Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira,
Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria
Published by Research Publishing, Singapore.
doi: 10.3850/ESREL2026061419_esrel26-p26342-cd

A Framework for handling Sodium Pool Fires for Fire Risk Assessment in Small Modular Reactors.

Ramprasad Sampath

Director, Centroid LAB, USA. E-mail: ram@centroidlab.com

Curtis Smith

Nuclear Sciences & Engineering, MIT, USA. E-mail: curtis@mit.edu

Kurt Vedros

PRA, AALO Atomics, USA. E-mail: kurt.vedros@aalo.com

Internal fires remain a major contributor to overall plant risk in nuclear power plants (NPPs), reinforcing the importance of fire probabilistic risk assessment (PRA/PSA) for informed design and regulatory decisions. Originally developed under the Light Water Reactor Sustainability (LWRS) Program, the Fire Risk Investigation in 3D (FRI3D) framework provides a unified 3D environment for modelling and assessing internal fire scenarios using Fire Dynamics Simulator (FDS) and CFAST coupled with codes for cable failure analysis based on Nuclear Regulatory Commission Reports (NUREG-2178, NUREG-6931 along with a database of validated Heat Release Rates for the most sources.

This paper presents a methodology for extending FRI3D to evaluate sodium pool-fire scenarios in liquid-metal-cooled Small Modular Reactors (SMRs). The approach does not model sodium combustion through physics directly but employs heat-release-rate (HRR) curves and sodium burning rates derived from experiments and software such as that found in the SOFIRE-II simulations. The resulting HRR profiles represent the effective thermal power of sodium pool fires and serve as source terms for CFAST (to capture enclosure and ventilation effects) and FDS (to resolve convective and radiative heat transfer). The workflow automates mapping of sodium spill geometries from CAD/BIM models, configuration of HRR boundary conditions, and visualization of resulting temperature and heat-flux distributions within FRI3D's 3D interface.

Keywords: Sodium pool fire; Fire PRA; Small Modular Reactors; FRI3D; CFAST; FDS.

1. Background

1.1 Fire Risk Assessment and FRI3D

Fire Probabilistic Risk Assessment has long been recognized as a critical contributor to overall plant risk in nuclear facilities. FRI3D (Sampath, Prescott and Christian 2022) was developed to simplify and automate the generation, simulation, and evaluation of internal fire scenarios by integrating deterministic fire modeling, plant geometry, and Probabilistic Risk Analysis (PRA) logic within a unified software environment. The framework couples commonly used fire models—such as CFAST (National Institute of Standards and Technology 2019) for zone modeling and FDS (National Institute of Standards and Technology 2022) for computational fluid dynamics—with PRA tools including SAPHIRE (Idaho National Laboratory 2022), RiskSpectrum PSA (RiskSpectrum 2025), and Computer Aided Fault Tree Analysis System (CAFTA) (Electric Power Research Institute 2014).

Previous applications of FRI3D focused primarily on light water reactors and conventional combustible fire sources. The increasing deployment of advanced reactor concepts, particularly sodium-cooled Small Modular Reactors (SMR), motivates extension of the framework to address non-traditional fire hazards while preserving PRA and regulatory compliance.

1.1 FRI3D Interface

FRI3D provides a graphical user interface that includes Computer Aided Design (CAD) based modelling tool to view different compartments and associated scenarios, then assign or modify the spatial information in the center Three Dimensional (3D) area. By combining 3D visualization directly with the PSA data and fire calculations, FRI3D provides a single interface for developing and analyzing fire models, while automating many steps. *Figure 1* shows the Graphical User Interface (GUI) which has five primary areas:

- Compartment/Scenario Editor: Displays all the items in the current compartment or scenario;
- Properties Editor: Editing equipment properties;
- 3D View: Allows for 3D modelling and viewing the spatial relationships, along with fire simulation results;
- Fire Logic View: Shows the logical mapping of raceways, cables, components, and PSA basic events;
- Timeline: displays the timing results from fire simulation and failure calculations (i.e., when items fail);

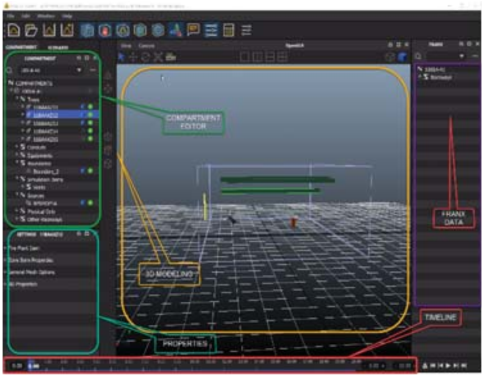

Figure 1: FRI3D User Interface

Fire scenarios can be created manually or preferably automatically by running a fire simulation using FRI3D. The automations eliminate the need for the various stages of hand calculations and manually assigned failed components and is thus less error-prone. The following steps are used to auto-generate a scenario:

(i) Import CAD/BIM (Building Information Management) data from CAD software such as Revit (Autodesk Revit Documentation 2023) .

(ii) Construct fire models from FRI3D's model with 3D data and properties.

(iii) Simulate fire using specified Heat Release Rates (HRR)s.

(iv) Determine if there are any secondary combustibles after an initial fire simulation, results, use the FLASH-CAT (McGrattan 2012) Method, generate a new HRR and go back to step 2.

(v) Use simulation results to determine additional cable failures using the Thermally Induced Electrical Failure THIEF (Nowlen, et al. 2008) method if cable data exists. If cable data do not exist, use the heat soak method (Nowlen, et al. 2008). Also, use simulation data to determine direct component failures for the compartment.

(vi) Use the fire logic mapping to determine subsequent components that failed due to cable failures.

(vii) Save failures, timing, and other data as a scenario for the compartment.

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

1.2 Zone-Models using CFAST

For fire analysis involving large scenario sets, fires are evaluated using a dual zone model such as CFAST. Compartments are represented as two well-mixed zones with conservation of mass and energy enforced in each layer. Sodium fire HRRs could be applied as prescribed source terms, enabling calculation of upper-layer temperatures, layer interface heights, and incident heat fluxes to targets. The appropriate compartments and targets are generated as representations suitable for CFAST from either CAD/BIM imported geometry or as a result of modelling using the FRI3D interface.

CFAST results are post-processed within FRI3D to determine cable and component failures using NRC-endorsed methods, including FLASH-CAT and THIEF where applicable. Scenario timing and failure information are automatically stored for PRA coupling.

1.3 CFD Models using FDS

FDS is employed selectively for scenarios where zone-model assumptions may not hold, such as strong stratification, complex ventilation, or localized heating of safety-critical components. FRI3D automatically generates FDS input from the same model exhibited by the FRI3D interface.

FDS simulations provide spatially resolved temperature and heat-flux fields that are used to validate zone-model results and refine damage assessments for high-consequence scenarios.

1.2 Sodium fires

Liquid sodium presents a fundamentally different fire hazard compared to hydrocarbon or electrical fires. Upon release and exposure to air, sodium may ignite spontaneously, producing high heat fluxes, significant aerosol generation, and strong coupling to ventilation and enclosure boundaries. Sodium fire scenarios are commonly categorized as pool fires or spray fires. Pool fires, which involve burning sodium collected on a surface. This approach first considers pool fires for Fire PRA, due to their longer duration and sustained thermal loading.

Extensive experimental programs and analytical tools have characterized sodium pool fire behavior over several decades. These include the ABCOVE (Moisseytsev 2021) experimental program conducted at the Hanford Engineering Development Laboratory, as well as semi-empirical and mechanistic analysis tools such as SOFIRE-II (Beiriger 1973) and sodium fire and aerosol modeling codes developed at Argonne National Laboratory. While these efforts provide a validated foundation for sodium fire energetics, aerosol generation, and enclosure response, they were not developed to support large-scale scenario generation, automated geometry integration, or direct coupling with modern Fire PRA workflows based on tools such as CFAST and FDS.

2. FRI3D Methodology for Sodium Pool Fires

2.1 Sodium fires

The extension of FRI3D to sodium pool-fire scenarios assumes that fire risk assessment requires reliable thermal and flow-field consequences rather than detailed combustion chemistry. Accordingly, the methodology does not attempt to model sodium oxidation kinetics or aerosol chemistry directly. Instead, sodium pool fires are represented through effective heat-release-rate (HRR) time histories derived from experimental and semi-empirical sources and subsequently applied within established fire modeling tools.

This approach aligns with the objective, which is to quantify enclosure temperatures, heat fluxes, equipment damage, and timing of failure, rather than to resolve the underlying combustion mechanisms. The methodology leverages validated sodium fire research while retaining compatibility with based zone and CFD fire solvers for solving the transport equations.

2.2 Derivation of Heat Release Rates from Experimental Data

Heat release rates for sodium pool fires are derived using data from the ABCOVE and supporting semi-empirical models implemented in SOFIRE-II. While ABCOVE test reports do not generally publish explicit HRR(t) curves, they provide time-resolved measurements of sodium mass loss, oxygen depletion, enclosure temperatures, and pressure histories from which HRR can be reconstructed.

For a sodium pool of surface area A_p, the effective heat release rate is expressed as:

$$\dot{Q}(t) = \dot{m}_{Na}(t)\,\Delta H_{eff}$$

Equation 1: Sodium Pool Fire

where $\dot{m}_{Na}(t)$is the sodium mass-burning rate and $\Delta H_{eff}$is the effective heat of combustion accounting for incomplete oxidation and enclosure effects. The value of ΔH_{eff} is selected based on published sodium oxidation energetics and sensitivity studies.

This process yields an HRR(t) profile representative of sodium pool-fire energetics without explicitly resolving combustion physics.

.

3. FRI3D Modeling for Sodium Fire Scenarios

3.1 3D Modelling/Ingestion

Given the innovative and evolving nature of SMR designs, there is an increasing reliance on advanced CAD tools and modelling environments. These tools support efficient design iteration, digital verification against regulatory requirements, and early-stage assessment of fabrication and assembly constraints. In parallel, the adoption of BIM has introduced the capability to create comprehensive 3D models that serve as digital twins, supporting design, construction, operations, and maintenance activities.

A key enabler of interoperability within BIM workflows is the use of industry foundation classes (IFC), an open data standard maintained by buildingSMART (buildingSMART International, 2024). IFC facilitates consistent exchange of building and infrastructure data across disciplines, which is essential in nuclear projects where systems are developed and reviewed by a wide range of stakeholders. Most modern CAD platforms, including Revit, Navisworks, and CATIA, support IFC export. Figure 6 (left) depicts the turbine room of an SMR imported in FRI3D as a CAD/IFC model..

Figure 2: 3D Model Visualization of an SMR

FRI3D enables seamless integration of these models into fire analysis workflows through its ability to import and interpret IFC data. Component tags and classifications embedded in the IFC allow FRI3D to automatically recognize and categorize architectural elements such as walls, doors, raceways, vents etc. This enhances simulation fidelity by allowing zone model and CFD based outputs to treat such components appropriately, for instance, treating a door as a potential ventilation boundary or a window as a heat flux-loss interface.

FRI3D can import plant geometry using industry-standard CAD and BIM formats, including Industry Foundation Classes (IFC). Architectural elements such as walls, doors, and vents are automatically classified and translated into appropriate boundary conditions for zone and CFD models based upon its categorization in the IFC class. This enables consistent treatment of ventilation and heat losses across modelling fidelities. If CAD/BIM models are not available, the facility and raceways could be modelled using the integrated 3D modelling interface in FRI3D.

3.2 Plant Logic Data Import/PRA

The FRANX (Electric Power Research Institute 2015) database file and format was developed and is used by EPRI for external hazards modelling in their Computer Aided Fault Tree Analysis System (CAFTA) risk analysis software and was used to import the fire scenarios, compartments and mappings from cables to raceways to components and its associated basic events FRI3D’s flexible design enabled the import of existing fire model data and scenarios from the FRANX database formats as well as a Microsoft Excel Spreadsheet.

In addition, plants may have their internal database comprising of various cable routes, location of equipment etc which may or may not be PRA relevant. FRI3D’s interface provided a set of tools to ease raceway modelling by providing a flexible import mechanism.

If the plant is not ready for PRA yet this step is optional and hazard analysis for aiding design could be done without PRA.

3.3 Sodium Spill and Pool Definition

Potential sodium release locations are identified from 3D plant models, including piping for Sodium, raceways and sodium-bearing components. A source with a prescribed area is therefore identified as a scenario pool and the appropriate HRR profile is applied towards that scenario. FRI3D supports automating creation of multiple scenarios with varying areas to describe alternative scenarios.

3.4 Fire Simulation

FRI3D can be used to orchestrate downstream fire simulations using either CFAST or Fire Dynamics Simulator (FDS), depending on the analysis objective. In CFAST, the HRR(t) is applied as a prescribed fire source to evaluate enclosure temperature stratification, pressure rise, and ventilation effects. In FDS, the same HRR(t) is imposed as a surface-based heat source, allowing resolution of convective flow patterns and spatial temperature distributions.

After a simulation is performed the simulation results are automatically re-ingested into FRI3D, enabling three-dimensional visualization of thermal fields and direct coupling to fire PRA damage and timing models.

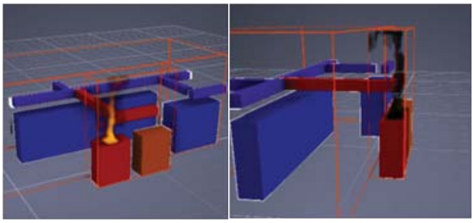

Figure 3: Fire and Smoke Visualization of FRI3D Simulation

3.5 Damage metric extraction

Deterministic fire simulations produce time histories of gas-layer temperatures, surface temperatures, and incident heat fluxes. These outputs are mapped to component and cable failure criteria by means of methodologies such as THIEF/HeatSoak/FLASH-CAT to generate failures.

3.6 PRA integration

FRI3D exports scenario results directly to PRA tools such as SAPHIRE, RiskSpectrum PSA or CAFTA linking the failures with fire induced basic events, enabling calculation of conditional core damage frequency and risk metrics. The integrated workflow minimizes manual data transfer and reduces the potential for modelling inconsistencies.

3.7 Results

A given room of a dimensions of 9m x 9m floor x 12m height with raceway placed at a height of 6 meters above the ground was constructed in FRI3D based on the intention of the SMR design.

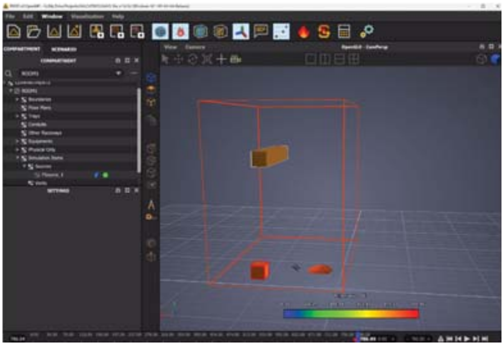

Figure 4: Equipment Failures from Na Pool Fire Source

FRI3D features an exhaustive list of predefined fire source properties and their time dependent Heat Release Rates (HRRs), also allowing the user to enter a custom heat release rate curve. Based on *Equation 1* a custom heat release rate curve was entered which defines the property of the specified Sodium fire pool of a given area. *Figure 4* depicts the heat release rate specification. A Sodium Pool spill accumulating on the floor comprising an area of 4 sq m was induced as the source of the fire.

Name: Sodium_Fire
Heat of Combustion: 7000 kJ/kg
Radiative Fraction: 0.35
Mass Burn Rate: 0.09 kg/m2/sec
Density: 870 kg/m3
Empirical Constant: 1.4 m-1
C: 7 N: 0 H: 16 Cl: 0 O: 0

	Time (s)	HRR (kW)	Height (m)	Area (m²)	CO Yield	Soot Yield	HCN Yield	TS Yield
1	0	0	0	4	0.01	0.01	0	0
2	30	6.8	0	4	0.01	0.01	0	0
3	60	27.2	0	4	0.01	0.01	0	0
4	90	61.2	0	4	0.01	0.01	0	0
5	120	108.8	0	4	0.01	0.01	0	0
6	150	170	0	4	0.01	0.01	0	0
7	180	244.8	0	4	0.01	0.01	0	0
8	210	333.2	0	4	0.01	0.01	0	0

Figure 5: Time Dependent Heat Release Rate for Na Pool Fire

CFAST and FDS simulations were then performed to determine the failures of equipment as well as to determine temperature distributions and operator visibility due to smoke accumulation in the room. . Figure 4 is the visualization of peak zonal temperatures of the room along with the failures indicated in the timeline with the location of the targets for a simulation performed for 1000 seconds using CFAST. The same simulation was performed in CFAST now with two vents, a supply and a return vent with a vent efficiency of 90% and a flow rate of 0.1 m^3/s for both the supply and return vent. Whereas in the first case without the vents indicated two failures one at 50 seconds and other at around 775 seconds (*Figure 5*), the second case running with the two aforementioned vents indicated only one failure (the source equipment) and no other failures (*Figure 6*). These scenarios used the equipment failures as a metric. Further scenarios can be run using a CFD solver like FDS with smoke obscuration for failures.

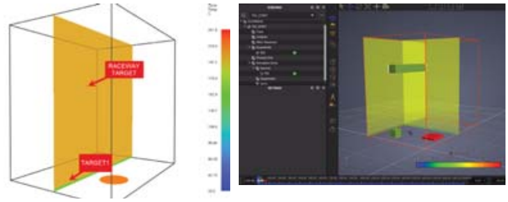

Figure 4: FRI3D Targets and Zone Temp with Failure Visualization (CFAST).

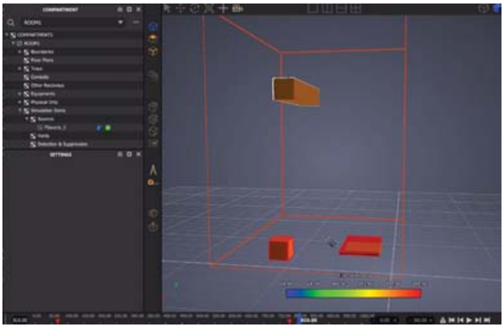

Figure 5: Tray/Raceway Failures with no vents

Figure 7 illustrates the same compartment modelled using the Fire Dynamics Simulator (FDS), employing a fully three-dimensional computational fluid dynamics (CFD) approach.

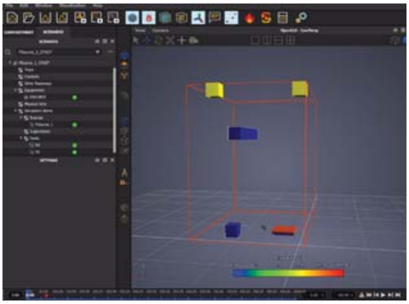

Figure 6: Tray/Raceway Failures with Supply and Return Vents

The FDS simulation provides spatially resolved predictions of gas temperature, smoke (soot) concentration, and velocity fields, enabling detailed assessment of heat and smoke transport within the compartment. In addition to thermal fields, FDS yields metrics not available from zone models, including local smoke concentration and flow patterns that govern smoke layer development and descent.

At approximately 200 s into the simulation, the predicted smoke layer interface is located at an elevation of about 4 m above the floor. In NRC-endorsed fire PRA methodology, the impact of smoke on human actions is evaluated at an assumed personnel breathing height of approximately 1.8 m above the floor, with emphasis on local conditions such as smoke concentration, temperature, and heat flux rather than on a prescriptive, compartment-level definition of “uninhabitability” (Nowlen et al., 2005). For plant areas that are not continuously occupied—such as an SMR reactor room—loss of habitability is assessed in terms of whether environmental conditions would prevent safe personnel access or the execution of credited manual actions.

Extended simulation results indicate continued descent of the smoke layer at later times (up to 2000 s). While smoke layer descent alone does not necessarily imply loss of access, confirmation of habitability requires evaluation of smoke concentration metrics, such as optical density, at the 1.8 m elevation.

The availability of these additional, spatially resolved outputs from CFD-based fire simulations supports more informed assessment of room habitability and personnel access during sodium pool fire scenarios. Consequently, such analyses can be used to inform room layout, ventilation design, and fire protection features during the design phase, reducing downstream design modifications and associated cost and schedule impacts.

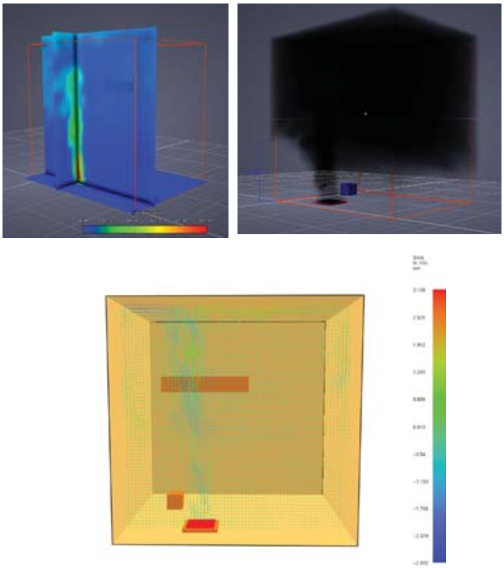

Figure 7: FRI3D - Visualization of Temp, Soot/Smoke (Density) and Velocities (FDS)

4. FRI3D for SMR Design Decisions/Modifications

FRI3D plays a critical role in informing design decisions during the layout and development of SMRs by enabling early-stage fire hazard analysis. Using IFC-integrated models, designers can simulate a wide range of fire scenarios under varying operational conditions and component arrangements. For example, analyses can be performed to assess the impact of placing electrical cabinets, cable trays, or ventilation ducts near potential ignition sources. Multiple simulations can be run in parallel, each varying the location or configuration of key components, enabling comparative risk assessments to be generated.

These simulation outputs help quantify risk profiles, identify high-consequence zones, and guide design teams toward configurations that minimize fire propagation pathways and improve compartmentalization. Moreover, the ability to iteratively test design changes using actual model geometry ensures that fire safety considerations are integrated into the SMR development process from the outset, rather than being retrofitted later in response to compliance reviews.

This proactive, simulation-based approach supports not only safety case development but also cost optimization by reducing the need for conservative overdesign and allowing targeted placement of passive and active fire protection systems.

5. Conclusions & Future Work

The FRI3D platform provides an advanced environment for conducting detailed fire modelling and analysis in support of Fire PSA and Fire Hazard Analysis (FHA). Its architecture enables integration of both zone models (e.g., CFAST) and CFD models to simulate a wide range of fire scenarios across nuclear facilities. This dual-modelling approach allows for scalable fidelity supporting rapid assessments using zone models as well as high-resolution analyses for critical areas using CFD.

Its automated scenario generation, support for 3D geometry, and enhanced visualization tools – such as item temperature tracking and failure timelines enabling efficient development and analysis of complex fire scenarios.

By streamlining scenario development and enabling informed scenario binning, FRI3D enhances the accuracy, efficiency, and cost-effectiveness of fire modelling for advanced reactor designs – supporting credible, risk-informed safety evaluations.

This paper presents a PRA-oriented methodology for evaluating sodium pool fires in liquid-metal-cooled SMRs using the FRI3D framework. By integrating CAD-driven geometry, reduced-order modelling using a Heat Release Rate based source term with a zone model, and integrating the results with PRA, the approach provides a scalable and regulator aligned solution for sodium fire risk assessment. While zone models like CFAST provide conservative, computationally efficient screening for most scenarios for pool fires, CFD simulations ensures adequate transport of heat and subsequent failures resulting from heat transport.

The extension of FRI3D to sodium pool fires demonstrates that this approach can provide representations that can be effectively integrated into a modern Fire PRA framework.

However, current limitations include reliance on existing sodium fire datasets and exclusion of spray fire and quasi-explosive phenomena, which are better addressed using system-level codes such as MELCOR(Louie et al., 2017). Future development will focus on incorporating such effects through coupled or surrogate modelling approaches, thereby supporting both rapid screening and high-fidelity analysis, enabling risk-informed design and safety evaluation of advanced reactors.

References

buildingSMART International. (2024). *Industry Foundation Classes (IFC) 4.3.2.0 Specification*. https://ifc43-docs.standards.buildingsmart.org/

Louie, D. L. Y., Humphries, L. H., & Denman, M. R. (2017). *Containment Sodium Chemistry Models in MELCOR* (Numbers SAND2017-3798J). https://www.osti.gov/servlets/purl/1429762

2023. "Autodesk Revit Documentation." San Francisco, CA.

Beiriger, P. 1973. "SOFIRE II User Report." Canoga Park, California.

Electric Power Research Institute. 2014. "Computer Aided Fault Tree Analysis System (CAFTA), Version 6.0b." https://www.epri.com/research/products/000000003002004316.

Electric Power Research Institute. 2015. "FRANX v4.3." https://www.epri.com/research/products/3002000098.

Gauntt, R. O. 2000. "MELCOR Computer Code Manuals, Volume 1: Primer and User's Guide, Version 1.8.5." Albuquerque, NM. https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6119/v1/index.html.

Hilliard, R.K., J.D. McCormack, and A.K. Postma. 1979. "Aerosol Behavior During Sodium Pool Fires in a Large Vessel – CSTF Tests AB1 and AB2."

Hilliard, R.K., J.D. McCormack, and A.K. Postma. 1983. "Results and Code Predictions for ABCOVE Aerosol Code Validation – Tests AB5 and AB6."

Idaho National Laboratory. 2022. "SAPHIRE – Risk and Reliability Assessment Tools for the 21st Century." https://saphire.inl.gov/.

Louie, D. L. Y., L. H. Humphries, and M. R. Denman. 2017. "Containment Sodium Chemistry Models in MELCOR." https://www.osti.gov/servlets/purl/1429762.

Louie, D. L., and M. A. Aoyagi. 2022. "Sodium Fire Collaborative Study Progress (CNWG Fiscal Year 2022)."

McGrattan, K. 2012. "Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Phase 1: Horizontal Trays." https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7010/v1/index.html.

Moisseytsev. 2021. *Development of Sodium Fire Analysis Code Capabilities.* ANL.

National Institute of Standards and Technology. 2019. "CFAST: Fire Growth and Smoke Transport Modeling." https://www.nist.gov/el/fire-research-division-73300/product-services/consolidated-fire-and-smoke-transport-model-cfast.

National Institute of Standards and Technology. 2022. "FDS-SMV: Fire Dynamics Simulator (FDS) and Smokeview (SMV)." https://pages.nist.gov/fds-smv/.

Nowlen, S. P., J. A. Lambright, V. F. Nicolette, and F. J. Wyant. 2008. "Cable Heat Release, Ignition, and Spread in Tray Configurations: Results from Full-Scale Fire Experiments."

Prescott, S., M. Schairer, and R. Sampath. 2023. "A pilot study of using Fire Risk Investigation in 3D (FRI3D) software for performing fire analysis of plant modifications." Canadian Nuclear Society.

RiskSpectrum. 2025. "RiskSpectrum PSA."

Sampath, R., S. Prescott, and R. Christian. 2022. "Fire Modelling Automation and Visualization in the Context of Fire

Probabilistic Risk Analysis for Nuclear Plants." *17th International Seminar on Fire Safety in Nuclear Power Plants and Installations.* https://www.grs.de/sites/default/files/2023-02/GRS-705.pdf.

Stroup, D., G. Taylor, and G. Hausman. 2004. "Fire Dynamics Tools (FDTs): Quantitative Fire Hazard Analysis Methods for the U.S. NRC Fire Protection Inspection Program." https://www.nrc.gov/docs/ML1321/ML13211A097.pdf.

U.S. Nuclear Regulatory Commission. 2016. "Refining and Characterizing Heat Release Rates From Electrical Enclosures During Fire (HEAF)."