boundaries and then the targets (cable raceways and components) in the room. Due to a software bug, this had to be done a second time. This provided good data to show the difference between a first-time user with basic training and someone with more experience as well as how long it takes to become fairly proficient at modeling. The second time modeling was only 2 hours which is half the time of the first. With just the compartment boundary, the same analysis was done following the old process could be done by just adding the three different oil fire scenarios.

The next step in the test case was modeling the raceways. One possible challenge in modeling raceways is identifying them in the plant drawings. In most cases, only the safety system raceways need to be modeled, but the plant schematics can have all the raceways, and many of the drawings have hand annotations and naming schemes that do not match the plant database naming. This can make initial modeling of the raceways difficult for someone not familiar with the information. There were approximately 100 raceways for the test case compartment. It took roughly 16 hours to model nearly all the raceways, not just the safety system ones. Select raceways were excluded based on difficulty identifying the raceway in drawings and insignificant mapping to PRA equipment. If only the safety systems trays were modeled, which would be typical if they do not contribute to secondary combustibles, it may have taken roughly half the time, 8–10 hours depending on visually finding the raceways.

The last step was adding the fire sources for the new equipment and running the fire simulation. The version of FRI3D used by EPM did not have the library of fire materials available so they had to add the HRR curve by hand. This manual process took approximately 4 hours to add the ignition sources. While this time would be significantly reduced by using the library, it was noted by EPM that there could be cases where finding data or comparing it against other results would be necessary, and this could increase scenario development time. Giving this process, a time range of 2–4 hours is estimated for the eight scenarios with the library available. Centroid is updating FRI3D's modeling tools to ease the creation of raceways which will also shorten this time.

5.1.5 Pilot Comparison

With the requirement change for this plant modification, a few different comparisons can be made:

1) Evaluating and comparing the different options for the 100% oil spill containment.
2) Comparing the analysis time required for current methods vs. FRI3D.
3) Comparing the analysis time required for a new FRI3D model vs. an existing FRI3D model.

5.1.5.1 Containment Options (3–4h FRI3D vs. 4–8h)

The main evaluation needed for this plant modification was exploring methods to prevent the 100% oil fire scenarios from having failures beyond the zone boundary. There were three options evaluated: a curb around a large area, confinement around the two pieces of equipment, or crediting existing drains a distance away. This took 4–8 hours using EPMs current process. The steps to perform the same analysis in FRI3D are to do the boundary modeling and then just add the three options as fire sources. Just these pieces, without raceway modeling and assuming a full room burn up, take about 3–4 hours.

5.1.5.2 Scenario Comparison New Zone 3D (12–20h FRI3D vs. 16–32h)

Initially, there were eight fire source scenarios that would need to be redone for the components being moved. To create a scenario with specific cable/component failures, all the raceways and components need to be modeled and included in the fire simulation. The current steps for scenario development by EPM is to identify applicable source properties (bin type, position, oil quantity, vented, etc.); calculate ZOI based on identified properties; manually identify targets on raceway drawings; and add results to FRANX for PRA analysis. EPM estimates that it takes 4 hours per scenario/source to do this process; with their current practice and several data sets for the sources being repeated in this scenario, the total time is estimated at 16–32 hours.

The FRI3D time needed, is the raceway modeling time (because no analysis was previously done in this compartment using FRI3D) and the scenario development time. As stated, EPM modeled almost all the raceways in the compartment, where the analysis could have been done with just the safety-related equipment raceways. If they had modeled only the safety-related raceways, it would reduce the number of raceways by half but could make it slightly more difficult to identify them in the drawings as you are visually searching the drawings for a particular raceway instead of going through all the raceways on the drawing and typing it in the FRI3D model. To be conservative, a range of 10–16 hours was used for the raceway modeling time and 2–4 hours for the source/scenario development for a total of 12–20 hours vs. 16–32 for the current method. It must also be noted that, since most of the time spent during FRI3D modeling is modeling the raceways, the raceway modeling tool which will be available in subsequent versions of FRI3D would further reduce the time to model in FRI3D.

5.1.5.3 Scenario Comparison Existing Zone 3D (2–4h FRI3D vs. 16–32h)

If the FRI3D compartment model, with all the items modeled in 3D, already existed, then the only task would be to add the sources and run the scenarios. This would only require 2–4 hours for scenario development time. The time taken using the existing practice would remain the same, between 16–32 hours.

5.1.6 Generalized Results

The following provides generalized time results for using FRI3D:

- Import Plant Data for FRI3D Model – (1–3 days). It was assumed that FRANX fire data was used the same way between facilities and contractors. This was incorrect and required a slight modification for the one-time import process. It is planned that the first use of FRI3D will require help from the vendor to import the plant data, and the time needed could be more.

- Learning Curve – (1.5 days). Initial FRI3D training takes about 1 day, and the user can become fairly proficient at the basic modeling features in FRI3D after about a half a day after that training. Advanced feature usage could take more time for training.

- Initial Compartment Modeling – (CompartmentModelingTime = 1.5h + [10min * Number of Components] + [5min * Nummber of Raceways]) The first time a compartment is modeled, it will require a significant effort by the modeling team. However, this modeling time is similar to the time typically needed for not using FRI3D as FRI3D automates many of the tasks previously done.

- Subsequent Compartment Scenarios – (15min-1h). Once a compartment has been modeled in 3D, time for adding further analysis for new scenarios would be minimal unless there is difficulty in getting data for the source. This case is where FRI3D provides significant cost savings.

The following table provides estimations of time comparisons for using FRI3D vs. current analysis methods using provided average estimates and extrapolating time from the pilot test results.

Table 5-1. Generalized time comparison for plant modifications between traditional methods and FRI3D depending on the three criteria shown in gray.

FRI3D (Hours)	Traditional (Hours)	# of new Sources	# of Raceways	Existing FRI3D Compartment
19	32	8	100	False
2	32	8	100	True
11	32	8	50	False
2	32	8	50	True
7	8	2	25	False
0.5	8	2	25	True

Once a plant has imported their existing fire model/data into FRI3D, it is available for plant modification analysis. They do not need to model compartments in 3D until a scenario needs that compartment. They may also not need to model all the components in the compartment, depending on the scenario. In general, the first plant modification in a compartment will take about the same time as current analysis methods if there are just a few scenarios as shown in Table 1-1. If it is a new compartment to be analyzed or a modification with many scenarios, FRI3D will be significantly faster to use. After a compartment has been modeled, it will only take a few hours for the analysis turn-around time.

5.1.7 Feedback and Industry Comments

Part of the project was to get open and constructive feedback from EPM on the use of FRI3D and its potential for industry use. Their response lines up with our analysis of the most significant savings coming for new fire models and subsequent compartment modifications, as initial compartment modeling is similar to existing because of the 3D modeling time. Their comments are in italics below (C. Weiser, email to author, August 4, 2023):

> *FRI3D shows high potential. The software is still in development so naturally, there are small bugs and operability issues that could be resolved to make the software more convenient or optimize efficiency for users to model a fire zone faster. EPM is confident these issues would all be addressed in the final product so these issues were not reflected in this final opinion. The largest downfall of FRI3D is the significant upfront effort required to model the applicable fire zones.*
>
> *For stations that have not already created a fire PRA or performed the necessary fire modeling, I would advise using FRI3D as it serves as an excellent tool to help stations efficiently minimize fire modeling conservatisms.*
>
> *For stations that have already performed fire modeling in high risk areas, I see this as good validation but expect most fire modelers to view it as rework to replace the existing fire modeling analysis' [sic]. However, as noticed in the pilot plant example, if the fire zone is already built in*

FRI3D, then the user can create sensitivities or examine the impacts of a major plant mod more efficiently, relative to the effort involved with modifying existing fire modeling analysis.

We would also note, the time involved in altering existing fire modeling analysis' [sic] can vary significantly from each station depending on the controls and tools used.

It should be noted that the EPM work was performed on a prerelease version of the software that had not run through full quality control measures, Centroid states that they have a deployment ready version and will continue to make improvements to satisfy customer needs over time. To address a concern from above of the "significant upfront effort to model applicable fire zones," the strategy for entities using FRI3D is to only model those areas when plant modifications for that area come up. This would provide some minimal cost savings early on but still provide significant savings as time progressed and already modeled areas were reused.

5.1.8 Items Not Considered

The evaluation performed was fairly conservative as a few factors were not included. First, the library of fire sources materials, discussed in Section 3, was not available for this analysis. This would reduce the time for each fire scenario generation. Second, documentation time was not considered. EPM said about 1 hour of time is taken for documenting each scenario. Under a different project, FRI3D is working on automated documentation that would eliminate most of the time currently spent documenting scenarios. Finally, repeated use was not considered. After using a tool or software several times, efficiency typically significantly improves.

5.2 Full Plant Fire PRA

In addition to plant modifications, FRI3D could provide significant cost savings for full plant fire PRA model development. This area has a significantly higher cost savings as there would be many scenarios for the same compartment, and the compartment modeling takes the most time. However, most U.S. operating NPPs that intend to perform a PRA-based fire model following the NUREG/CR-6850 have already done so. Facilities that have not done so hesitate because they see the benefits as not been as significant as expected and have seen the cost of the fire modeling for other facilities go beyond what they can justify. FRI3D could help change that ratio, but that would be a significant effort and higher risk for an NPP not already planning on the task. If a pilot project could demonstrate a cost benefit analysis using FRI3D for a full plant PRA fire model, then other NPPs would be more likely to follow suit.

Outside the United States, more facilities are endeavoring to perform fire PRA analysis, and a foreign NPP expressed interest in using FRI3D. A demonstration was provided to the NPP, and several areas of concern were discussed. The primary hold up was the PRA software used by almost all foreign NPPs is Risk Spectrum, and FRI3D was designed to couple with EPRI's CAFTA software. However, a small research project done for INL use implemented the Systems Analysis Program for Hands-On Integrated Reliability Evaluations (SAPHIRE) PRA software instead of CAFTA. This took less than 2 weeks of development time and demonstrated that other tools could be added. During this same period, the Risk Spectrum software owners also expressed interest in a collaboration or partnership with Centroid Lab and INL for coupling FRI3D with their software.

5.2.1 Risk Spectrum

Engagement with Risk Spectrum is ongoing. Work with Risk Spectrum would allow FRI3D to directly link with the software to generate scenarios it could solve. This would allow FRI3D to be compatible with the majority of nuclear facilities around the world. Centroid Lab is working toward a agreement for the use of FRI3D through Risk Spectrum. This work will move FRI3D toward a full plant fire PRA.

6. CONCLUSION

The FRI3D software has significant potential as a cost savings tool for nuclear industry fire analysis. To do some quick preliminary evaluations, such as the fire exceeding zone boundary in the pilot, FRI3D can save up to 50% of the time. For the first plant modifications in a compartment, FRI3D would save between 0–50% time depending on the number of raceways and scenarios to run, with more savings in cases with less raceways and more scenarios. For subsequent changes, the time savings would be over 90%.

Pilot results show that for plants with high-quality existing fire models, the initial effort of using this version of FRI3D is similar to current practices but can provide significant time or cost saving the more it is used. The largest potential is for full plant fire PRA analysis, but a pilot needs to be done to demonstrate this potential of use for a full plant fire PRA. This does not include the value of FRI3D's other benefits such as more accurate modeling using fire simulation vs. conservative ZOI calculations, the reduced expertise required for much of the work, and easy maintenance of the plant fire model.

Recent changes and features have addressed many needs or concerns of industry, and FRI3D is at the first stages for effective industry use. The collaborating partner Centroid Lab has acquired initial licensing rights and is in the process of commercialization and initial use by industry through several avenues.

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