Light Water Reactor Sustainability Program

Fire Risk Investigation in 3D (FRI3D) Software and Process for Integrated Fire Modeling

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ABSTRACT

Modeling and implementing fire safety for nuclear power plants is a costly activity. Because of the complexity of fire phenomena and multiple operational procedures, it is difficult to provide assurance that mitigation methods are adequate for critical areas using current analysis methods in a cost-effective manner. The nuclear industry needs more efficient methods to accurately model and optimize mitigation methods and improve understanding of fire scenarios at nuclear power plants.

This report describes the work done over the last 2 years on the Fire Risk Investigation in 3D (FRI3D) software. This software simplifies the modeling process by importing existing plant models and data, incorporating a 3D modeling environment, and coupling with the fire-simulation software Consolidated Model of Fire and Smoke Transport (CFAST). This eliminates the manual labor and errors associated with much of the fire modeling process. The report lays out the status and path of FRI3D software for the Risk-Informed Safety Analysis pathway of the Light Water Reactor Sustainability project at Idaho National Laboratory, as well as for industry collaborators, to help reduce costs and improve realism in fire Probabilistic Risk Analysis.

CONTENTS

FIGURES

ACRONYMS

API	Application Program Interface
CAFTA	Computer Aided Fault Tree Analysis System
CFAST	Consolidated Model of Fire and Smoke Transport
CFD	Computational Fluid Dynamics
DLL	Dynamic Link Library
DOE	Department of Energy
EPRI	Electrical Power Research Institute
FDS	Fire Dynamics Simulator
FDT	Fire Dynamics Tool
FRI3D	Fire Risk Investigation in 3D
HRR	Heat-Release Rates
INL	Idaho National Laboratory
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NSP	non-suppression probability
NUREG	Nuclear Regulatory Commission technical report designation
NUREG/CR	Contractor prepared NUREG
PDMS	Plant Data Model System
PRA	Probabilistic Risk Analysis
SAPHIRE	Systems Analysis Programs for Hands-on Integrated Reliability Evaluations
SSCs	structures, systems, and components
STTR	Small Business Technology Transfer
THEIF	Thermally-Induced Electrical Failure
UI	User Interface

1.   INTRODUCTION

The primary goal of this project is to develop software tools and methods that can improve the efficiency and realism of fire modeling for the commercial nuclear industry. These tools will provide realistic insights by reducing unreasonable conservatism in Probabilistic Risk Analysis (PRA) models in a cost-effective manner for the current nuclear operating fleet. This project will combine research goals from the Department of Energy (DOE) and Idaho National Laboratory (INL) alongside more practical aspects from Southern Nuclear Co. to develop a tool that can improve the operations, maintenance, and realism of fire PRA. Fire Risk Investigation in 3D (FRI3D) will provide immediate benefits to facility operations in fire analysis and updates. In the long term, this software's Application Program Interface (API) will provide the back end for advanced time-dependent fire analysis research.

2.   CURRENT FIRE MODELING PROCESS

The overall fire PRA process, as defined in NUREG/CR-6850, is illustrated in Figure 1. The workflow consists of a series of steps, requiring a considerable amount of time and effort as well as a variety of tools and methods. It must also be stressed that, at various stages of the fire PRA process, plant walkdowns are essential to confirm the existence, integrity, and detailed locations of components, systems, and cables. In this section, we describe some key tasks of the fire PRA workflow along with associated tools and methods, focusing on static PRA (as opposed to dynamic PRA), since currently most safety analysis and current toolkits are based on static analysis methods.
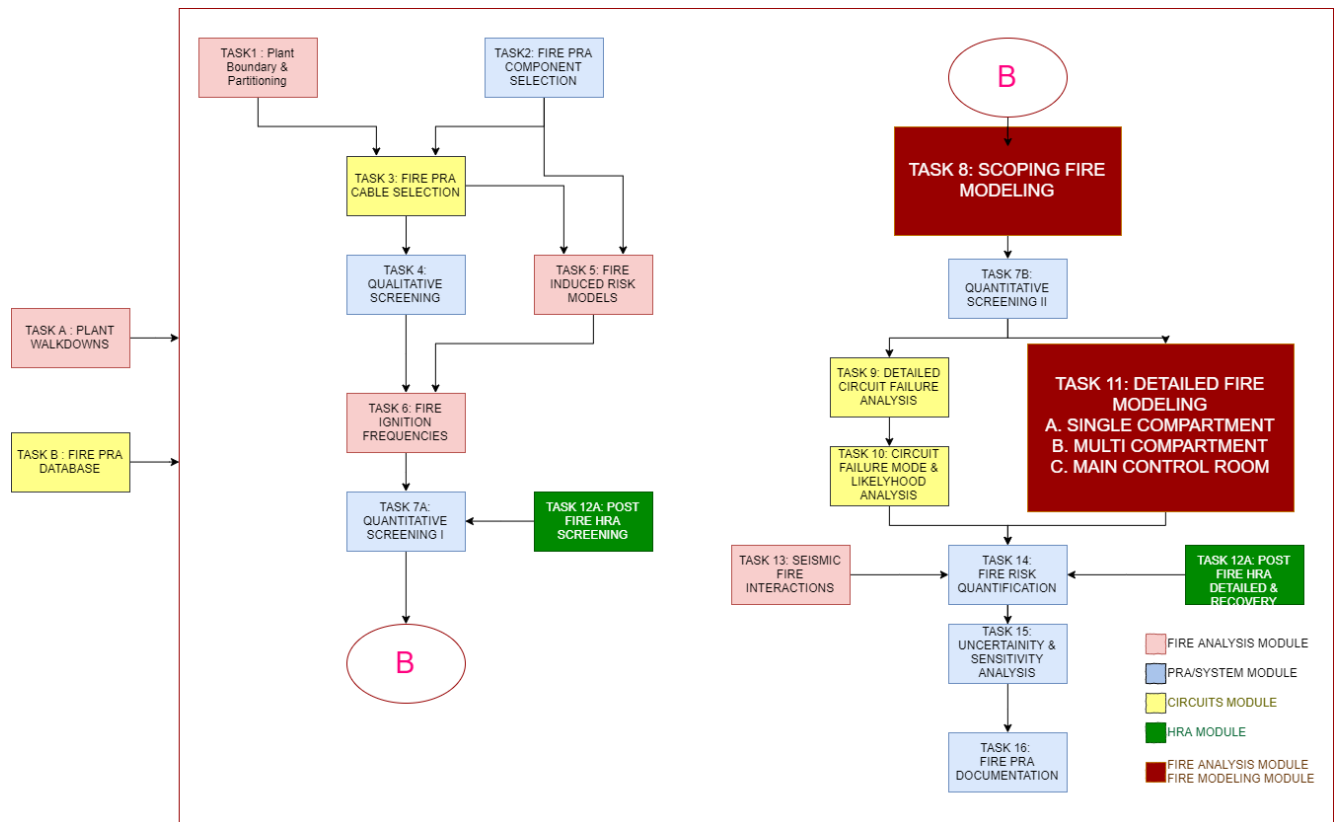

Figure 1: FIRE PRA Workflow.

Tasks 8 and 11 are the primary modeling tasks outlined in NUREG 6850. They outline how to create specific scenarios and assess them. Current fire modeling processes require the modeler to partition the plant into fire areas. These fire areas determine physical location(s) and components to include in the

analysis. Once the fire areas are established, the next step is to identify the risk-significant areas. These areas are the primary drivers of risk to the plant and will indicate the level of fire modeling the modeler would need to use to adequately assess the areas. The first approach to fire modeling is to use a full-compartment-burn approach. This methodology is extremely conservative but allows for a quick analysis to identify the risk-significant fire areas in the fire PRA. The full compartment burn approach uses an assumption that any fire in the fire area, when ignited, will immediately fail all the equipment and targets (e.g., cables) housed in the area immediately. This simplified conservative approach allows the modeler to quickly identify extremely risk-significant areas. The fire areas that are not as risk significant, even with this conservative approach, are essentially modeled to their fullest extent and do not need any more detail before being added to the fire PRA. This allows resources to be spent on spent refining the risk-significant fire areas, utilizing more accurate modeling detail to reduce conservatism.

Once the risk-significant fire areas are identified, a more detailed modeling approach is used. Some computational fluid dynamic software that can be used are CFAST and FDS. PRA modelers manually create code-specific 3D spatial models for the significant fire areas. Different simulation tools have different levels of detail, but they allow the PRA modeler the ability to define the ignition source(s) and how the fire, smoke, and heat will transfer, spread, and damage targets within the area. This approach breaks the fire areas down into individual fire scenarios that consist of an individual ignition source and a set of targets that determined by the heat-release rate of the ignition source, as well as the geometry and spatial information within the area.

The fire sources identified using either the full compartment burn approach or the detailed modeling, approach are inserted into the fire PRA.

2.1   Risk-informed methodology

The methodology for the static fire PRA is outlined in NUREG/CR 6850 [1] and NFPA 805 [2]. It is built on the same event tree/fault tree approach as an internal-events PRA. The major differences lie in what is to be considered in scope for the fire PRA compared to the internal event PRA. In addition to the safety system mitigation equipment, fire PRAs must consider fire-specific equipment, such as suppression and detection systems and fire barriers. The equipment credited for specific fire-related operator actions must also be addressed. Another unique major contributor to fire risk is cabling for the equipment credited to mitigate accidents. Identifying the cabling is significant to ensure that fires do not prevent specific equipment from performing their mitigation function. To create the overall fire scenarios, it is important to lay out the plant boundaries and identify where fires would originate, and what types of fires are possible. Once boundaries are established, scenarios need to be made that incorporate the heat-release rates (HRRs) of fire types, fire-spread from target to target and compartment to compartment, suppression and detection equipment, and additional operator actions. The goal of the fire PRA is to analyze these scenarios to identify the risks to the plant, including the types and locations of fires that cause the most significant amount of risk to core damage or a release of radionuclides.

- Equipment fire affecting other equipment
- Raceway fire affecting other raceways
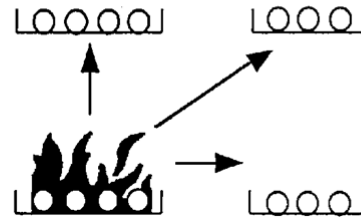
- Equipment fire affecting raceways
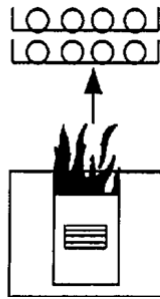
- Transient fire affecting equipment and/or raceways
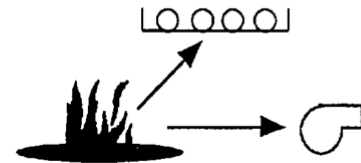
Figure 2: Sample scenarios for fire spread and impacts.

The components that can cause fire (e.g., electrical cabinets, pumps, oil reservoirs, transient combustibles, cables) and then impact targets around them are shown in Figure **2**. Initially, the direct impact of fires on the component must be evaluated. Next, it must be determined if the fire can create a hot gas layer which can damage components indirectly. Finally, the consideration of the fire (or hot gas layer) propagation into an adjacent compartment(s) must be analyzed. These steps provide the immediate scope of the fire analysis. Subsequently, the analysis needs to be expanded to identify components affected by cable damage, determine timing of equipment failures, and identify impedances for operator actions. All these factors must be, then incorporated into the fire scenarios.

There are multiple ways to incorporate the scenarios into the PRA model. A scenario can be added directly into fault trees or event trees. Also, a new PRA model does not need to be built for the fire PRA, but rather scenarios can be incorporated directly into existing internal-events PRAs. There are different types of logic modeling software such as RISKMAN, Computer Aided Fault Tree Analysis System (CAFTA) [3] and Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE).

2.2 Fire Simulation

Computational fire modeling aims to predict fire behavior in different environmental conditions. These computational models need to consider the various physical processes of combustion, fluid dynamics, and heat-transfer processes. The complexity in modeling the physical process of fire propagation arises from the dynamic turbulent nature of the internal processes. Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that provides methods and tools that help in modeling, prototyping, testing, and analysis. NUREG-1824 documents the five software toolkits used in modeling fires in a typical NPP. They are (1) NRC's NUREG-1805 Fire Dynamics Tools (FDT) [4], (2) EPRI's Fire-Induced Vulnerability Evaluation Revision 1, (FlVE-Rev1), (3) NIST's Consolidated Model of Fire Growth and Smoke Transport (CFAST) [5], (4) Electricité de France's (EdF) MAGIC [6], and (5) NIST's Fire Dynamics Simulator (FDS) [7].

Algebraic models, such as FDT from NRC and FIVE-Rev1 from EPRI, take minimal inputs and create quick analytical calculations, which is their advantage. However, these models might be too conservative. Zone models CFAST and MAGIC perform more detailed analyses than FDT and FIVE-Rev1. They can compute hot gas layers as well as target heat fluxes. A hot gas layer is a layer of smoke and heat that forms at the ceiling, then fills the entire ceiling. It slowly descends, damaging additional targets as it lowers (see

Figure **3**). However, these models also have limitations with respect to complex room geometries and large horizontal paths.

In terms of the types of analysis, FDS is broadest in scope. Moreover, its dynamic nature and simulations can be performed in three-dimensional (3-D) space. Chapter 3 of NUREG-1934 specifically lists seven generic scenarios considered for a fire at an NPP. In many of those scenarios, CFD models are either recommended or necessary to provide detailed analyses that include obstacles in the path of the fire. Since FDS is a CFD model, it allows the analyst the ability to simulate fire conditions in complex geometries with complex vent conditions. However, it takes a significant effort to properly create the model for simulation, and computation times could be quite long. This modeling is used to simulate the types of fires that can cause damage to components by showing the specific HRRs that would damage nearby targets via direct impact or through a hot gas layer.
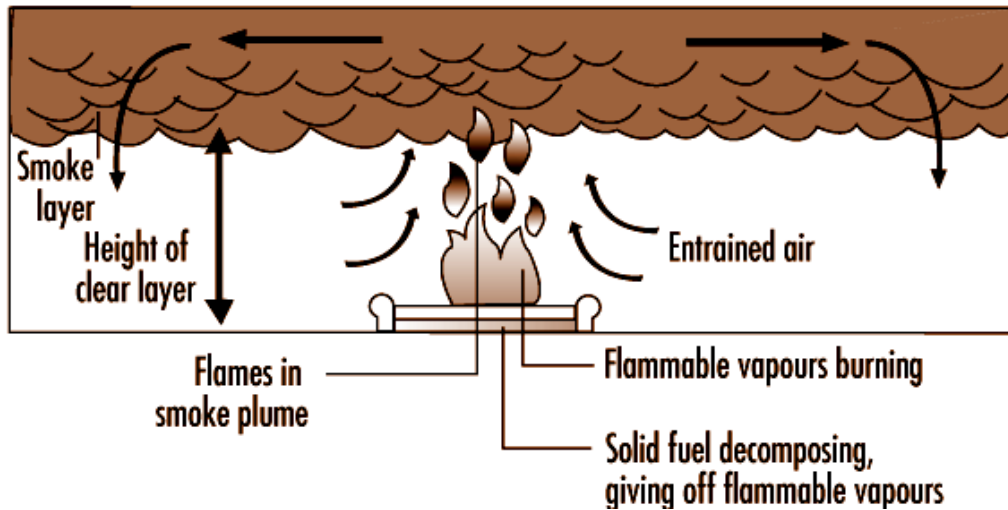
Figure 3: Smoke and hot gas layer formation and behavior.

Each simulation provides an estimate of the scope of damage and determines the components that will be available to help mitigate the specific fire scenario. Figure **4** shows the percentage or likelihood that a fire heat release will create a scenario needing further investigation because the resulting peak HRR can damage additional targets. These scenarios will be incorporated into the PRA. The fires that generate a peak HRR below this point only damage the ignition source itself and no other targets.

Peak HRR Probability Distribution

Minimum intensity leading to spread/damage

Severity Factor tied to fraction of distribution above this minimum HRR

Probability

Peak HRR
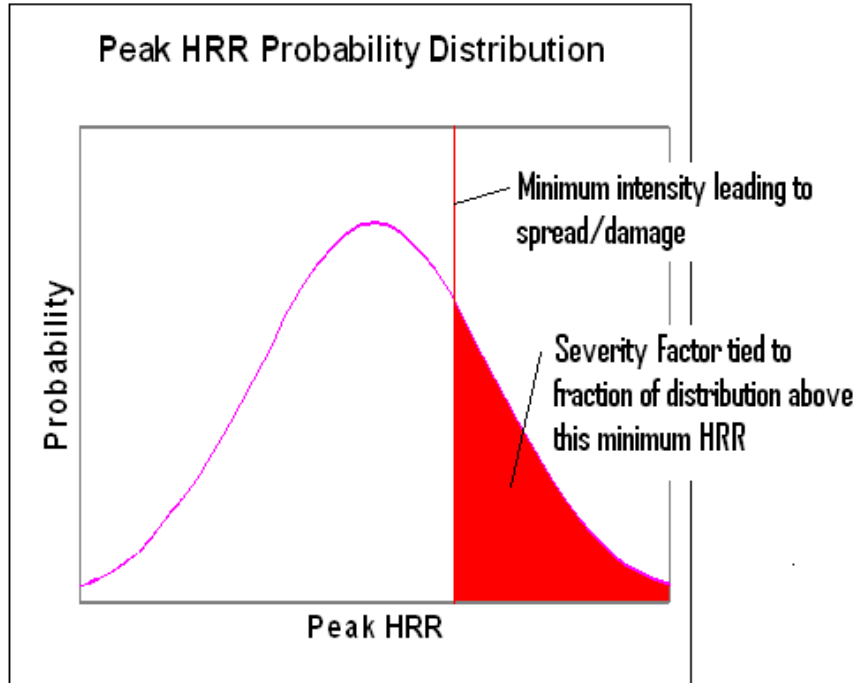
Figure 4: Example heat-release rate with the severity factor for a particular component.

Computer modeling also provides information about the timing of the specific fire and how long it takes to damage targets or create a hot gas layer. It additionally provides an estimate of how long it takes for suppression and detection systems to actuate, which can be incorporated with plant procedures and training times. Further, the information can be used as time measurements for fighting the fire and preventing it from damaging targets. This timing information can also be used to remove the impacts of fire scenarios from the PRA models if indicated when incorporating a non-suppression probability and the severity factor, into the ignition frequencies. The graph in Figure **5** shows how the non-suppression probability (NSP) approaches 1 on the NSP axis as the time to detection approaches the time to damage. Removing the conservatism in either the time to damage and/or the time to detect can have a significant impact on the fire scenario in question.

All Events Mean Non-Suppression Curve
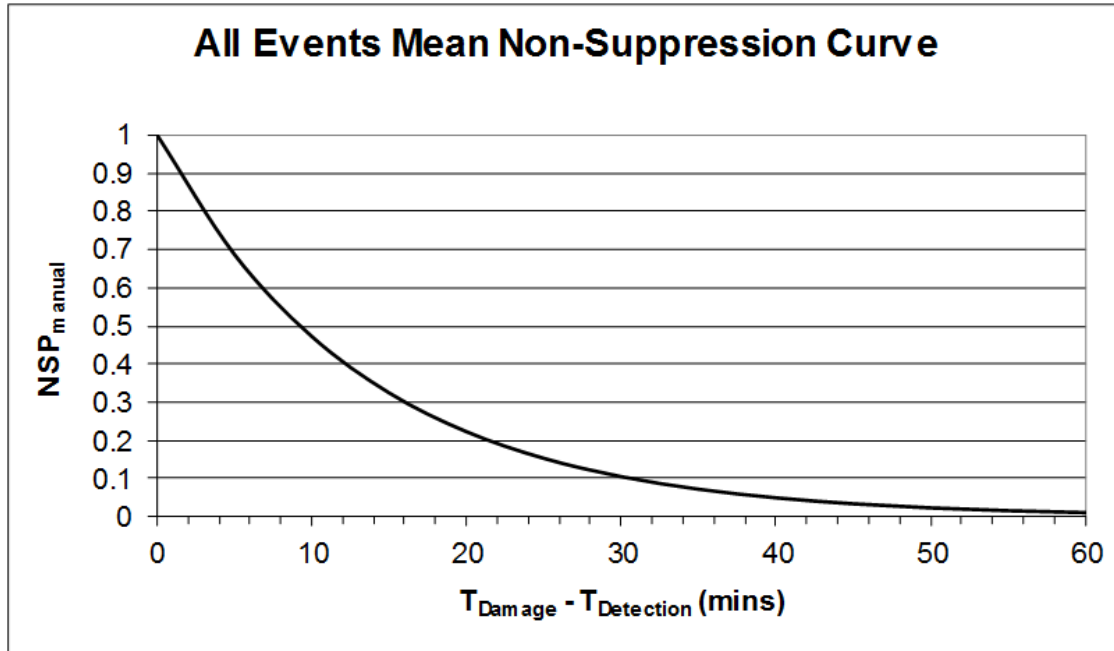
Figure 5: Example NSP over time.

2.3 Incorporating Simulation into PRA

Fire simulations are incorporated into the fire PRA in a variety of ways. Primarily, the targets and initiators are directly included into the fire PRA with the use of basic events that will fail when a given initiator occurs. The target sets for initiators are derived from the fire modeling. A computational fluid dynamic model simulation for a specific initiator, will identify targets that fail due to the heat generated by the ignition source as well as any secondary combustibles that ignite. A specific target set will be identified for each specific fire scenario and those scenarios will be individually modeled within the fire PRA. After the target sets, timing of failure of components due to the fire can be established with the computational fluid dynamic modeling. This information will be used to identify time of fire detection to alert operations to initiate firefighting tactics, as well as any operator actions that are required in bringing the plant to a safe and stable state.

3. FRI3D DESIGN

While the existing fire modeling process can conservatively capture fire risk, more accurate modeling quickly becomes very time consuming and maintaining or updating the model for plant modifications can be very expensive. The 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 following sections describe how the software integrates with existing data/models and eliminates manual processes such as applying simulation results to the PRA model.

3.1 Linking with Existing Plant Data

Most NPPs fire models use EPRI's CAFTA and FRANX [8] software tools and the FRI3D software currently requires and assumes existing models. The FRI3D software imports two main pieces of existing NPP data, shown on the left side of Figure **6**. The data described in the following two sub-sections were tested with Southern Nuclear Company's Vogtle model.
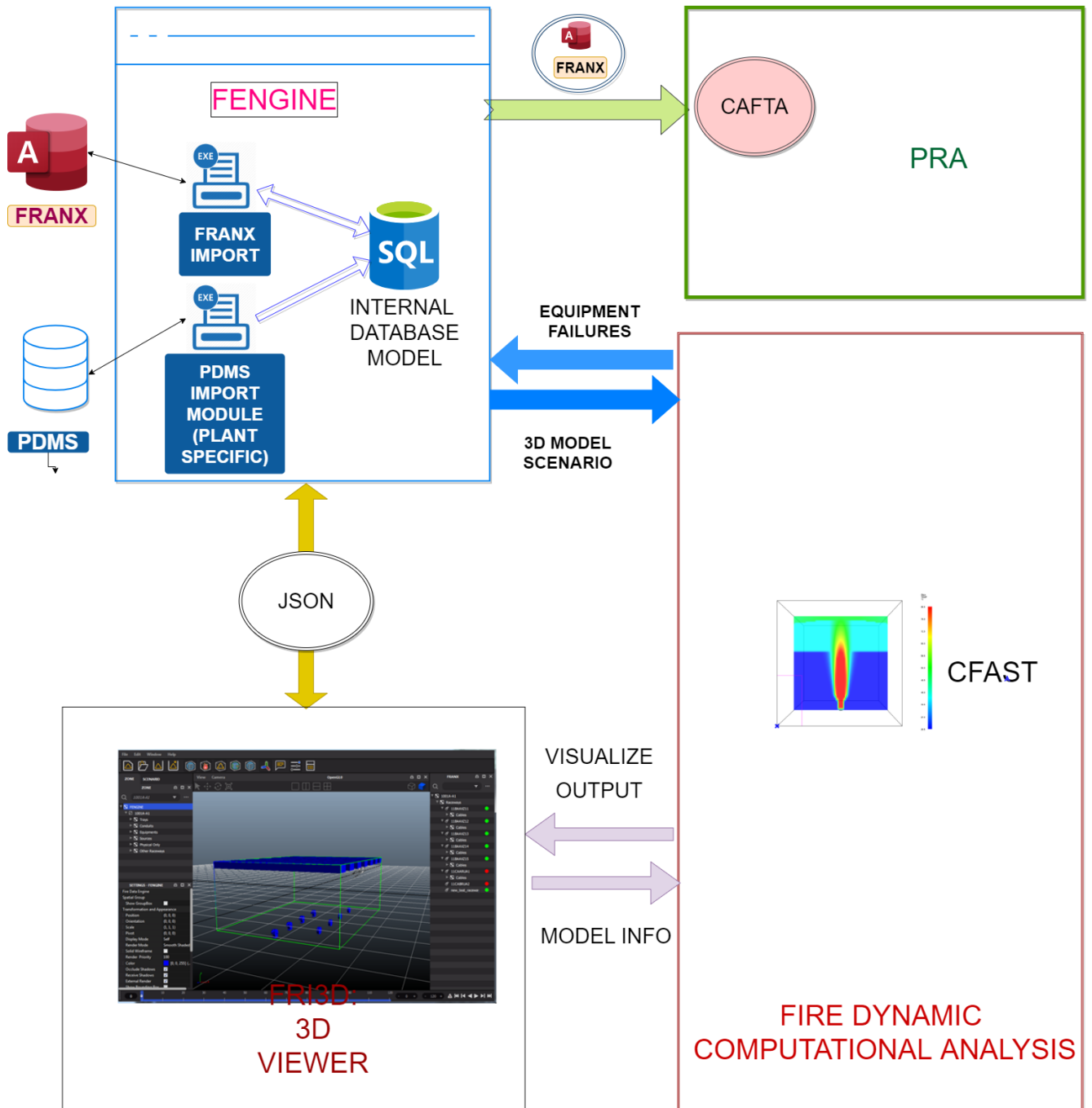
Figure 6: Modules and interaction for the FRI3D software.

3.1.1 FRANX Module

The FRANX format is consistent between NPPs, and a fixed module imports this data to an internal database, to be combined with other information. The FRANX database stores the relationships between the following items of the nuclear facility in a tree-like structure.

- Zone – The physical area of a facility is divided into logical fire zones

- Raceways – Varying types of equipment that carry cables from one location to another
- Cables – Wiring that runs from either a power source or controller to another piece of equipment
- Component – A physical component in the facility that can be affected by fire directly or through the failure of a connected cable
- Basic Event – Failure modes for a component that reference a basic event in the PRA for calculation purposes
- Scenarios – These consist of an ignition source and determine what items in the zone will fail.
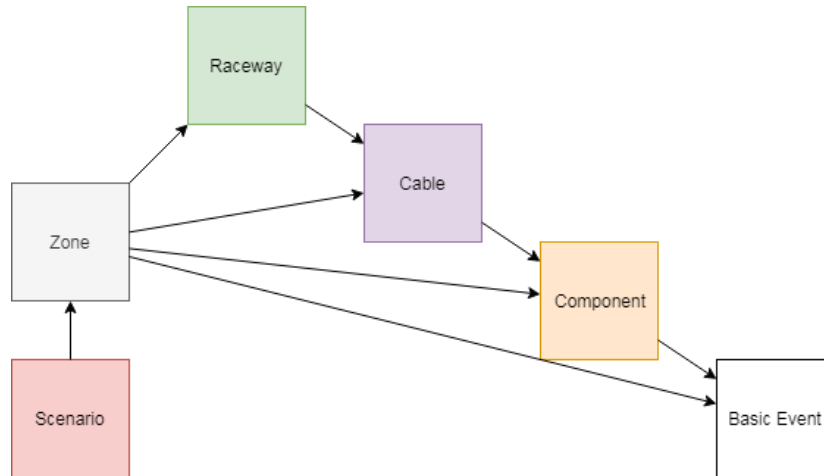
Figure 7. Relationship between fire model items.

A Microsoft Access database used for FRANX and was designed for readability and manipulation by humans. Relationships between different elements such as what cables are in a raceway are done through a name comparison, without any keys or referential integrity. While this works for its intended purpose, the design is not suitable for fast lookups and other requirements for advanced analysis and can also lead to unseen errors due to changes in spelling or typos.

The unique information contained in the FRANX model are the scenarios. These scenarios define what things can happen in a zone and the effects of a scenario on the items in the zone. When running the FRANX model, failed items are propagated clear down to the basic event level where they are used to fail basic events in the PRA model for quantifying a result, shown in Figure **7** (above).

To use this data, as shown in Figure **6** (above), a module processes the FRANX database, retrieving all the items and saving them in an internal database structure. While some of the FRANX models represent a physical location relationship, such as zones, raceways, and cables, much of the data is logical only, meaning that if this item fails, then all the child items also fail. For example, a cable may have wires for many sensors located in various locations, and if that cable is burned, those sensors may fail in different ways. FRI3D needs to maintain this relationship but separate it from the physical location relationship.

3.1.2 Plant PDMS Data

The Plant Data Model System (PDMS) database format and detail of information may be different from plant to plant, but this database contains a comprehensive list of all the components, fire sources, descriptions, and other plant-specific data. This data is typically stored in a Microsoft Access database. Because it can be different between plants, an open template interface was created to port this data in. The template interface has the data access calls stubbed out and the specific location for the data is filled out specifically for that plant, as shown in Figure **8**.
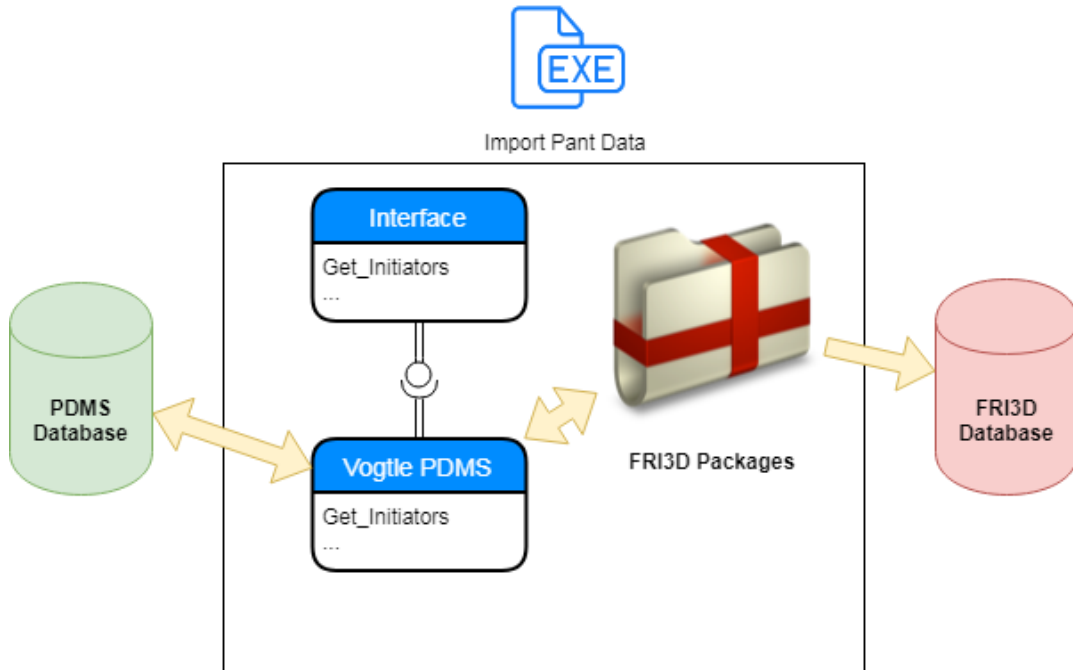
Figure 8: Modular design for importing Plant Data Model System.

3.2   Decoupled Backend and User Interface

As shown in Figure **6** (above), a decoupled design between the user interface and the processing backend was used. All communication between the user interface (UI) and the data processing backend is handled through a Dynamic Link Library (DLL) API. This is for two reasons: first, the 3D UI required a different programming language used for development, so a DLL API was chosen for communication. Second, future development in advanced fire modeling required the decoupling of the UI from data processing so it could be used with other tools. Calls requiring data structures are passed through as JSON strings. JSON is a common data-exchange format with libraries in every standard language. [9]

The coupling of the simulation software CFAST was accomplished by programmatically generating a CFAST model, running CFAST, and opening and processing the results file. No direct communication between the two codes was necessary. More detail on the full process is described in Section 5.

3.3   Design Architecture (code/packages)

FRI3D software consists of two main parts: the API backend with the logical fire model, and the graphical program interface with a 3D visualization front end. This combination allows users to develop and see spatial relationships, along with existing fire models.

3.3.1   FRI3D Engine API

The API was developed using C# in a visual studio .net environment. This was chosen because of packages available for reading and manipulating Microsoft Access databases. C# DLL libraries typically can only be accessed by other .net applications because of the "Managed Code" base. Because the API needs to be accessed from the C++-based UI, an unmanaged export wrapper was needed. The internal database is built using SQLite. The following C# packages were used in the API development:

- Lucene.Net – Search engine library
- Newtonsoft.json – For JSON data communication over the API calls

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- NLog – Error and debug logging
- XUnit – Unit testing package
- UnmanagedExports – C style DLL construction for unmanaged code
- Dapper – Internal database access for SQLite.

3.3.2   FRI3D Modeling & Visualization Engine

FRI3D 3D Interface is developed in C++ and using the Qt Framework with OpenGL. The following are additional libraries which are used by the FRI3D interface and which are bundled along with the application. All the libraries are available under Open Source Licenses except for NDYN and NVIS frameworks which is proprietary to Centroid LAB.

- NDYN: The Computational framework 3D Modeling/UI and Visualization Library from Centroid LAB. The following are the sub-components of the NDYN Library system:
    - NECore: Core Architectural Libraries for the system
    - NEGeometry: Geometry Processing Library. Mesh/Volumes, etc.
    - NEPhysics: Physics Base Module Library
    - NEPostProcessor: Post Processor/Visualization Library
- NVIS: Visualization framework and API in C++ developed by Centroid LAB which implements advanced near to real time visualization of 3D geometry, fluid simulation outputs, smoke, fire. NVIS uses the latest advances in Computer Graphics and Visualization techniques as well as hardware accelerations provided by graphics cards from NVIDIA and AMD and associated technologies such as OpenGL and CUDA.
    - NEGLI: Interactive CAD Modeling Library
    - NERender: Realtime and Photorealistic Visualization Library
    - NEUIProperties: User Interface Property Library
    - NEUIUtilities: User Interface Utilities Library
- Half: Library to use half precision arithmetic
- Python27: Python Libraries
- PythonQt: Qt Interface to Python
- OpenVDB: Volumetric Library
- TBB: Intel's Threaded Building Block Library
- FTGL: GL Font Rendering Library
- OpenGL: OpenGL Graphics Library Provided by the Graphics card vendor
- AssImp: Library to read a variety of 3D Formats
- Boost: C++ Utilities Library
- ZLib: Compression Library
- QT: Cross Platform User Interface and Utility Library.

3.3.3   External Requirements

To read/modify Microsoft Access databases, the "Microsoft Access Database Engine 2010 Redistributable" needs to be installed. [10]

4.   FRI3D INTERFACE

FRI3D interface is the main component used to set up the model. It gives the user the ability to see the spatial relationships of the objects. The relationship of the FRI3D interface with other modules is depicted in Figure **6**, above. The UI is designed to build and show the link between the fire logical model and physical relationships. This is done by breaking up the data into three areas: the physical compartment items on the left, the 3D model in the middle, and the FRANX model on the right, as outlined in Figure **9**.
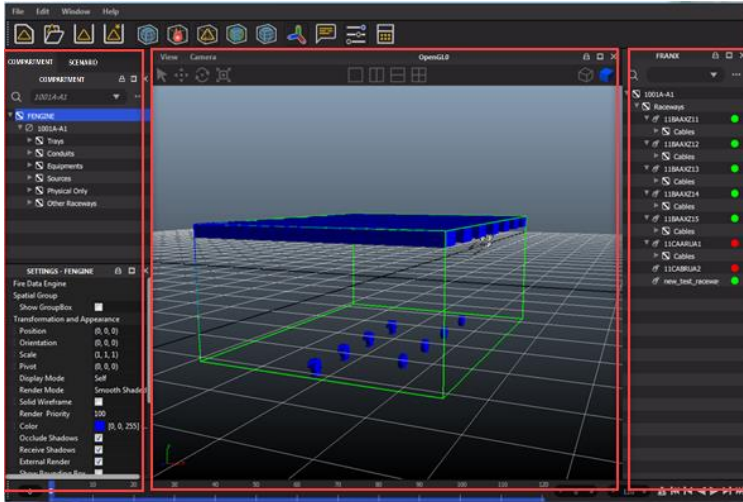
Figure 9: FRI3D Graphical User Interface (GUI) for developing and modifying scenarios.

4.1   Compartments & Scenarios

When a user opens a project, they then can either load a compartment or a scenario using the tabs in the top left of the UI and selecting the "…" button (see Figure **10**), then selecting the corresponding scenario or compartment of interest from the combo box. This provides two different ways to look at the model. If the user wants to modify the physical attributes of the compartment or create a new scenario, they would load the compartment they are interested in and stay in this view. From here the user can modify properties of all the items physically in the compartment so those modifications can be applied to all the scenario in the compartment.
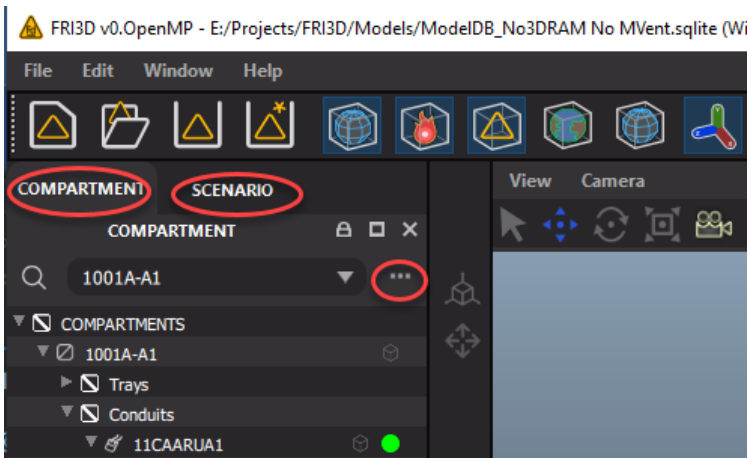
Figure 10: Compartment vs. scenario-view tab.

The scenario view is used if there is a specific scenario the user is interested in exploring. The same 3D model is loaded for both the compartment and scenario views if there is a single-compartment scenario. If it is a multi-compartment scenario, the compartment dropdown list lets the user change compartments. Items that are not part of the scenario are grey, as shown in Figure **11**. The scenario view only shows the items that are part of the current scenario. Here the user could try "what if" scenarios such as removing a particular cable by right clicking on the item in the left tree view and selecting "Remove From Scenario."
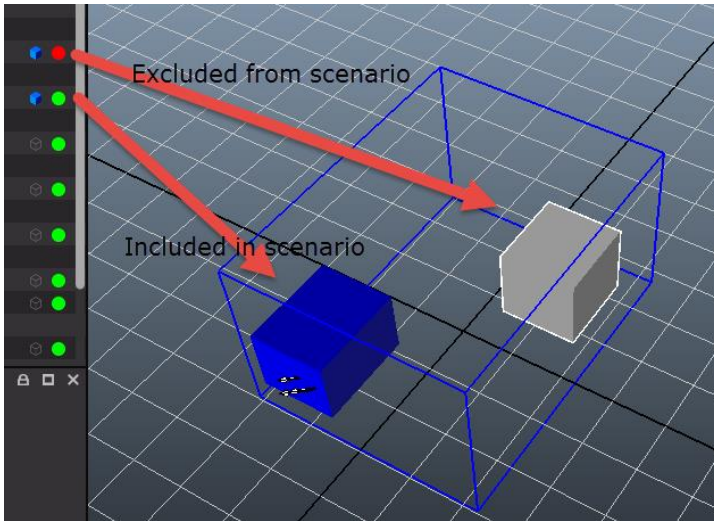
Figure 11: Red and green dots indicate inclusion or exclusion from the current scenario.

4.1.1　Tree Item Types

Items in the tree views are a combination of FRANX, PDMS, and simulation features. Only items applicable to the scenario show up in the scenario view. All items listed are physically located in the current compartment. The following table lists the item types, descriptions, and availability under the Compartment or Scenario tree view.

Type	Description	Compartment View	Scenario View
Trays	A type of raceway defined by the PDMS type	Yes	Yes
Conduits	A type of raceway defined by the PDMS type	Yes	Yes
Other Raceway	Raceways in the FRANX model not given a type in the PDMS	Yes	Yes
Cables	Cables contained under a type of raceway	Yes	Yes
Equipment	Components defined in FRANX	Yes	Yes
Simulation Items	Vents and other items that are only part of the fire simulation	Yes	Yes
Sources	Equipment form the FRANX model marked as a source in the PDMS for the compartment	Yes	Yes
Physical Only	These are items in the PDMS but not in the FRANX model or part of the quantification, but that could affect the simulation if modeled in the 3D environment	Yes	No
Boundaries	These are used to define the compartment boundaries and only affect the simulation	Yes	No

4.1.2   Settings Panel

When selecting an item in the Compartment or Scenario tree, the "Settings" panel shown in Figure **12** allows the user to view and edit various properties of that item. There are several categories of data depending on the type of item selected. The "Plant Item" information gives the description, material, etc. The "3D Properties" shows data affecting the item in the 3D view if they have an associated 3D Object.
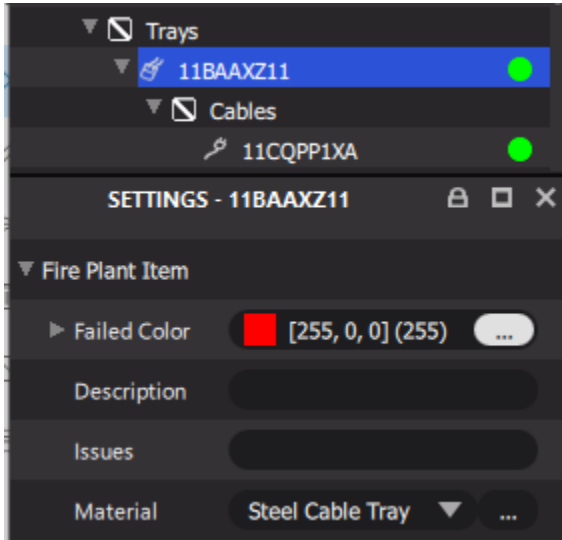
Figure 12: Selected item properties panel.

4.2   3D Modeling

The 3D modeling window is displayed alongside the various inspectors which can be used to setup a 3D Scene suitable for running simulations of different scenarios associated with compartment(s). There are sets of tools associated with the 3D modeling workflow, which are categorized broadly as:

- Camera interaction tools: FRI3D has an inbuilt set of cameras, both perspective and orthographic. Perspective cameras can be created from the interface although a default one is used and can be manipulated in the interface. Hotkeys like Alt + Left Mouse (Rotate), Alt+Middle Mouse (Pan), Alt+Right Mouse (Zoom) can be used to manipulate the position and where the camera looks at. Focal length can be manipulated from the camera properties to create a narrow-angle/wide-angle lens to make the rendering look realistic. Additionally, the Top/Side and Left View Orthographic camera views can be used to view/manipulate objects from those points of view orthographically.
- 3D object creation and positioning: New Plant Items, Sources, Vents, and Boundaries of Compartments can be created and modified by dragging/dropping the 3D Icon present next to the appropriate inspector objects. The various 3D Objects can be snapped to either a fixed discrete grid position or to boundaries.
- Object selection/manipulation tools: Various tools to manipulate the 3D Objects in the scene are provided. Objects can be scaled/translated and rotated to match their actual locations. Also, there are several modeling tools provided that snap objects to the intended positions like "Snap to Boundary"/"Snap to Grid," etc. The following figure represents ways of placing 3D objects in the scene to be simulated.
- 3D spatial information to zones and equipment and storage of items on the database: The actual spatial positions of the various plant items are stored in the database and each has an associated zone. These plant items also can be part of various scenarios and the user can modify which plant item is part of which scenario via the Graphical User Interface (GUI).

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- 3D model + CAD modeling and geometry import from various formats: By default, the 3D representation of the plant items/sources/vents are simple proxy objects. However, if the full 3D CAD geometry exists for that item, it can be loaded and displayed in FRI3D. Various standard CAD format files can be used.
- Add new 3D equipment in zone and its surface materials zones.
- 3D simulation visualization: The results of the simulations of CFAST can be viewed in the 3D viewer, including the failures of plant items. The failure criteria are established in the Failure Criteria editor. Figure **13** illustrates a typical workflow of creating 3D geometry for the different plant items.
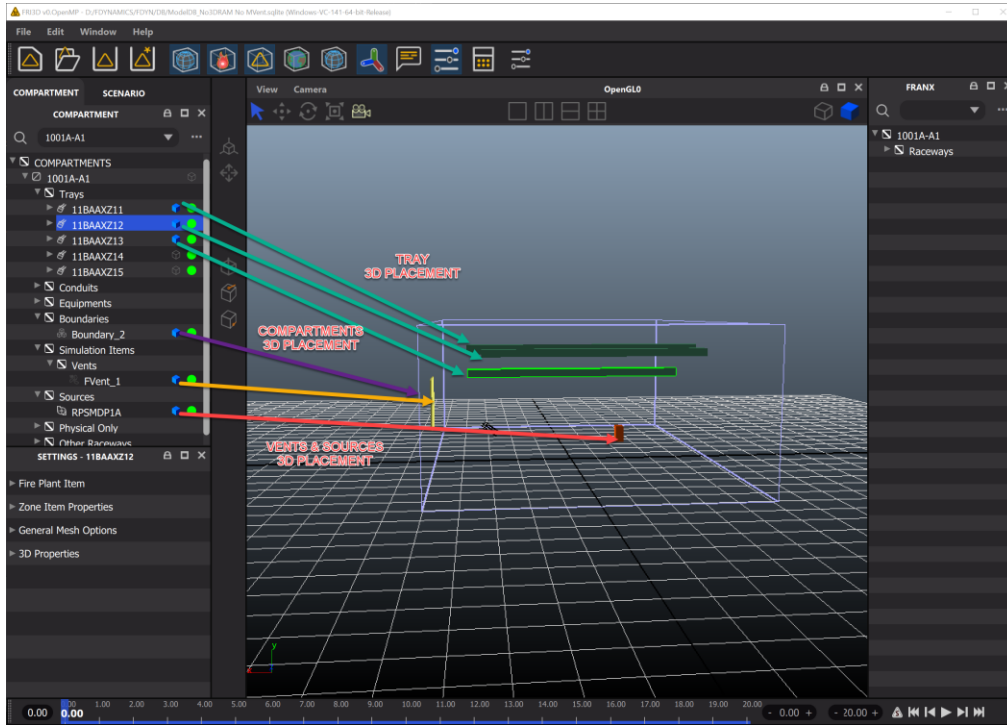
Figure 13: FRI3D 3D modeling workflow.

4.3   Simulation Data

The data used for a fire simulation comes from both the 3D model of included items and user-entered data in the "Setting" panel for the scenario and simulation items. Materials for surfaces and properties for fire in terms of heat-release rate curves are also specified in the interface via various forms and dialogs which are described in the following sections. In addition, vents, failure criteria of the plant items, and equipment are also specified.

4.3.1   General Materials

Materials are assigned using the material editor, as indicated in Figure **14**. Each plant item/piece of equipment can be assigned a material from the associated combo box next to its specification. The default materials are automatically loaded by FRI3D. In addition, the boundary walls and their materials are assigned in a similar way by the appropriate property assignment in the Compartment.
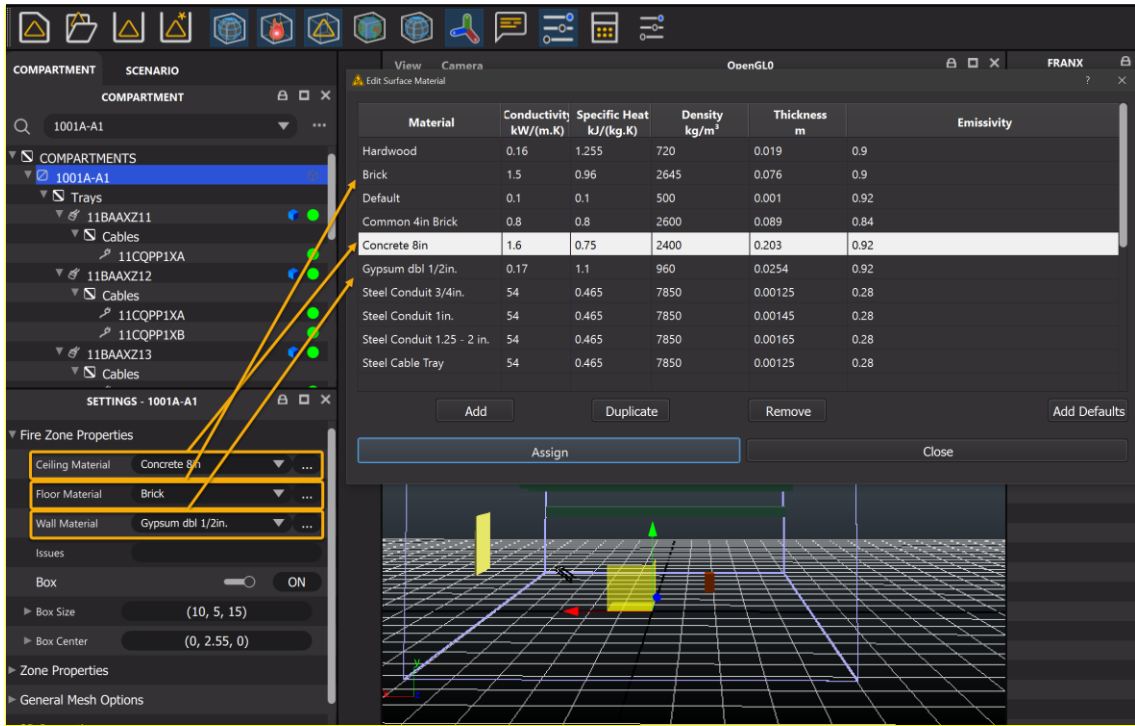
Figure 14: Wall material assignment in FRI3D.

Figure 15: FRI3D material assignment.

4.3.2 Cable Materials

Cables and their associated properties can be assigned in the Cable Properties window shown in Figure **16**. There is a set of known cable types loaded, and assignments can be made to the cable using this dialog. However, if there is no associated cable material, the default heat-soak method is used for determining the failure evaluation for a cable. Further explanation on the heat-soak method is given in Section 5.3.2.

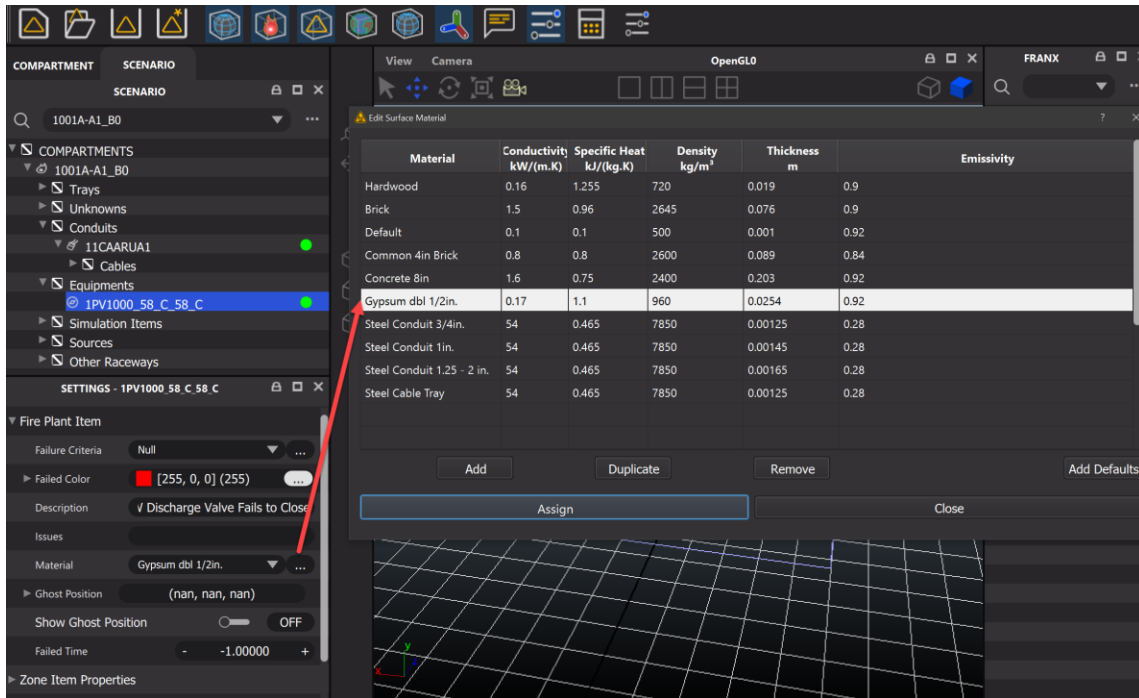| Name or Manufacturer	Model	Insulation Type	Jacket Type	Outside Diameter mm	Kg/m	Jacket Thickness mm	Gauge	#Conductors	Description	Grade
General CableVNTC	VNTC	2	0	44.958	4.16102	2.794	0	0	VNTC	0
American Insulated WireTYPE TC Power	TYPE TC Power	1	0	45.466	5.0212	2.794	0	0	TYPE TC Power	0
DrakaGeneral Purpose Control XLPE	General Purpos...	1	0	45.974	5.14174	2.794	0	0	General Purpos...	0
DrakaPower & Control Type TC XHHW-2	Power & Contro...	1	0	45.974	5.14174	2.794	0	0	Power & Contro...	0
General CableCHTC Type TC-ER	CHTC Type TC-...	1	0	44.831	4.16102	2.794	0	0	CHTC Type TC-...	0
General CableCVTC	CVTC	1	0	44.831	5.12537	2.794	0	0	CVTC	0
General CableEHTC	EHTC	1	0	44.831	4.16102	2.794	0	0	EHTC	0
General CableEHTC	EHTC	1	0	45.466	5.20127	2.794	0	0	EHTC	0
General CableUltrol 325	Ultrol 325	1	0	44.0436	5.22657	2.794	0	0	Ultrol 325	0
Rockbestos-SurprenantFirewall SR Power Cable	Firewall SR ...	3	0	47.244	5.26824	1.016	0	0	Firewall SR ...	0
Rockbestos-SurprenantFirewall III Power Cable	Firewall III Pow...	1	0	44.45	5.3873	2.794	0	0	Firewall III Pow...	0
Generic (TP TP 4/0 3+G)	GENERIC	2	0	41.402	4.16548	2.032	0	0	GENERIC	0
Generic (TS TS 4/0 3+G)	GENERIC	1	0	44.45	4.33067	1.524	0	0	GENERIC	0
DrakaType MC Power Cable 3 XHHW-2 (1 bare or 3 bare)	Type MC Power...	1	0	44.45	4.86642	1.524	0	0	Type MC Power...	0
DrakaType MC Power Cable 3 XHHW-2 (1 bare or 3 bare)	Type MC Power...	1	0	44.45	4.33067	1.524	0	0	Type MC Power...	0
DrakaGeneral Purpose Control XLPE	General Purpos...	1	0	40.132	4.06875	2.032	0	0	General Purpos...	0
DrakaPower & Control Type TC XHHW-2	Power & Contro...	1	0	40.132	4.06875	2.032	0	0	Power & Contro...	0

Figure 16: Cable properties.

4.3.3 Fire Properties & Sources

Fire sources are also created in 3D by dragging/dropping from the 3D icon present next to the source item in the Zone Inspector. The source can be placed into the correct position with the various 3D tools. Fire Properties are specified via HRR and the chemical properties of the Fire Source. The Fire Property dialog can be accessed by the combo button present next to the "Fire Material Property" of the fire source. This dialog has an interactive curve editor feature which allows the user to specify time series of the HRR and other physical fire properties. The following figure depicts the workflow.
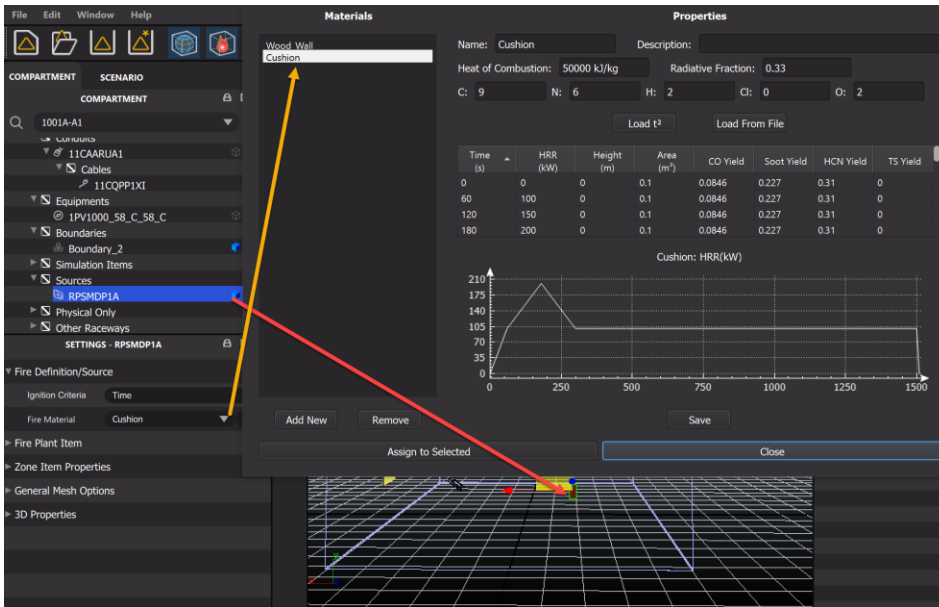
Figure 17: Fire source specification.

4.3.4 Criterion

Equipment and Plant Item Fail Criteria are specified by the user from the Criteria Editor Dialog. Time- and temperature-based fail criteria can be specified for the failure evaluation, shown in the following figure.
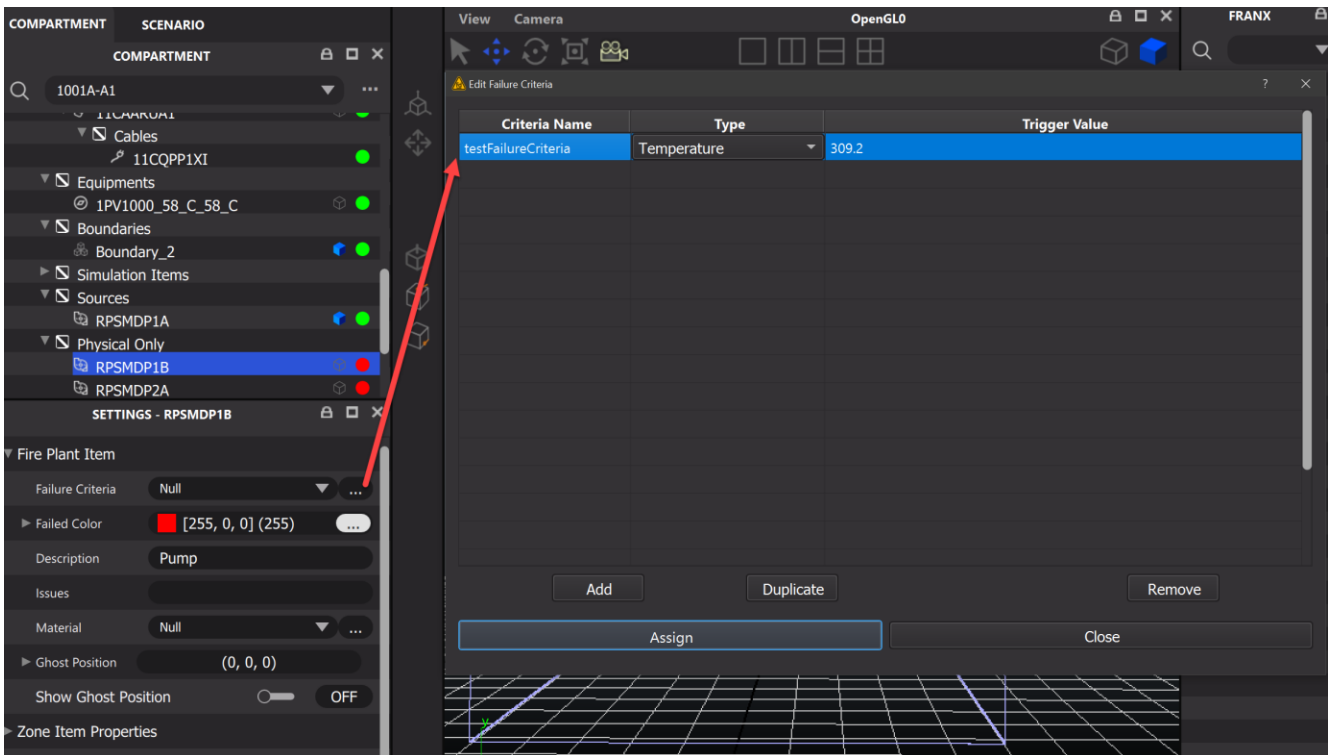
Figure 18: Equipment failure criteria spec.

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4.3.5   Boundaries

A realistic depiction of the compartment or room might involve the compartment to be non-rectangular (cuboidal) in shape. However, CFAST simulations accept only axis-aligned boxes as compartments. To accommodate for this, FRI3D has a flexible interface by which the user can create the non-rectangular (non-cuboidal) compartment by drag/drop of multiple boundary areas like the following figure. FRI3D automatically computes a bounding box needed for a CFAST compartment preserving volume (see Figure 19). It also determines ghost positions whereby the equipment is automatically moved inside the CFAST compartment. Boundaries can also be split and merged and there are several tools available in the 3D interface to snap the movement of boundaries so they can be adjacent.
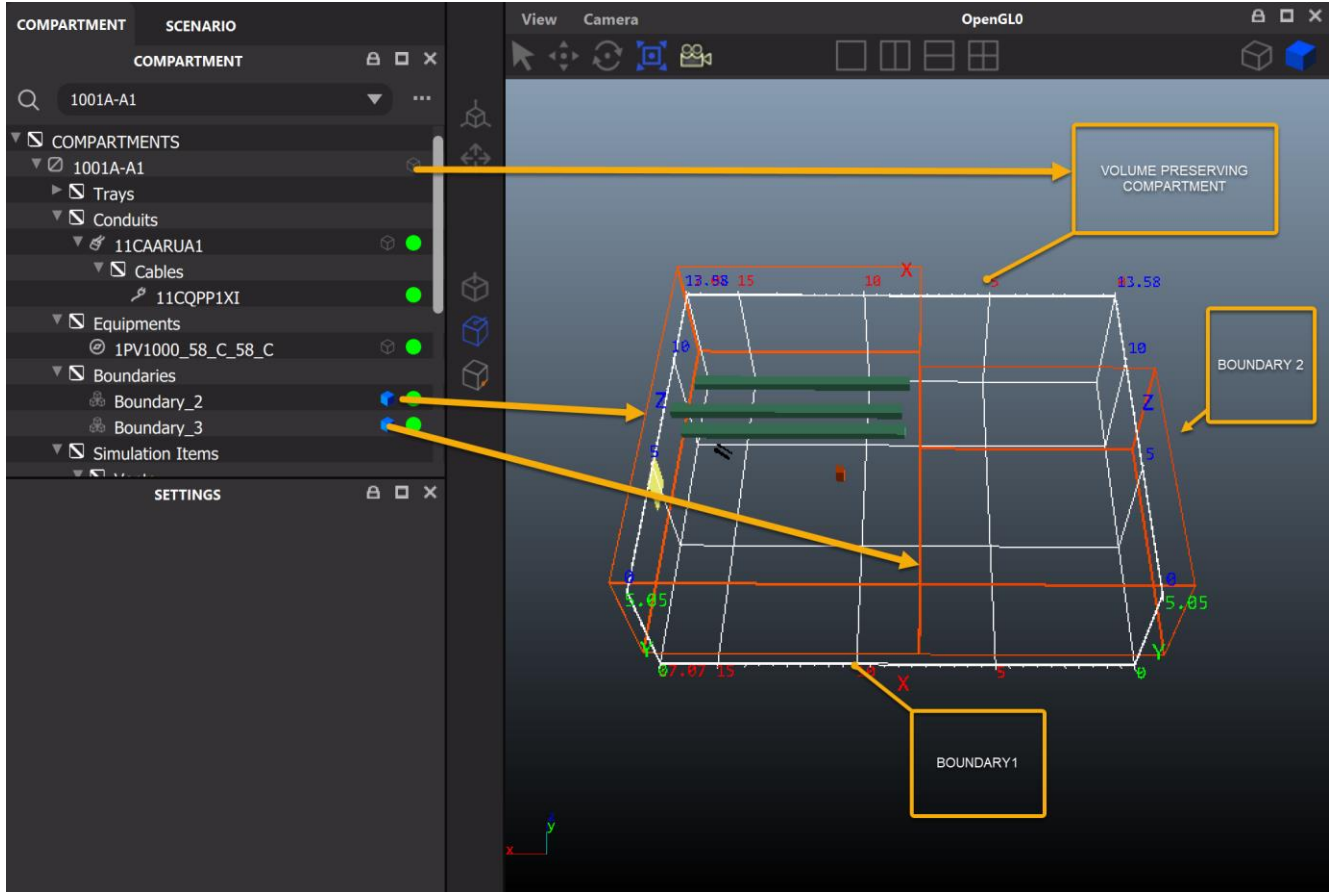
Figure 19: Boundary/wall specification.

4.3.6   Run CFAST

CFAST simulation properties can be specified by running the current scenario in the Scenario Inspector or using the context menu for the source in the Zone Inspector window. The dialog where the user can specify the appropriate simulation parameters is depicted by the following figure.
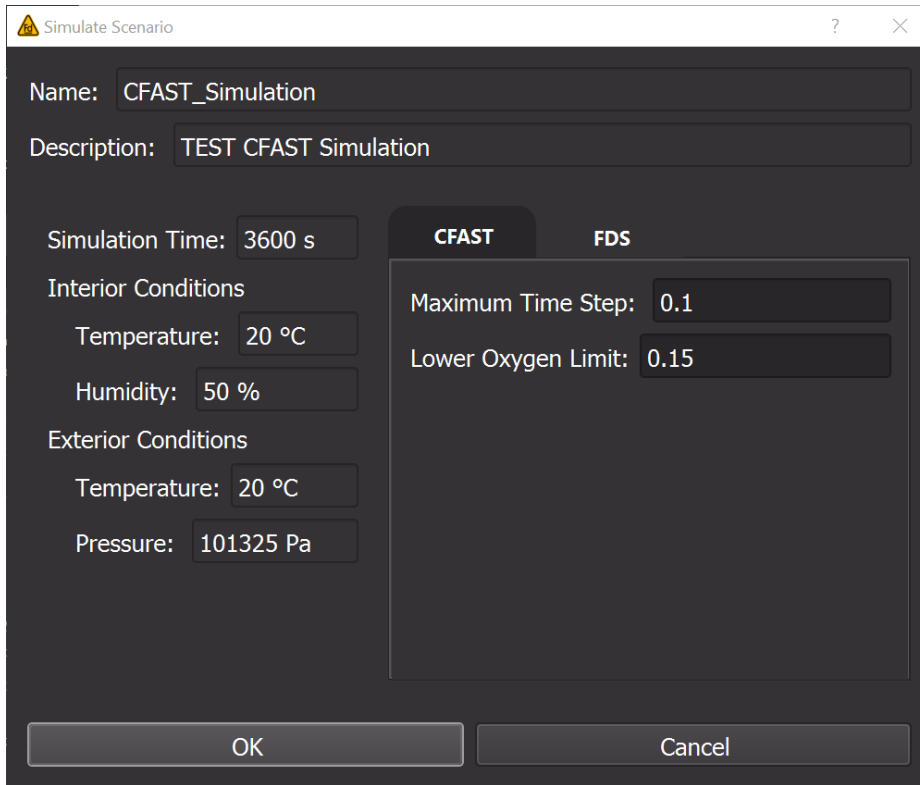
Figure 20: CFAST run specification.

4.3.7 Vents & Vent Criteria

Natural vents include doors, windows, and openings in ceilings. Mechanical vents are those vents which can be powered like an A/C duct, fan, etc. Both kinds of vents can be added via the interface shown in Figure **21** by first creating them in the Zone Inspector, then dragging and dropping them into position at the appropriate place in the 3D Compartment area. When the vent is released in the 3D window, it snaps to the closest boundary wall. They can also be moved along the boundary and objects can orient themselves appropriately.
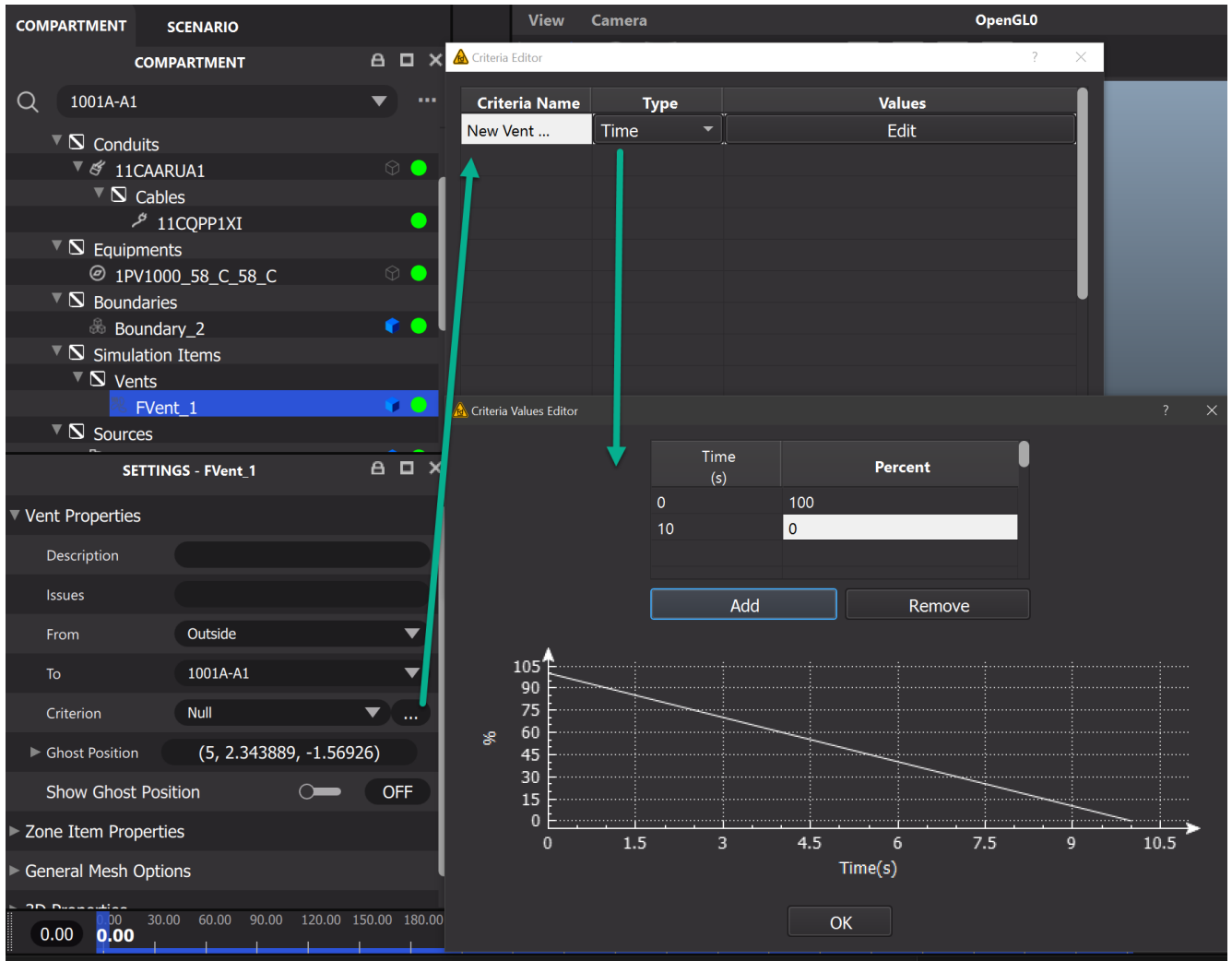
Figure 21: Vent specification.

5.   FIRE-SIMULATION COUPLING

5.1   Fire Modeling Guidance

NUREG 6850 [16] outlines the acceptable methodology for completing the fire modeling task for a fire PRA. The conservative approach and CFD are both acceptable methodologies. The primary reason for using the conservative approach is economics. With limited resources, this method allows for the fire areas to be assessed even if it is extremely conservative. Using a computational fluid dynamic approach requires a much greater level of effort to complete the analysis. Choosing between a more simplistic modeling software like CFAST versus a more advanced software like FDS is up to the modeler. The primary difference is the level of resolution required for the scenarios. The information needed in either approach remains the same: you must collect information on spatial information on the fire area itself, and data on distances from ignition sources to specific targets. You also need to identify all possible ignition sources, as well the potential for transient combustibles, finally identifying the targets that are associated with safe-shutdown equipment. This includes both the equipment itself and the cable associated with the functionality credited within the fire PRA, whether they are power cables, indication cables, or control cables. CFAST was used in this project to show how FRI3D can develop scenarios and gather scenario information and how it can feed directly into the detailed modeling analysis to make detailed fire modeling more cost

effective. Through FRI3D the CFAST model is constructed automatically and by joining the 3D model directly to the existing fire model, a module can easily be added to use other simulation codes.

5.2   CFAST Modeling

The CFAST computer program was developed by the National Institute of Standards and Technology (NIST) to simulate fire growth and the transport of the resulting smoke [11]. It simplifies the simulation environment by clustering it into a maximum of two zones. The primary assumption of a zone model is that properties such as temperature can be approximated throughout a control volume by a representative average. The fire drives combustion products from the lower to the upper layer via the plume. The temperature within each layer is uniform, and its evolution in time is described by a set of ordinary differential equations derived from the fundamental laws of mass and energy conservation. The transport of smoke and heat from zone to zone is dictated by empirical correlations.
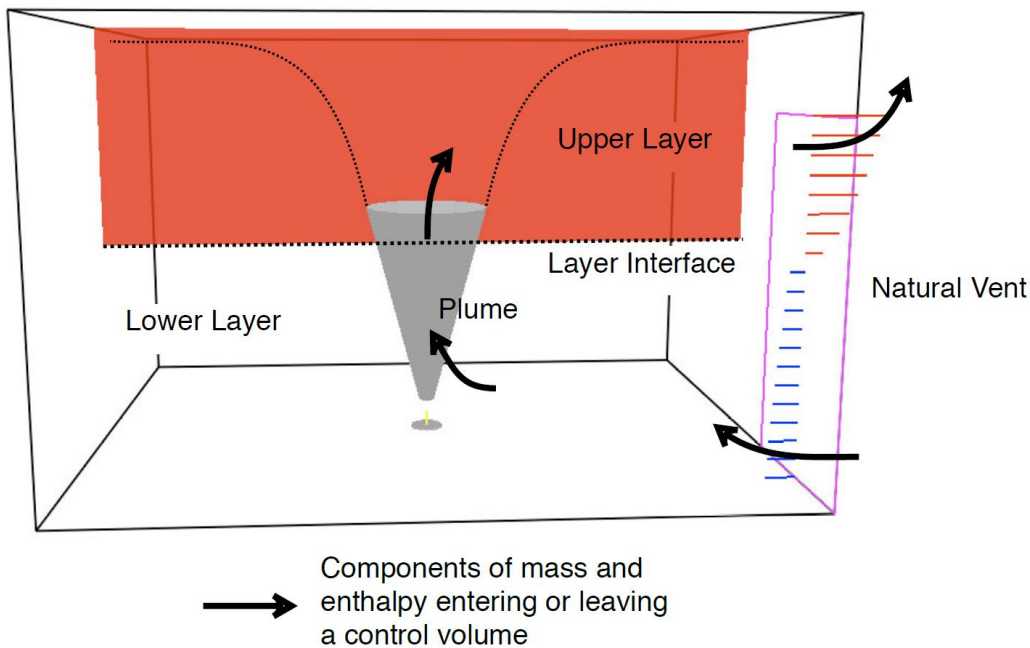
Figure 22. Control volumes in a two-zone model.

5.2.1   CFAST Calculations

The CFAST model is built on the governing equations of conserving mass and energy. The momentum within any one zone is assumed to be zero. Meanwhile, the momentum between zones is modeled in terms of horizontal or vent-flow equations following the Bernoulli's law [12]. CFAST uses a simulation domain termed as a compartment. Each compartment consists of two layers (i.e., a relatively cooler lower layer and a hotter upper layer), as illustrated in Figure **22** (above). The gas temperature and density are assumed constant in each layer. The compartment as a whole is assumed to have a single value of pressure P. All thermodynamic parameters are assumed to be constant. The specific heat at constant volume and at constant pressure, c_v and c_p, the specific gas constant, R, and the ratio of specific heats, γ, are related by $\gamma = c_p/c_v$ and $R = c_p - c_v$. Regardless of the composition of the gas mixture, $c_p = 1012$ J/(kg K) and g = 1.4. The CFAST program solves a system of ordinary differential equations for the compartment pressure, upper-layer volume, and upper- and lower-layer temperatures as follows:

$$\frac{dP}{dt} = \frac{(\gamma - 1)}{V}(\dot{q}_1 + \dot{q}_u) \tag{1}$$

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$$\frac{dV_u}{dt} = \frac{1}{P_\gamma}\left((\gamma - 1)\dot{q}_u - V_u\frac{dP}{dt}\right) \qquad (2)$$

$$\frac{dT_u}{dt} = \frac{1}{c_p m_u}\left(\dot{q}_u - c_p\dot{m}_u T_u + V_u\frac{dP}{dt}\right) \qquad (3)$$

$$\frac{dT_1}{dt} = \frac{1}{c_p m_1}\left(\dot{q}_1 - c_p\dot{m}_1 T_1 + V_1\frac{dP}{dt}\right) \qquad (4)$$

It also solves the following equation for each wall surface temperature (ceiling, upper wall, lower wall, and floor):

$$\dot{q}'' + k\frac{dT_w(0,t)}{dx} = 0 \qquad (5)$$

Where $(dT_w(0,t))/dx$ is the temperature gradient at the wall surface, $\dot{q}''$ is the net radiative and convective heat flux from the adjacent gas layer. CFAST solves these equations by using a differential solver named DASSL [13, 14]. This method has the advantage over other solvers such as Runge-Kutta or Adams-Bashforth because the latter solvers require small time steps in order to track the rapid transient phenomena in fire modeling scenarios, such as pressure. Meanwhile the DASSL method, which is based on the Jacobian technique, is more stable and accurate for stiff dynamic problems.
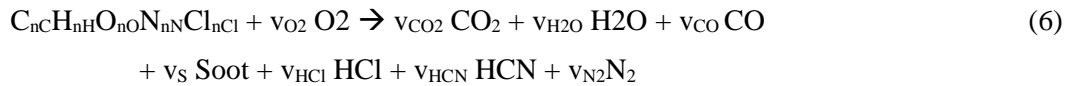
Fires in CFAST are specified by the user in terms of a time-dependent HRR, an effective fuel molecule, and the yields of the products of incomplete combustion like soot and CO. Fires can be specified in multiple compartments and are treated as totally separate entities, with no interaction of the plumes. These fires are generally referred to as "objects" and can be ignited at a prescribed time, temperature, or heat flux. CFAST does not include a pyrolysis model to predict (as opposed to specify) the growth and spread of the fire. Rather, the transient pyrolysis rates for each fire are prescribed by the user. Whereas this approach does not directly calculate the increased pyrolysis due to radiative feedback from the flame or compartment, in theory these effects could be prescribed by the user. For larger fires, this can be an important consideration, and the specification used should reflect the actual conditions as closely as possible.

Although the fire HRR is specified by the user, it may be constrained by the oxygen concentration in the compartment. The reaction that describes the combustion of a hydrocarbon fuel is given as follows:

$$C_{nC}H_{nH}O_{nO}N_{nN}Cl_{nCl} + v_{O2}\ O_2 \rightarrow v_{CO2}\ CO_2 + v_{H2O}\ H_2O + v_{CO}\ CO \qquad (6)$$
$$+ v_S\ Soot + v_{HCl}\ HCl + v_{HCN}\ HCN + v_{N2}N_2$$

Therefore, the user also needs to provide the composition of the fuel molecule and the yields of soot and CO, y_s, and y_{CO}. As fuel and oxygen are consumed, the heat is released as radiation and convection heat:

$$\dot{Q}_r = X_r\dot{Q} \qquad (7)$$

$$\dot{Q}_c = (1 - X_r)\dot{Q} \qquad (8)$$

where $\dot{Q}$ is the HRR released by the fire. The parameters $\dot{Q}_r$ and $\dot{Q}_c$ are the heat released by radiation and convection, respectively, and X_r is the fraction of the fire's HRR emitted as radiation.

The user specifies the HRR along with a characteristic base diameter, D, to be used in the plume temperature and mass entrainment correlations. User also inputs the radiative fraction, which is taken as 0.35 by default (35% of the fire's energy is released via radiation). The typical range for the radiative fraction is from about 0.05 to 0.4. The assumed and constant values for the combustion efficiency and

radiative fraction may add uncertainty to the calculated results, so the HRR and radiative fraction should be chosen carefully to best model the scenario of interest.

A fire pumps mass and energy from the lower layer into the upper layer. The vertical flow of mass through a horizontal plane at height z above the base of the fire is called the mass entrainment rate, $\dot{m}_e(z)$. The vertical flow of energy through this horizontal plane is given by $\dot{Q}_c + \dot{m}_e(z)c_pT_1$. The empirical correlation for the mass entrainment rate depends on whether the plume is unobstructed, against a wall, or in a corner. CFAST uses the Heskestad's correlations to estimate the centerline plume temperature and velocity. It also assumes that the temperature and velocity decrease following a Gaussian profile about the plume's centerline. The Heskestad's correlation has a maximum plume temperature of 900 K.

CFAST also models the transport of air between compartments through doors and windows. These openings are termed as vents. The mass flow is calculated by dividing the opening into discrete horizontal segments, each of which is bounded by the top or bottom of the opening, the zone interface of either compartment, or the neutral plane, which is where the velocity changes direction. This is shown schematically in Figure **23**. The figure indicates schematically how the various mass flows through the opening are distributed. For the flow originating in the upper layer of the upstream compartment flowing into the upper layer of the downstream compartment, or the flow from the initial compartment lower layer to the lower layer of the downstream compartment, the mass is applied directly to the downstream layer. The mass flow from the upper layer of the upstream compartment to the lower layer of the downstream is assumed to rise into the upper layer via a spill plume.
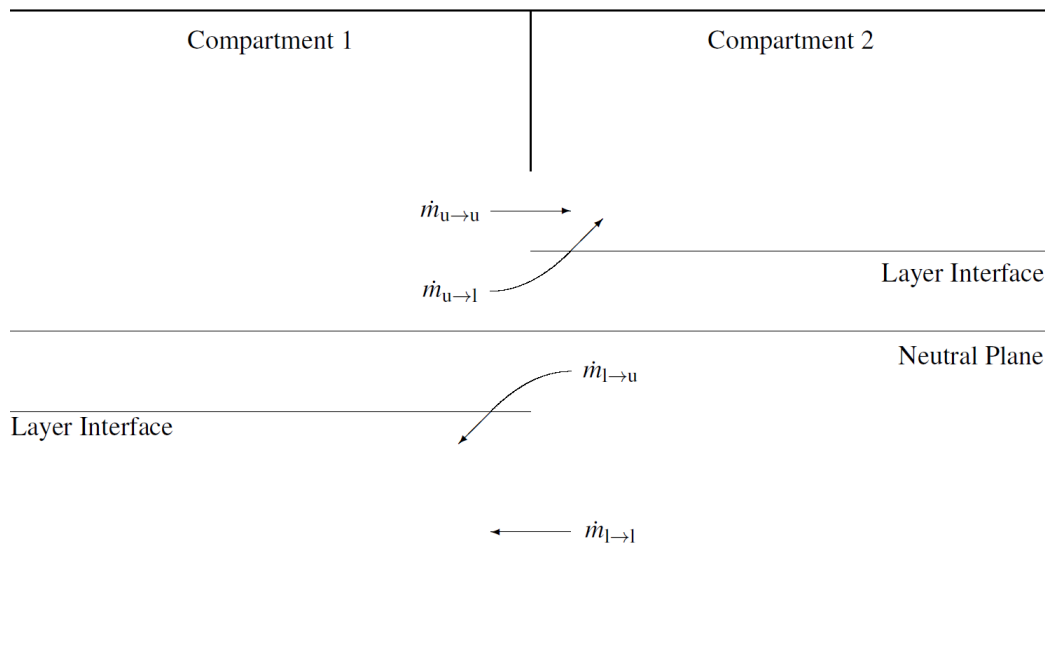
Figure 23. Flow patterns for horizontal flow through a vertical vent.

In case a compartment has no open doors or windows, the modeler should set a default wall vent to model air leakage from the wall, ceiling and floor surfaces. Details of this air leakage are given in reference [13]. FRI3D automatically adds the default leakage unless removed by the user, preventing a common modeling mistake, because unless specifically designed for it, all rooms have some air leakage. and this causes invalid fire progression in the simulation due to no oxygen. The default vent area in FRI3D is taken as 1.7E-4 m^2 leakage area/m^2 wall area and 5.2E-5 m^2 leakage area/m^2 floor or ceiling area this is the value set in CFAST v7.5 input.

5.2.2   CFAST User Interface

The user sets up a CFAST model through the use of a GUI called CEDIT, as shown in Figure **24**, Figure **26**, and Figure **27**. This section goes over the GUI capabilities and the counterpart in FRI3D. The input parameters are organized via tabs near the top of the CEDIT window, which include [14].

- Simulation Environment includes simulation time, specification of model outputs, and ambient conditions. Also included on the page is a constantly updated list of errors, warnings, and messages about the input file specification or model simulation.

- Thermal Properties defines the thermal conductivity, specific heat, density, thickness, and emissivity values for all materials and fuel sources used in a simulation.

- Compartments defines the size, construction characteristics, and position of the compartments in a simulation.

- Wall Vents define doors and windows.

- Ceiling/Floor Vents define holes in the ceiling/floor.

- Mechanical Ventilation defines forced air ventilation.

- Fires include user specification of the initial fire source and any additional burning objects in one or more of the compartments of the simulation.

- Targets provide the ability to calculate the temperature and net heat flux to objects placed and oriented arbitrarily in the structure.

- Detection/Suppression define any heat or smoke alarms and sprinklers in the compartments of the simulation.

- Surface Connections allow for more detailed description of the connections between compartments in the simulation to better depict the transfer of heat from compartment to compartment in the simulation.

- Visualizations allows specification of one or more 2D and 3D visualizations to be added to the simulation for viewing with Smokeview. Note that these can require significant additional computational time compared to a basic CFAST simulation without visualizations.
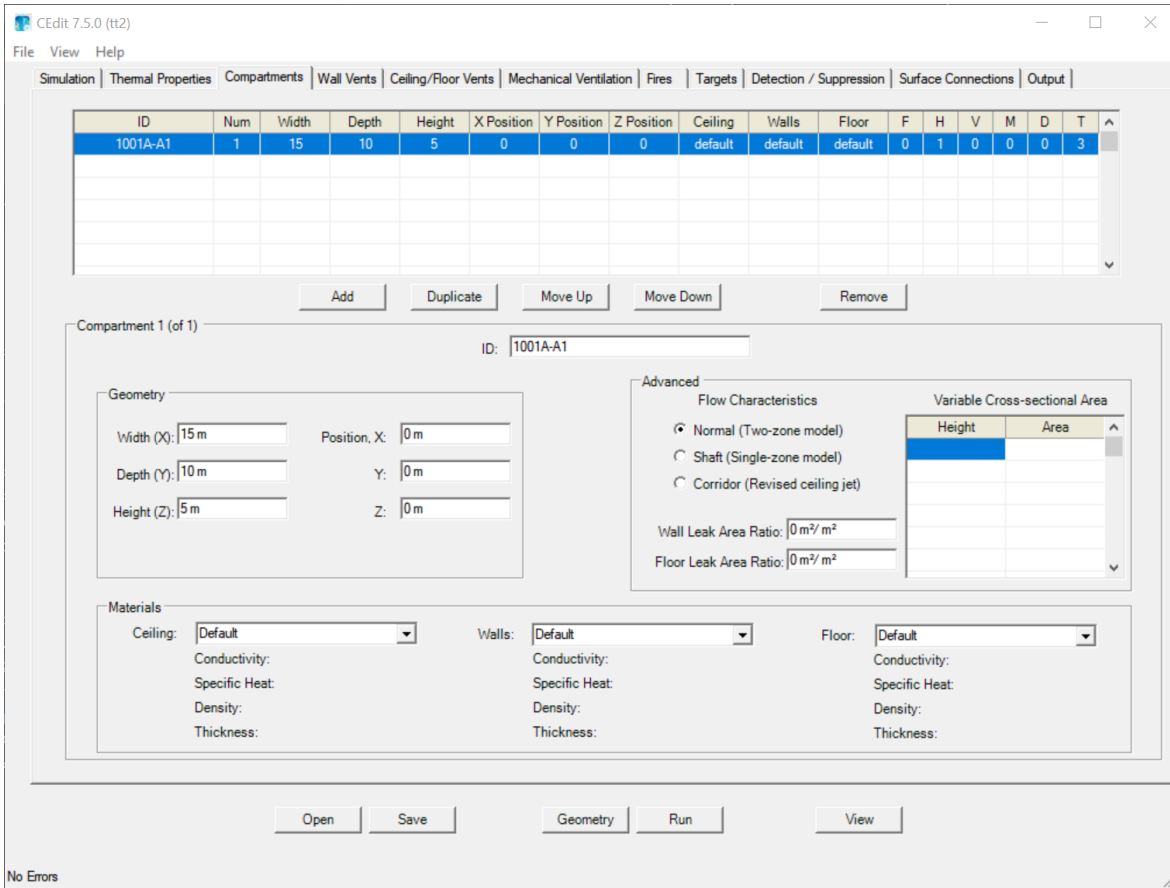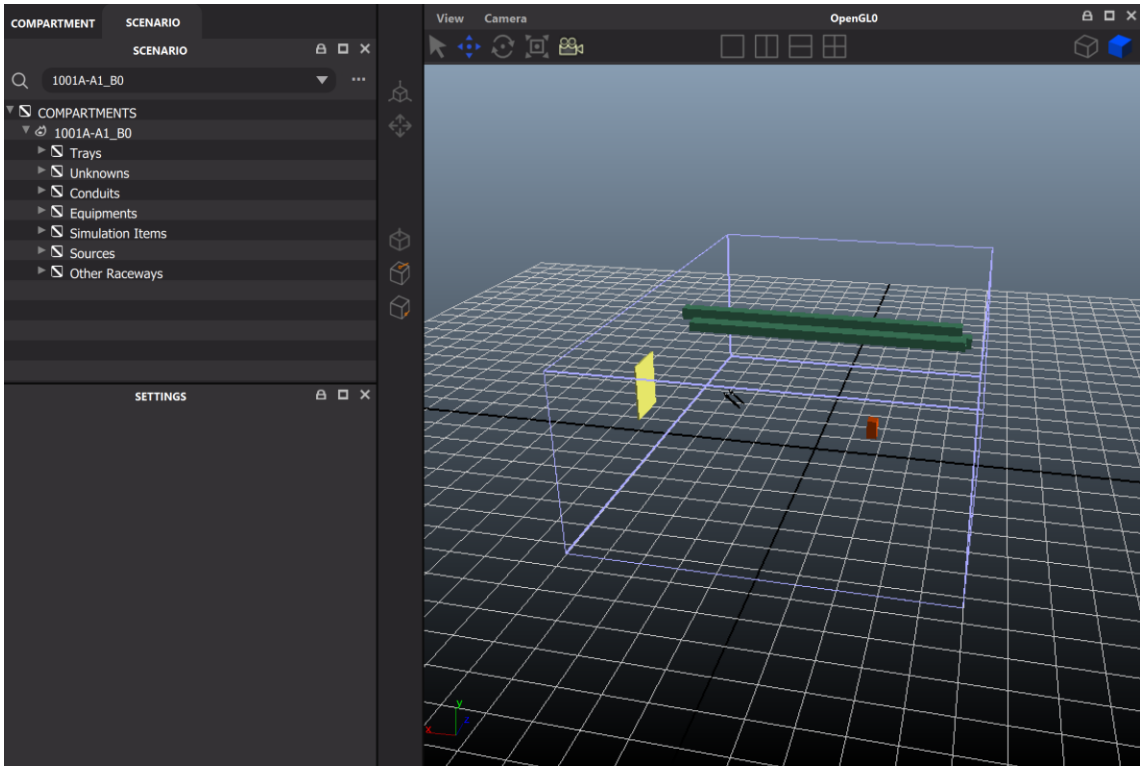
Figure 24: CEdit interface for compartments.

Figure 25: FRI3D interface for compartments uses a 3D modeling environment.
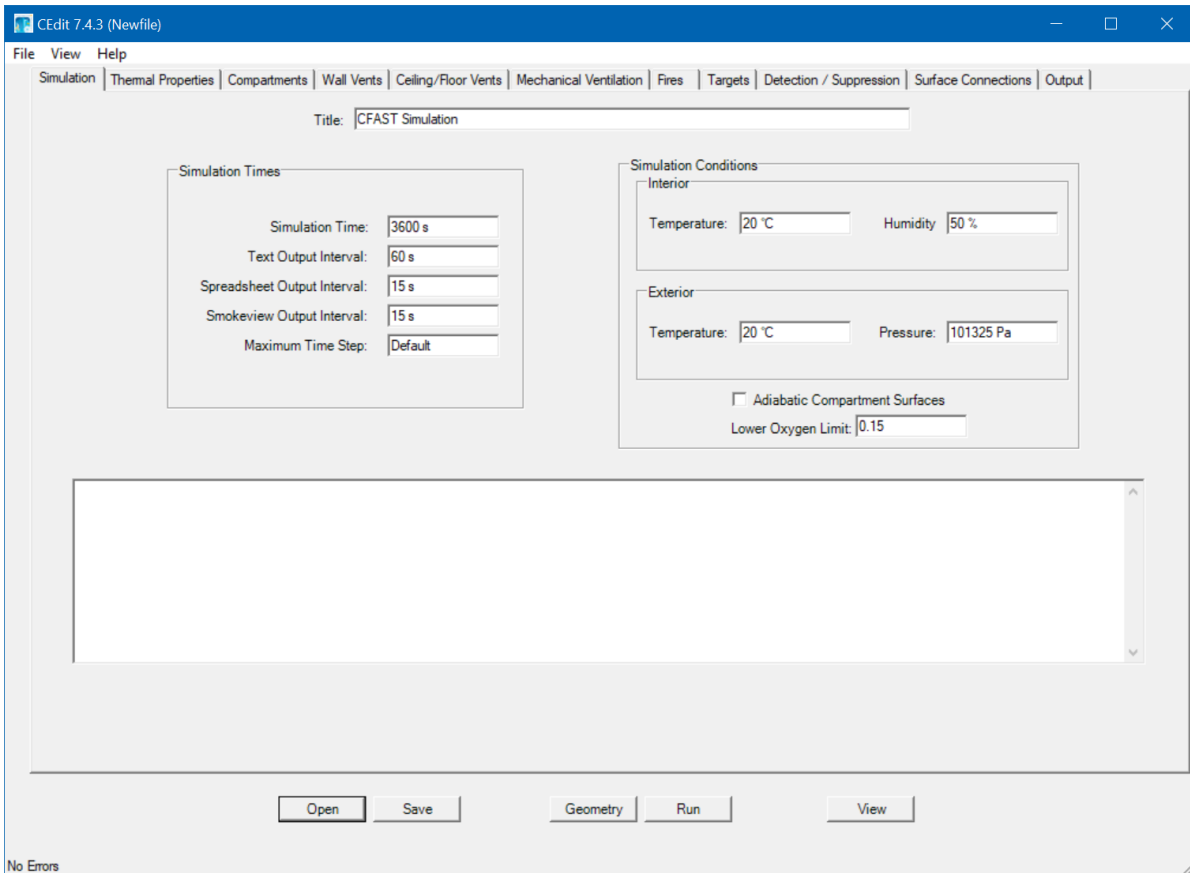
Figure 26: CEDIT interface for Simulation Data; FRI3D equivalent is shown in Figure 20.

An important input parameter in CFAST is about the fire as shown in Figure **26**. Fires in CFAST are defined in two parts: a "Fire Definition" that specifies the fuel composition, heat-release rate, and species yields for the fire, and a "Fire Instance" that specifies the placement of a defined fire within a compartment in the simulation. A single fire definition may be associated with more than one fire instance in a simulation if desired. For a new fire, click on the Add New button or Add t^2 button within the fire definition block of inputs. The Add t^2 button is useful because it has predefined quadratic growth-rate options commonly used in fire analyses.

Fire properties can also be defined as time dependent. Following is a list of fire properties that can be specified as a function of time. The properties are linearly interpolated between specified points. If the simulation time is longer than the total duration of the fire, the final values specified for the fire are continued until the end of the simulation.

- Time (default units: s, default values: none): Time from ignition.

- HRR (default units: kW, default values: none): Heat-release rate of the fire.

- Height (default units: m, default values: 0 m): Height of the base of the fire.

- Area (default units: m^2, default values: calculated from heat-release rate such that the fire Froude number is unity1): Area of the base of the fire. The plume correlations used in CFAST generally regard the base to be circular. Do not set this value to zero because it is used in the various plume correlations.

- CO Yield (default units: kg/kg, default value: 0 kg/kg): Mass of CO produced per unit mass of fuel consumed.

- Soot Yield (default units: kg/kg, default value: 0 kg/kg): Mass of soot produced per unit mass of fuel consumed.

- HCN Yield (default units: kg/kg, default value: 0 kg/kg): Mass of hydrogen cyanide produced per unit mass of fuel consumed.

- TS Yield (default units: kg/kg, default value: 0 kg/kg): Mass of user-defined trace species per unit mass of fuel consumed. The trace species is transported along with the other products of combustion, but is assumed not to take part in the combustion reaction and is assumed not to be a significant source of overall mass for the system-mass balance. This implies that the production rate of trace species specified should be small.
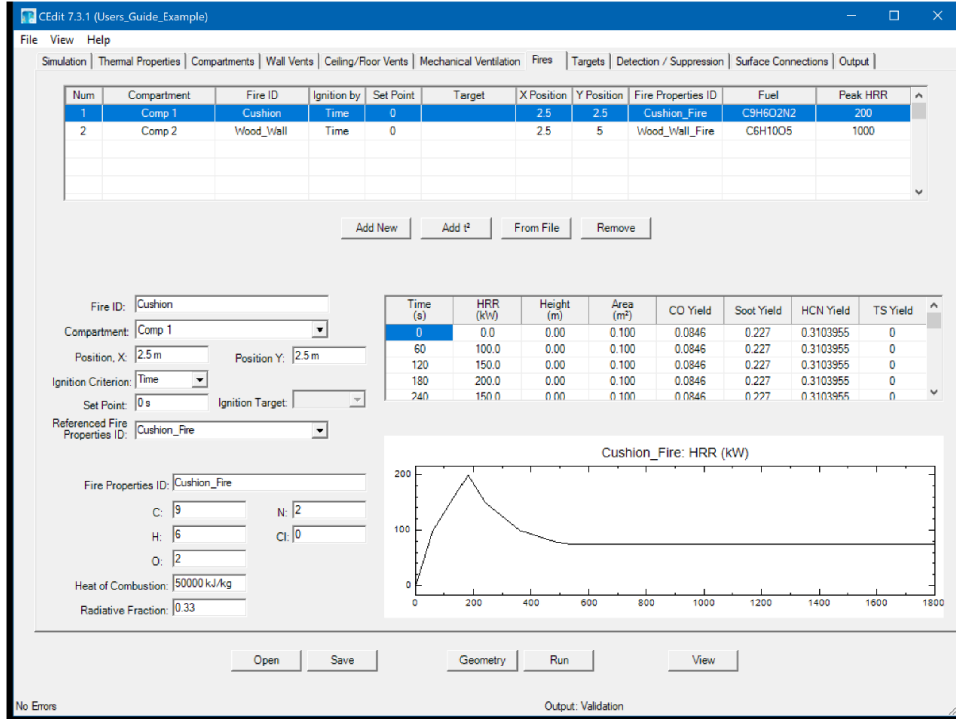
Figure 27: CEdit Interface for fire data, the FRI3D equivalent is shown in Figure 17.

The fire HRR can be set as time dependent using a CFAST built-in function called t-squared fire. User can click the Add t^2 button to create a fire with an HRR that grows as a function of the time squared following this equation:

$$\dot{Q}(t) = \dot{Q}_{peak} \left(\frac{t}{t_{peak}} \right)^2 \tag{9}$$

The t^2 parameters are:

- Fire Growth Rate: A set of specific t-squared fires labeled slow, medium, fast, or ultra-fast such that the fire reaches 1054 kW (1000 BTU/s) in 600 s, 300 s, 150 s, and 75 s. A custom selection allows the user to define any growth or decay rate desired.

- Time to Peak (default units: s, default value: 300 s): The time for the fire to reach the peak HRR.

- Peak HRR (default units: kW, default value: 1054 kW): The peak heat-release rate of the t-squared fire.

- Steady Burning Period (default units: s, default value: 300 s): Duration of time that the fire continues burning at the rate specified by the peak HRR.

- Decay Time (default units: s, default value, 300 s): Duration of time for the fire to decay back to a zero value. Decay follows the inverse of the t-squared growth rate.

After the user defines the simulation environment, material properties, compartments, vents and ventilations, fires, targets, and detection/suppression items, CFAST saves the model in a text-based input file that can be edited using any text editors. The user can then click "Run" on the CEDIT window to simulate the fire scenario in the input model, and receive the results in the form of tabulated .csv files. Data can be extracted automatically from these .csv files using custom programming language tools, or they can be viewed and processed using spreadsheet programs.

Much of the data, shown above, needed for a CFAST model do not exist in the existing FRANX or PDMS models and so they still need to be entered into FRI3D in the forms specified in Section 4.3. This data along with the 3D model are used to programmatically create the model and run as described above. However, once finished, the other manual processes are eliminated and changes to the FRI3D model are propagated to subsequent simulations, as described in Section 5.3.

5.3   FRI3D Automated Scenario Process

One of the main objectives of this software is to simplify and reduce the manual process determining item failures for a fire scenario. To do this, data are pulled from both item properties and the 3D model to auto-generate and run a CFAST model used for determining the scenario failed items. FRI3D was designed so other simulation codes such as FDS could be added allowing the user to use the same model but select the required fire-simulation code. This section describes this process and work is still needed.

5.3.1   Starting a Simulation

The user can overwrite an existing scenario by selecting an existing scenario or create a new one from a fire source item, by right clicking it and selecting the option "Simulate (CFAST)".

5.3.2   Current Process

The current framework to determine component failures due to a fire scenario is shown in Figure **28**. First, the user builds the fire model in FRI3D and inputs the model properties as shown in Section 4.3. FRI3D then attempts to generate a CFAST input file that represents the model and notifies the user if there are missing datasets that need to be completed. If the CFAST input model is complete, FRI3D feeds the CFAST input file to the CFAST solver and fetches the resulting .csv output files. FRI3D extracts the temperature readings for the raceways and components from CFAST output and performs further evaluations. It iterates over each raceway in a compartment and performs a check to individual cables within the raceway. If the cable has detailed cable specifications, such as type and dimensions, FRI3D performs the Thermally-Induced Electrical Failure (THIEF) [15] analysis to calculate the cable temperature and compares it against its temperature failure threshold. Meanwhile if the user does not provide detailed cable specifications, FRI3D performs an empirical heat-soak analysis [16] to calculate damage integral and the time to failure (i.e., when damage integral exceeds unity). Failed cables are returned and linked to new or existing sequence and added to the internal database. Finally, FRI3D returns the scenario results to the user interface which consists of all failed items within the fire scenario and the time of those failures.
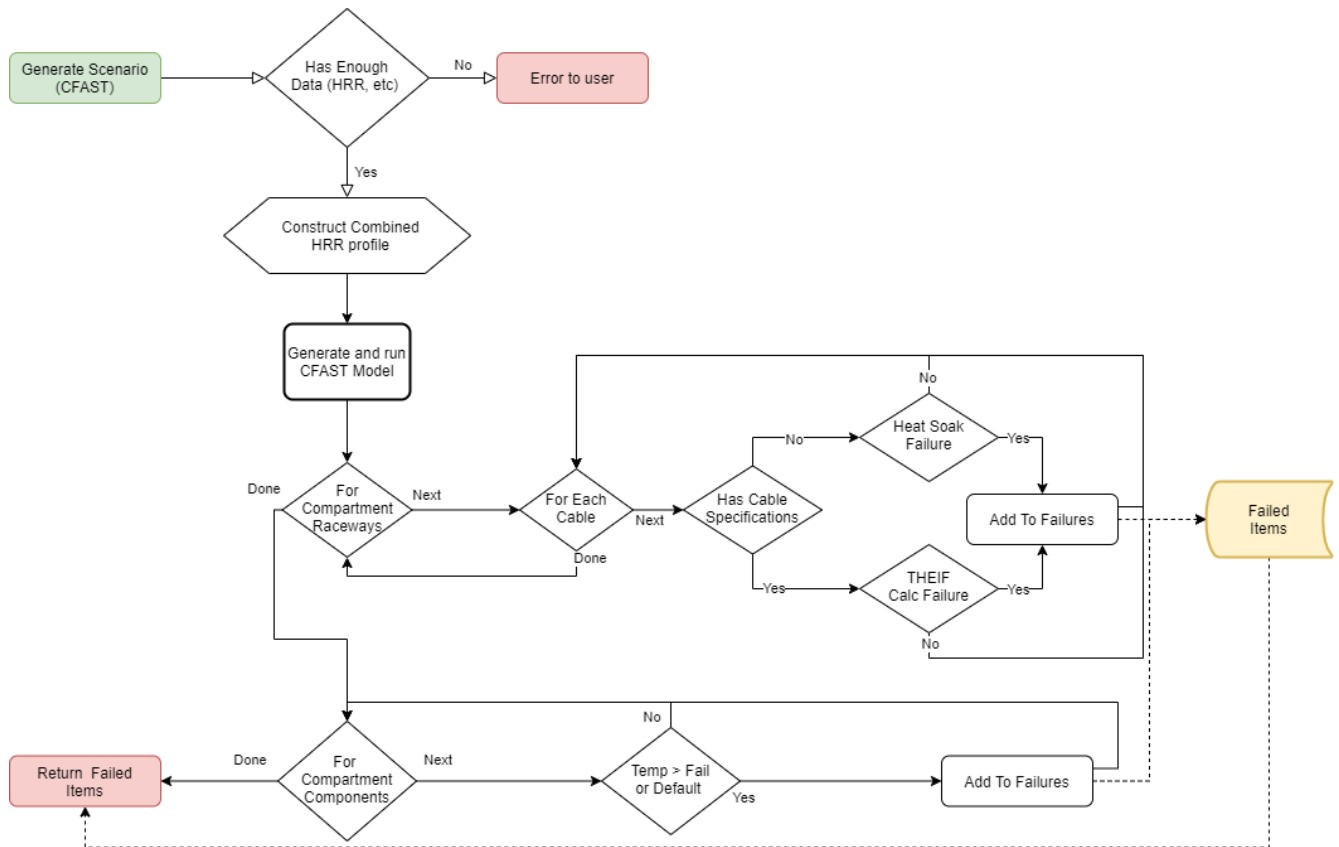
Figure 28: Automated process for determining failed components using CFAST results.

Two cable failure analysis methods are considered in this work as briefly explained in the previous paragraph. In general, there are three methods to assess fire damage to electrical cables as follows [17]:

1. Use of an exposure threshold: This method consists of using the exposure gas temperature or heat flux to determine cable failure. This method is the simplest among the three, since it only checks whether the cable temperature exceeds the failure temperature. However, it may not be accurate since it does not account for a "slow heating" mechanism where the cable is exposed to a relatively lower temperature for a period of time. For that reason, this method is not incorporated in this work.
2. Heat-soak method: This method uses a lookup table for time-to-damage as a function of constant exposure [18]. This approach allows one to credit the thermal inertia of cables in a generic manner. However, since the tables are based on constant exposures, they do not readily lend themselves to application in actual fire scenarios where temperatures will vary as a function of time.
3. Use of the THIEF Model (NUREG/CR-6931 [15]): This model performs a 1D, cylindrical heat-transfer calculation for a cable exposed to a time-varying exposure in order to determine when the cable jacket will fail based on the inner-jacket temperature. Validation of the model shows that it does well at computing the temperature rise of the cable jacket; however, since it requires cable-specific data (dimensions and mass), it cannot be applied in a generic screening manner like the heat-soak method.

The heat-soak method evaluates the time-cumulative heat damage to a cable by monitoring a variable called damage integral, which is defined as:

$$\Omega = \int_0^t RR(t)dt \qquad (10)$$

where Ω is the damage integral and the RR(t) is the time-dependent reaction rate. Damage occurs when Ω crosses a threshold value. By assuming the reaction rate is the inverse of the exposure duration, the cable will fail when damage integral is greater than or equal to 1 as formulated by:

$$\Omega = \int_0^{t_{dam}} \frac{1}{t'_{dam}(T(t))} dt \geq 1 \tag{11}$$

where T(t) is the exposure temperature at time t and t'$_{dam}$ is the time until damage for that temperature. This t'$_{dam}$ is tabulated differently for thermoplastic and thermoset cables. The same formula also applies for the time until damage as a function of heat flux instead of temperature. Reference [18] tabulates t'$_{dam}$ as a function of temperature and heat flux. Typically, damage integral is calculated from the plume temperature when the target is inside the fire plume. Otherwise, it is calculated using the heat flux. However, to account for the dynamics of fire growth, both approaches are utilized in this work to calculate the damage integral. At any given time step, the maximum damage integral is selected from both approaches for conservatism.

The THIEF calculation is more detailed than the heat-soak method. It assumes that the heat penetration into a cable of circular cross sections is largely in the radial direction. This assumption simplifies the formulation into a 1D radial-heat-transfer analysis. It assumes further that the cable thermal properties are independent of temperature, and that the cable does not decompose/deform during its heating. Therefore, given that the external time-dependent temperature is known as computed by CFAST, the governing THIEF formulation is given by:

$$\rho c \frac{dT}{dt} = \frac{1}{r}\frac{d}{dr} kr \frac{dT}{dt} \tag{12}$$

where ρ, c, and k are the effective density, specific heat, and conductivity of the solid, all-assumed constant. The boundary condition at the exterior boundary, r=R, is given by:

$$k\frac{dT}{dt}(R,t) = \dot{q}'' \tag{13}$$

where $\dot{q}''$ is the assumed axially-symmetric heat flux to the exterior surface of the cable. The partial differential equations are solved by creating a radial mesh of the cable and its jacket, forming linear heat-transfer equations over the radial meshes, solving them, and propagating the solutions to the equations in the next time step. This linear equation is written as:

$$\rho c \frac{T_i^{n+1} - T_i^n}{dt} = \frac{2k}{(r_{i+1} + r_i)}\frac{1}{2dr}\left[r_i \frac{T_{i+1}^n - T_i^n}{dr} - r_{i-1}\frac{T_i^n - T_{i-1}^n}{dr} + r_i \frac{T_{i+1}^{n+1} - T_i^{n+1}}{dr} \right. \tag{14}$$
$$\left. - r_{i-1}\frac{T_i^n - T_{i-1}^{n+1}}{dr}\right]$$

while the boundary condition is written as:

$$k\frac{T_{N+1}^n - T_N^n}{dr} = \dot{q}''(t'') \tag{15}$$

The cable fails when the inner-cable temperature exceeds 400°C for a thermoplastic cable, or 200°C for a thermoset cable.

As seen in the equations above, it is clear that THIEF has a better analytical basis to calculate a cable's temperature compared to the heat-soak method, which used experimental data in a lookup table. However, THIEF calculation require detailed properties of the cable such as cable dimensions, effective density,

specific heat, and conductivity. For that reason, the THIEF method is used instead of the heat-soak method only when the user provides these data in the FRI3D model.

5.3.3 Future Work

This work has implemented the minimal features needed for basic fire events. Additional work is needed to handle the variety of fire conditions and scenarios.

5.3.3.1 Secondary Combustibles

Often an initial fire will cause secondary combustibles to ignite. This can be due to both direct plume contact or when an item reaches a flash ignition point. For practicality, the latter is not necessary to model due to the high likelihood of entire room damage, captured in a full-room burnup probability in the PRA. To determine a chain of secondary combustibles, a loop is added to the flow described in Section 5.3.2 and shown in Figure **29**. This loop runs each time there is a new combustible added, along with its HRR and delay time in the CFAST model.
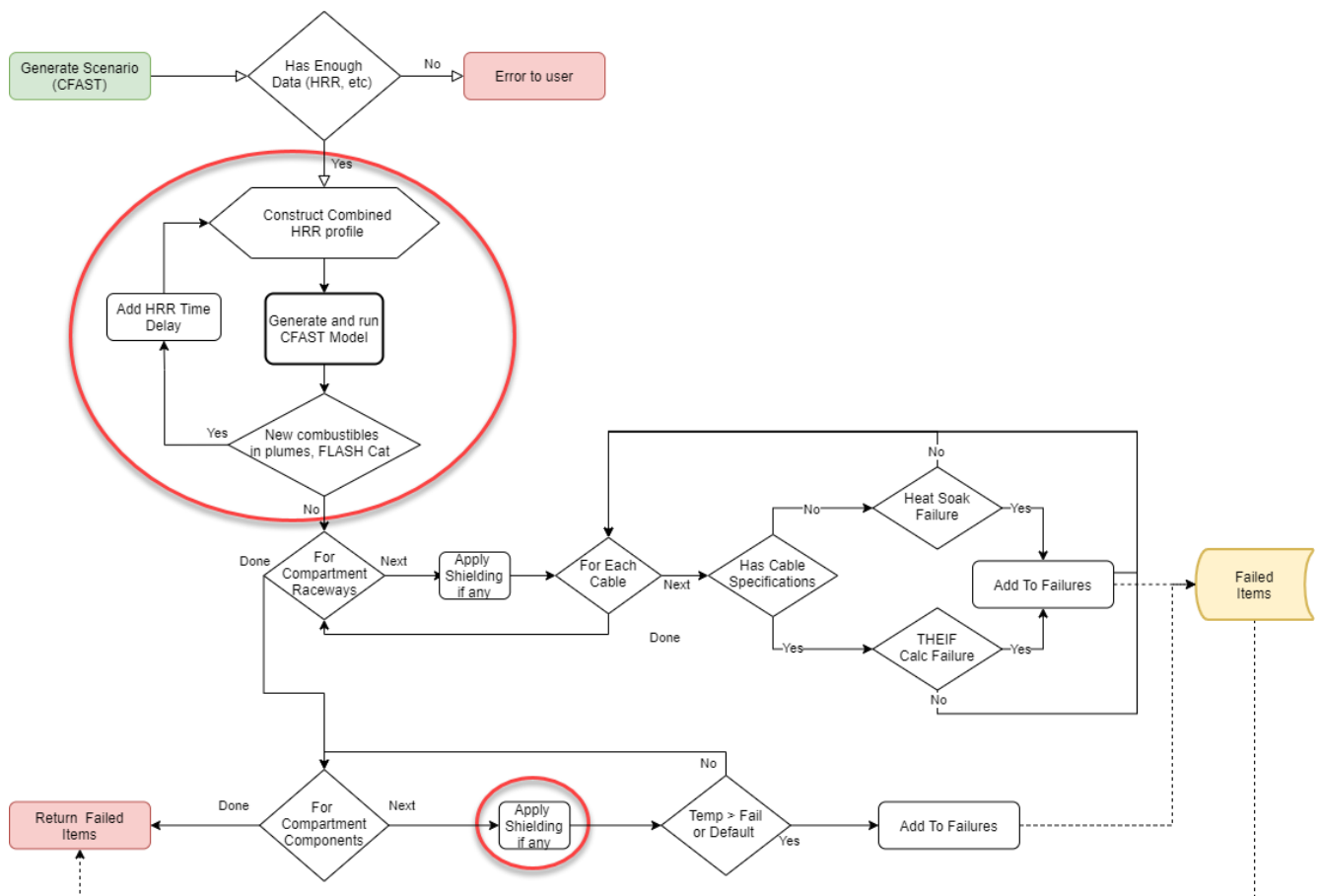

Figure 29: Added loop for determining secondary combustibles and crediting shielding for sensitive components.

5.3.3.2 Shielding

Sensitive or other equipment can have shielding added to protect it longer in a fire, increasing the likelihood of suppression before damage. This shielding will be added and applied to the time/temperature failure calculations.

6. INDUSTRY MODEL & TESTING

Several steps were taken during the development process of FRI3D to make sure it would be useful for both scientific research and a future shift to industry. This included use of an industry model, unit testing, and third-party verification of methods.

6.1 Model Import

INL collaborated with Southern Nuclear Co. to obtain their fire models for an existing facility. While small example problems are great for testing concepts, full models contain many scenarios and a large variety of components which allows to truly test the software. The following table lists a few of the item types and numbers imported from the industry model.

Item	Count
Zones	481
Scenarios	3,398
Raceways	23,181
PDMS Items	317,153

The algorithm used to auto-identify and link the source item for the scenario and combining plant FRANX data with PDMS data was successful for > 90% of the scenarios.

6.2 Unit Testing

Unit tests were incorporated into the development process for the API using the XUnit package. These tests are set up for every API call and other calculation processes in the code. These are used to verify that any code changes do not affect the successful execution of the desired outcome. The source code repository contains a dataset for each test case, and often a verified output file for comparison. This makes it easy to test new development and add testcases for the code. This unit test module will provide a platform for code compliance and validation when moving to industry production.

6.3 FRANX Results

There is no risk analysis engine built into the FRI3D software. To solve for the results of a scenario, the software depends on an existing FRANX model. When the user solves for one or more scenarios, the changes needed to build that scenario are applied to a user-specified model by adding or removing items to that model. Once those changes are made, CFAST is executed with the modified model and solves the marked scenarios.

This process was verified by Jensen Hughes consultants who worked on and are familiar with the original model. They used FRI3D to make changes to the model and quantify results. They then opened the model in FRANX and verified the changes were as expected. Finally, they used the FRANX software to make the equivalent changes to the original model and verified that the CFAST results from the two different models were equivalent.

6.4 Auto-Generating Scenarios

The process for auto-generating a scenario, described in Section 5.3 was verified by the fire modeling and CFAST experts at Jensen Hughes. This included reviewing a CFAST model auto generated by FRI3D. They identified a couple changes that needed to be made to our process, including performing a heat flux calculation for the heat soak in addition to just the temperature calculation. We also added default venting for to account for "Room Leakage", as they recommended. While we currently do not include the secondary

combustibles, the process implemented mimics the methods used when manually developing a fire model for complex scenarios. The next steps after this verification would be to develop a validation framework. This would be done using several models testing the various modeling features of FRI3D to validate the models it produces. These validation models would be added to the software testing architecture and part of the source code.

7.   Outcome

The outcome of this research and development has been a test version of the FRI3D software with the core capabilities needed to show coupling of key fire modeling tools and demonstrate value to the nuclear industry. Initially, this work was to include an analysis of probable time/cost savings. However, due to time limitations and travel/work limitations caused by COVID-19, collaboration on this effort was not feasible this year. Concurrently, a Small Business Technology Transfer STTR was announced and awarded for the FRI3D software and this effort will provide similar evaluation.

7.1   STTR

In June 2020 Centroid LAB was awarded DOE's STTR Phase I for Commercializing FRI3D to enable it to complete a go-to-market minimum viable product. FRI3D is currently a research product and Centroid LAB intends to take this product to industry. Toward this purpose, Centroid LAB plans to continue working with INL, and include industry partners like Zachry Nuclear (Zachry Group) for Phase I to build an MVP of FRI3D. During this phase an estimate of the total tangible and quantified market potential will also be determined. Industry practitioners including Caliburn, Jacobsen Analytics, French Institute for Radiological Protection and Nuclear Safety have expressed strong support for Centroid LAB's effort in development and commercialization of FRI3D.

7.2   Additional Features

Some additional features would help increase the value to industry. This project has focused on the basic tools needed to show the value of coupling existing models, tools, and 3D modeling. Current work has also identified a few other features that will be investigated as part of the STTR for a cost-benefit analysis, such as options for additional simulation tools like FDS or fire visualization capabilities. Dynamic PRA options, described in Section 8, will be added for the next stage of the lab research to determine proof of concept and could be added to the industry tool.

8.   SUMMARY AND/OR PATH FORWARD

The work done on FRI3D over the past 2 years completes the first stage of the enhanced fire analysis work. It provides a beta-test software application to combine 3D visualization into existing NPP logical fire models and coupling with the physics-based fire-simulation code, CFAST. With the easy-to-use interface and the coupling to existing models and simulation tools, FRI3D can help reduce efforts of industry in performing or adding more detail to fire modeling. An STTR will provide the market-benefit analysis and determine any features remaining to optimize industry application. The next stage of this research will use the API to perform enhanced fire analysis using dynamic PRA for critical industry scenarios.

8.1   Industry Significant Scenario

The first task under this project for FY 2021 will be the modeling of the switchgear room of an industry NPP. Due to the number of critical components and cabling in this room, it has a significant impact to the overall risk for most industry fire models. FRI3D will be used to model this room, which will test the modeling capabilities and verify necessary features are available and work properly.

8.2   Enhanced Fire Model Analysis

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. By combining the FRI3D API with dynamic PRA tools, we can determine critical timing events and reduce much of the conservatism.

Research using the switchgear room model will be done to analyze real life conditions such as a distribution of manual suppression actions and determine critical HRR factors for optimal binning of scenarios. Because of the limited use of dynamic fire PRA due to the time requirements, methods will be developed for how to best apply the results back into traditional PRA modeling for daily operation use.

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