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MELCOR CODE VALIDATION STUDIES ON FIRE ACCIDENTS IN NON-REACTOR FACILITIES

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ABSTRACT

Fire scenarios are a dominant contributor to nuclear installation risk around the world. Fires represent a significant hazard for non-reactor nuclear facilities. For these facilities, a containment structure is typically not present to provide protection against release of radioactivity. Fires in non-reactor nuclear facilities have the potential to lead to harmful radiological release to the environment. Analytical models provide a means to evaluate measures to mitigate such accidents. Such models enable simulation of thermal hydraulic conditions and aerosol transport under fire scenarios to quantitatively characterize radiological release to the environment (i.e., the source term).

In this paper, we discuss an on-going fire scenario validation study for the MELCOR code, developed at Sandia National Laboratories for the U.S. Nuclear Regulatory Commission. This paper presents MELCOR validation studies against single fire and multi-room fire scenario experiments. It further presents a code-to-code comparison to increase confidence in the thermal hydraulic conditions estimated by MELCOR for these validation simulations. Also presented are MELCOR validation studies focusing on aerosol physics modeling. These validation studies are based on aerosol transport experiments relevant to conditions occurring in fire scenarios. This set of validation studies demonstrates MELCOR's capability to model the thermal hydraulic conditions and aerosol transport necessary to characterize non-reactor nuclear facility source terms for fire scenarios.

KEYWORDS
MELCOR, Non-reactor Facilities, Fire accident, Source Term, Validations

1. INTRODUCTION

Fire scenarios are a dominant contributor to nuclear installation risk around the world. These scenarios represent a significant hazard for non-reactor nuclear facilities. For these facilities, a containment structure is typically not present to limit the potential for and extent of radioactive material release to the environment. Fires in non-reactor nuclear facilities have the potential to lead to harmful radiological release to the environment. Analytical models provide a means to evaluate measures mitigate such

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accidents. Such models enable simulation of thermal hydraulic conditions and aerosol transport under fire scenarios to quantitatively characterize radiological release to the environment (i.e., the source term).

Simulation becomes complicated if the nuclear facility contains numerous rooms/corridors and operations. A systems-level computer code provides a means by which the thermal hydraulic behavior and the aerosol transport through leak paths and attenuation of fission products inside the facility can be evaluated. Such analytical tools have proven valuable to providing a best estimate characterization of radionuclide release of the environment for these types of facilities.

The MELCOR code is a leading, state-of-the-art systems-level code used to perform safety assessments for a broad range of nuclear facilities. It has been actively developed at Sandia National Laboratories for the U.S. Nuclear Regulatory Commission (NRC) for over 30 years [1]. MELCOR has been used internationally with over 900 licensed users. MELCOR has been extensively applied recently to support safety assessment for both reactor and non-reactor facilities [2-3]. These recent studies are examples of the vast range of applications of MELCOR beyond its traditional use in the analysis of severe accidents in Light Water Reactors (LWRs). MELCOR has been used in application to assessment of advanced LWR and non-LWR designs, nuclear fusion, spent fuel reprocessing, and U.S. Department of Energy (DOE) nuclear and non-nuclear facilities. This range of applications is feasible because of the flexible code architecture adopted for MELCOR, with a focus on representing the broad array of phenomena and physical configurations necessary to characterize the progression and consequences of accidents at nuclear facilities. For example, MELCOR as a lumped parameter control volume (CV) code allows users to flexibly construct a geometric representation of essentially any facility through an arbitrary number of CVs and flow paths.

In this paper, the application of MELCOR to modeling of non-reactor facility fire scenarios is described. Since the primary aspects of these accident scenarios that are unique involve thermal hydraulic phenomena, the thermal hydraulic response of the facility is the focus of this paper. The appropriate representation of these phenomena is critical to characterizing the source term to the environment for a facility.

Traditionally, MELCOR has not traditionally been applied to analyze fire accidents because it does not include a dynamic hot gas layer model common in many fire accidents codes, such as CFAST [4-5]. However, MELCOR can utilize a number of segmented control volumes to represent hot gas layers. To validate MELCOR modeling capabilities for representing fire accident scenarios, a number of fire-specific benchmarking studies have been performed with MELCOR. These common combustible fire benchmarking studies range from liquid fires and solid combustibles, including sodium fires.

In this paper, we present a MELCOR demonstration calculation for a large non-reactor facility – spent fuel reprocessing plant. This paper develops the overall adequacy of MELCOR with respect to simulating fire scenarios, particularly for non-reactor and DOE nuclear facilities.

2. MELCOR Modeling in Fire Scenarios

MELCOR is a large multi-physics computer code with a vast range of applications, including both reactor and non-reactor facilities, so the code is structured modularly in packages that cover specific reactor designs, and thermal-hydraulics and aerosol physics models for transports between volumes. For example, a set of packages is needed to model the reactor type application. For a specific type of reactors, there may be a set of additional packages that are uniquely applicable for reactors. Here, we are only using the necessary packages within MELCOR needed for a fire scenario simulation resulting from a combustible burn, either from a solid or liquid combustible in a non-reactor nuclear facility.

2.1. Packages Needed

This section describes the packages in MELCOR is necessary to perform an accident scenario, since MELCOR does not have a specific fire energy release model nor a plume rise, stratification and particle entrainment model, including a lack of soot release model for fire modeling for example.

Table I describes the MELCOR packages and models that may be of interest to the safety basis community. As shown in this table, a number of packages should be included in the source term calculation. RN, CVH, and FL packages are the major packages utilized for the LPF analyses, since the RN package tracks the radionuclides and aerosol, and both CVH and FL define the thermal conditions of the problem. FL is also used to track the release of the radionuclide and aerosol to the environment. Also shown in this table are the number of models available for use in the source term calculations. Significant improvement in the aerosol deposition model has been added to MELCOR, namely the abilities to disable the aerosol deposition model, and to model the turbulent deposition in pipes and ducts (including bends in ventilation systems (see Table I for the model limitation).

Table I. MELCOR Package Descriptions for Non-Reactor Applications

Package	**Description/Comments**
EXEC	Main control of various processing tasks and control of the overall calculation sequence. Sensitivity coefficients of many package models can be redefined in MELGEN or changed at any restart via MELCOR input. Common block feature, which is designated in the input as starting with "(((name block" and ending with ")))" can be used to allow a single input file to simulate a number of different runs. The name block can be included during execution of the MELGEN/MELCOR calculations or included in the beginning of the input file. The use of the common blocks is extremely useful for sensitivity studies.
NCG	For consistency with the rest of the table, define each term, namely NCG, before explaining its usage. The NCG (non-Condensable Gas) package is used to define the gases in the control volumes.
CVH/FL	The CVH/FL (Control Volume Hydrodynamics/Flow Paths) package use time-independent volume for the environment, which prevent aerosols from being drawn back into the facility. A large environment volume (10^{10} m^3) may be too large, since its energy and mass may dilute any actual mass and energy errors in the problem. Therefore, it is recommended to use a reasonable size volume.
HS	The HS (Heat Structures) package allows the model of heat transfer surfaces in the facility as well as for any aerosol deposition or condensation of the water.
RN	The RN (Radionuclide Behavior) package is the most important package for the LPF analysis, because this package tracks and models much of the physics for the aerosols and radionuclides modeled. A new input, RN1_VISUAL, enables the extraction of aerosol information (such as aerosol section and deposition masses) as a function of time to store in files for post-processing, using "ResultsViewer" to display graphically or use SNAP* utility or another graphic program to discuss the results.
CF/TF	Both the control function (CF) and tabular function (TF) packages provide a way to control the problem as well as to read and write data for the problems.
EDF	The EDF (External Data File) provides a way to read or write a large amount of data that can be input to MELCOR, or that MELCOR can write out for plotting or inputs to other applications.
Models	**Description/Comments**
Counter-current flow (CCF) model	A new stratified counter-current flow of gases in a flow path was developed (see FL package input – FL_CCF). User input is available to allow coupling of flows in two paths through momentum exchange, using Epstein-Kenton correlations. This model can be used for modeling counter-current flow in a fire condition, but it is limited for the horizontal flow only.
Critical Flow	CVH package provides an option to select the critical flow in the atmosphere, when two-phase flow may be important. This input card, CVH_ATMCS, is provided. Additionally, the user can print out the sound speed of the flow using CVH_CSTBL.
Aerosol deposition model deactivation flag	RN1_ADFG input in the RN package permits disabling a particular aerosol deposition model – such as a gravitational, diffusive or thermophoresis aerosol settling model. This allows the users to determine which deposition model has the effect on the results.
Turbulent Aerosol Deposition	RN1_TURB input in the RN package allows the modeling of the turbulent aerosol deposition in pipe or duct that contains gas flows in the turbulent regime. Deposition in bends, venturi, and contraction of the pipe or duct transitions can also be captured. Because many of the benchmarks done for this model are from the reactor applications, cautions should be used when applying this model for the non-reactor application

Filters	Filter models within the RN2 inputs in the RN package are flexible enough to permit the user to model a variety of aerosol or vapor filters for capture and absorption and their degradation phenomena, because many of the filter inputs can be modeled using control function logic.
Sprays	The SPR package was developed for the containment spray in the reactor containment. Because of the generality of the spray inputs, this spray model can be used to simulate the fire sprinkler system to reduce the temperature of control volumes and can be used to scrub radionuclides/aerosols to minimize the source term release.

3. VALIDATION STUDIES

This section describes the MELCOR validation studies conducted for modeling fire scenarios. As a part of a recent MELCOR validation study [3], we validated the thermal-hydraulic responses of MELCOR for a single room fire experiment and conducted a code-to-code comparison with CFAST. In support a safety basis group at Los Alamos National Laboratory, we conducted a multi-room fire experiment benchmark on MELCOR as well [ICONE paper].

3.1. Single Room Fire

In 1986, Lawrence Livermore National Laboratory (LLNL) studied the effects of ventilation on enclosure tests [5]. The enclosure was 6 m long, 4 m wide and 4.5 m high. It contains a methane rock burner located at the center of the enclosure floor. The burner is 0.23 m height and 0.57 m in diameter. Figure 3-32 shows the layout of this enclosure. As shown in this figure, there are two inlet ducts, which are located near the top and bottom of the enclosure. The dimensions are not specified for the inlet ducts. The exhaust duct is dimensioned to be 0.65 m by 0.65 m near the top of the enclosure. For some tests, an upper plenum is used. As shown in this figure, the exhaust duct has a fan that can draw air out of the enclosure during the fire. A door with the dimension as shown in this figure is used for certain tests. The size of the fire is varied from 50 kW to 400 kW. The ventilation mass flow rate is varied from 100 to 500 g/s.

Since the experimental facility description was not completed [5], the information about the walls and ceiling/floor structures is based on the information from CFAST benchmark analyses. The principal reaction for the combustion of methane gas is given by:

$$\mathbf{CH_4 + 2\,O_2 \rightarrow CO_2 + 2H_2O} \tag{1}$$

For this experiment, we assume that the fuel mass fraction that results in carbon particle generation during combustion is ignored, since this simulation is targeted for the thermal-hydraulic results, rather than aerosol results.

3.1.1. Experiment data

For this paper, we would only focus on Test 9 from this experiment, which uses the full compartment and low inlet duct. The ventilation flow is active in this test, so that the modeling of CH_4 in the reaction is not required since the limitation of oxygen did not occur. The locations of the thermal couples in the experiments are near the top, middle, and lower sections of the enclosure. The experimental data for Test 9 included the air exhaust flow, the fuel flow rate, the oxygen and carbon dioxide mole fractions, the pressure drop, and the average five thermocouple temperatures in the upper, middle and lower enclosure (see [3] for details). As indicated before, no detailed information about the precise thermocouple locations is given.

3.1.2. MELCOR model

The development of the MELCOR model was done in stages. First, the appropriate number of volumes to capture the temperatures of the fire was needed. Initially, only three axial volumes were modeled, and resulted in high temperature near the bottom of the enclosure, which was incorrect (see [3] for more details). The hot gas should be located near ceiling of the enclosure. To model the observed natural recirculation and stratification, the 9-volume model was used Figure 1 shows the 9-volume model for this enclosure experiment. As shown in this figure, a flow path models the inlet plenum to the enclosure, and a flow path that goes to the exhaust fan in the upper layers of the enclosure. The reason for breaking the enclosure into three equal regions is the thermocouple layout in the enclosure, even though the exact location is not known. Therefore, each upper, middle, and lower region contains the average results of 5 thermocouples. The fire is located at the center of the room on the floor. In each axial region, three concentric volumes, starting from an inner, middle and outer volumes, are shown in this figure with their dimensions. Therefore, when the fire starts in the rock burner at the center of the floor, the high temperature gas would rise in the center to the upper region and move out toward the exhaust fan (see Figure 1).

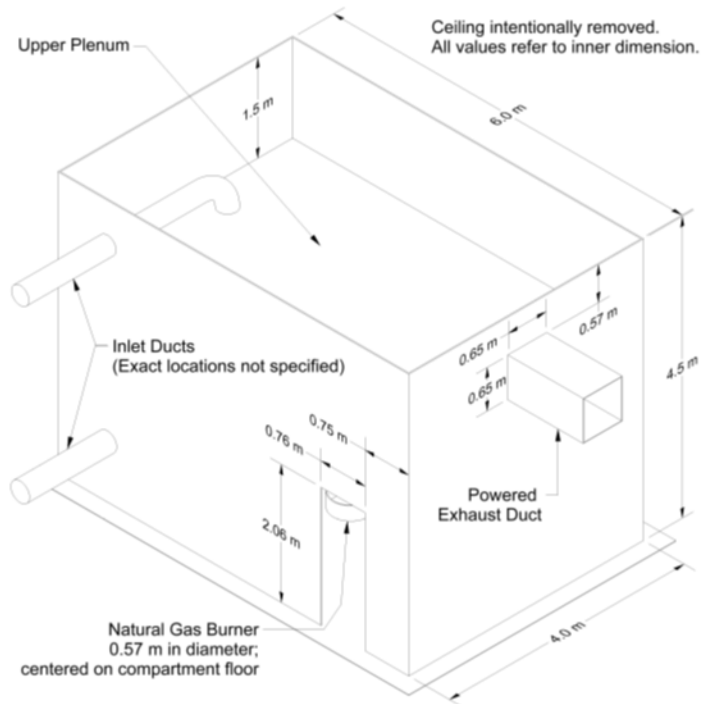

Figure 1. Layout of the LLNL Enclosure Experiments [Peacock 2016b]

In terms of the heat structures, the walls, floor and ceiling of the enclosure are modeled as heat sinks. Since there is no wall thickness information from the experiment provided, we utilized the information from the CFAST validation report [5]. In addition, the inlet flow area is taken from what CFAST used in the simulation as 0.018 m^2, which is a leakage area based on the initial exhaust rate and pressure. To capture measured response correctly, the radiation heat loss fraction of the combustion power is included. The provided radiation heat loss is consistent with the expected radiation loss in [6] (see [3] for details). For this validation test, we initialized the initial temperature and the pressure in the enclosure volume to be that of time zero experimental data. Additional atmosphere specifications are obtained from CFAST simulations for the test. For example, the relative humidity is taken to be 50%.

The thickness of the surfaces is modeled to be 0.1 m according to the CFAST. However, we assume all surfaces in the enclosure are made of stainless steel. A rock burner heat structure is modeled, and assumed to be an annular cylinder having a high of 0.23 m and an inner radius of 0.25 m and outer radius of 0.57 m. It is also assumed to be made of stainless steel. In the MELCOR calculation, we assume the end time of 4000 s with a ramp rate from 0 to 100% of the fire power for each test. To model the fire, we used a number of control functions to model Equation (1) and the oxygen consumption as a mass sink, and carbon dioxide and water vapor production as mass sources. The fire energy rate which has subtracted the thermal radiation loss is sourced, along with the gas sources and sinks for the fire to CV100. We used the fire start-up curve from CFAST [5]. The initial condition data from the experiment was used: room pressure of 100,927 Pa, 302.15 K, and mole fractions of 0.208 and 0.0005 for O_2 and CO_2, respectively (see [3] for details): Using the experimental pressure measurement as input, we created a control function to model this pressure drop using a "QUICK-CF" in FL 910 (see Figure 2).

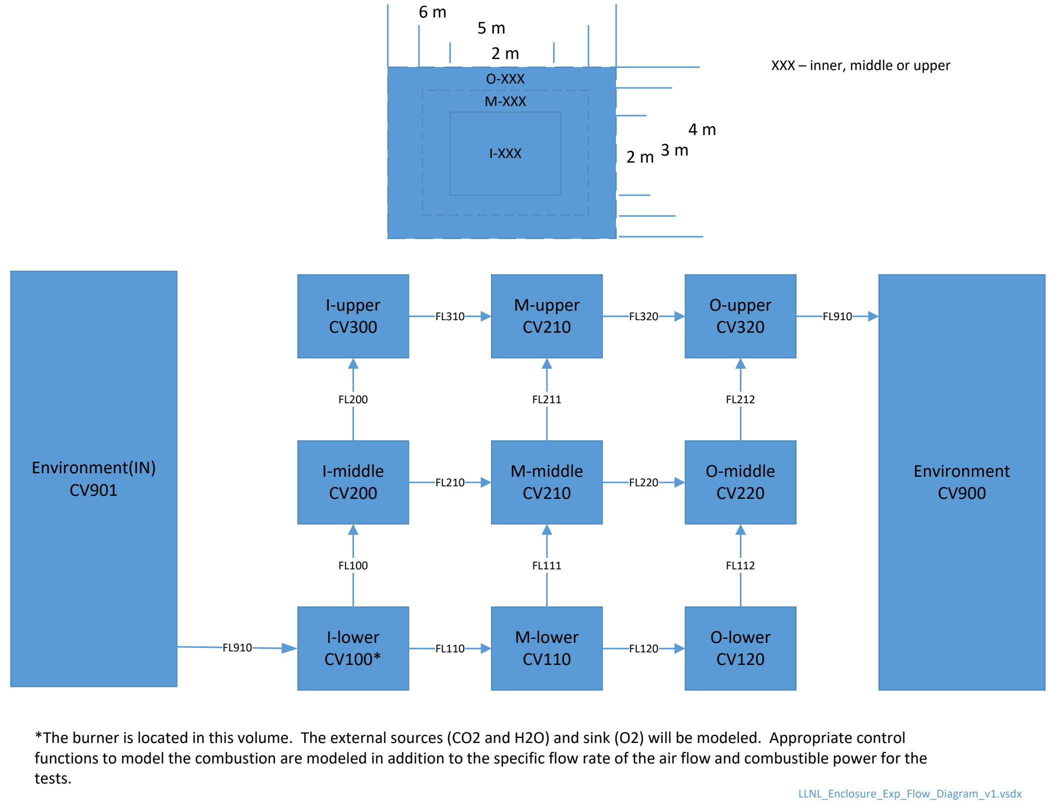

Figure 2. MELCOR 9-Volume Model for LLNL Enclosure Fire Experiment [3]

3.1.3. Results of MELCOR simulation

In the simulation, we used version 8018 of MELCOR 2.1. This version is an official release, which allows us to utilize the formula control functions. We assumed the thermal radiation loss of 20% of the fire energy. In comparison with CFAST, it assumes 35% for the thermal radiation loss. A 200 s time was used for establishing the steady state, before starting the fire at time zero. In the results, efforts have been made to compare the results of the CFAST simulations as documented in the CFAST validation report [Peacock 2016b].

The simulation for this test is based on the initial condition of pressure, temperature and gas composition in the enclosure and using the MELCOR model described above. Note that we had discovered an input error in the MELCOR after the publication of [3]. The results provided here corrected the error.
Figure 3 shows the pressure drop modeled by MELCOR for the enclosure volumes and compared to both CFAST and Experimental data. As shown in this figure, MELCOR is within the experiment data.
Figure 4 shows the calculated mass flow rate to the exhaust duct. As shown in the figure, there is an initial pulse and decay down slightly below the measured flow rate. This corresponds to the under-prediction of the pressure drop in Figure 3.

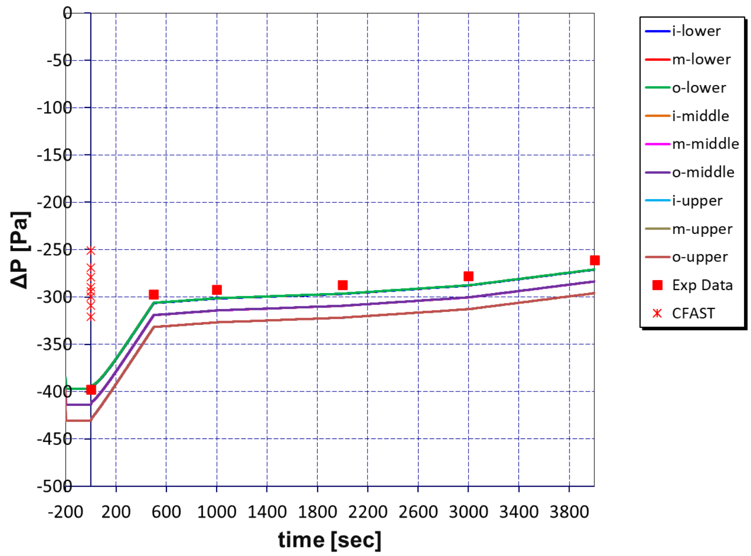

Figure 3. MELCOR Results on Pressures for Test 9.

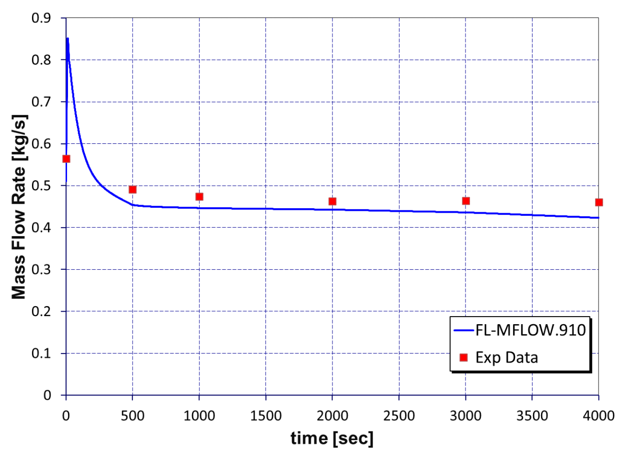

Figure 4. MELCOR Results on Exhausted Air Flow for Test 9.

In terms of temperatures, we compared three regions – lower, middle, and upper – where an average temperature of five thermocouples was used in the experiment. For the upper section as shown in Figure 3, MELCOR predicts with the experiment data while CFAST over-predicts compared to that of MELCOR and the data.

In terms of the reaction species prediction, we modeled the generation based on the discussion of the methane gas reaction in the previous sections. In comparison to the experiment data, Figure 6 shows the CO_2 mole fraction calculated by MELCOR. As shown in this figure, MELCOR under-predicts this mole fraction. A similar finding is true for the oxygen mole fraction (see Figure 7).

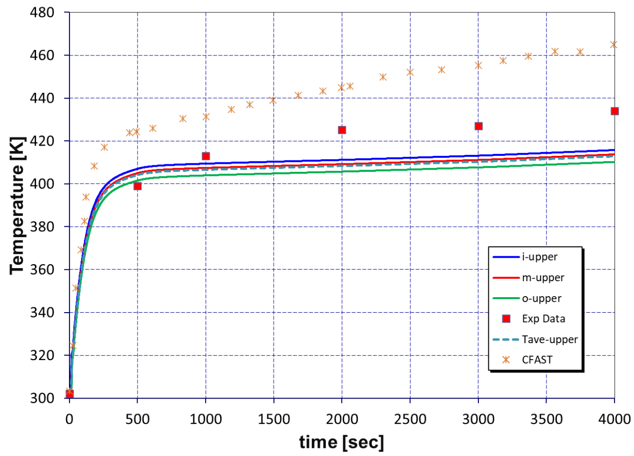

Figure 5. MELCOR Results on Upper Temperature for Test 9.

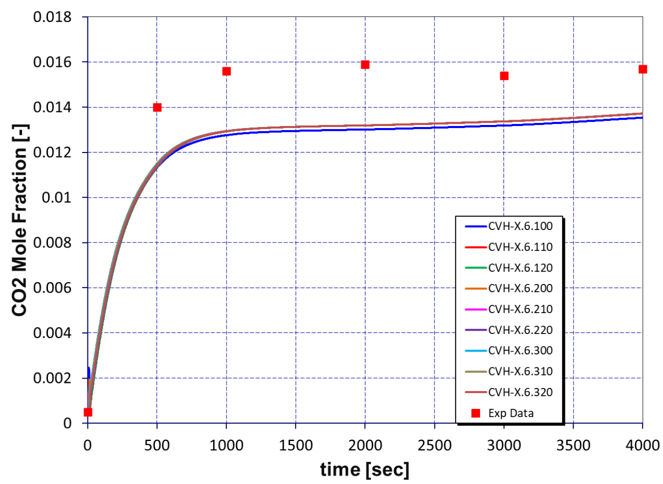

Figure 6. MELCOR Results on CO_2 Mole Fractions for Test 9

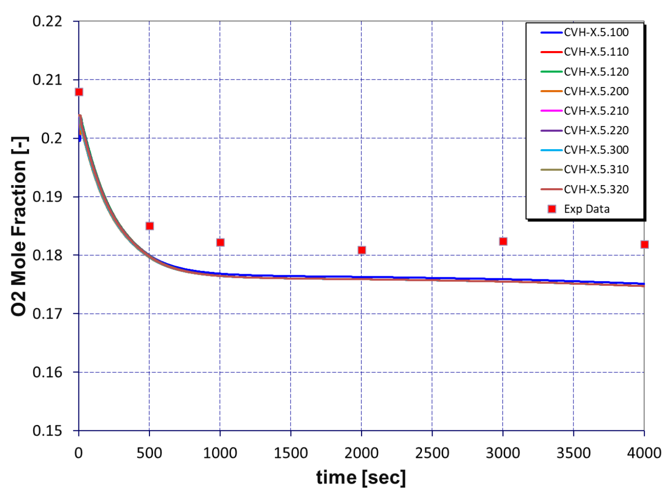

Figure 7. MELCOR Results on O_2 Mole Fractions for Test 9.

3.1.4. Summary and conclusion

For the LLNL enclosure methane gas experiment, we have demonstrated that MELCOR can be used to model the combustion reactions of methane gas for the T9 experiment. MELCOR tends to under-predict the product gas mole fraction, while MELCOR predicts the measured exhaust flow rate. In terms of temperatures, MELCOR underpredicts the hot gas layer (upper temperatures) before 1500 s but more closely later in time. In terms of comparison with CFAST, MELCOR predicts a lower hot gas layer temperature than CFAST, even though CFAST assumes a higher thermal radiation loss.

This simulation indicates that MELCOR can be used to model fire scenarios in terms of predicting the thermal-hydraulic behavior when the ventilation is operating. The models in MELCOR although allow simulation of combustible phenomena and a refined nodalization can calculate a hot gas layer.

3.2. Multi-Room Fire

In the previous section, we had demonstrated that MELCOR can be used to model a fire scenario, including the use of CFs to model the combustible phenomena of O2 consumption and the production of product gases. Since a constant air ventilation is modeled, no oxygen limit was imposed to maintain combustion. Here in this multi-room fire validation, no ventilation is modeled, and it is a closed system. Therefore, the oxygen may become limited, which will degrade combustion rate. A recent fire validation study involved with a multi-room fire test was conducted that shows MELCOR is well suited to simulate a multi-volume problem, in particularly with smoky conditions. As a part of the safety support for the safety basis group at LANL, a validation study was conducted to benchmark MELCOR for a multi-room fire experiment [7].

3.2.1. Facility Description and Instrumentation

A multi-room fire experiment from Factory Mutual Research Corporation (FM) [8] is briefly described here. The layout of the FM facility is presented in Figure 8. As shown in this figure, the experimental facility is housed inside a 67 m x 76 m x 18.3 m test building. The facility consists of a burn room (BR) where the fire is located and is shown on the top right corner of the plan view in this figure. A long corridor is connected to the BR via a doorway and the corridor is connected to two target rooms (TRs) – one is just across the BR and the other is at the end of corridor as shown in this figure. All rooms' dimensions are shown in this figure. Each room opening to the corridor is 0.88 m wide and 2.02 m high. In addition, Figure 8 shows the facility instrumentation, including the thermocouple array (8 levels), the vertical photometer array to measure the opacity of the smoke, and several wall pressures taps – at 0.39 m from the ceiling. Other measuring devices are also shown in this figure.

The combustible in this experiment is propylene, which is located at the back side of the BR. The combustion of propylene is given as below and the specific reaction heat (SRH) is 45.8 MJ/kg-propylene:

$$\mathbf{2\ C_3H_6 + 9\ O_2 \rightarrow 6\ CO_2 + 6H_2O} \quad (2)$$

With this reaction formula, the SRH, and the specified 522kW heat release rate (HRR) for test #21 of FM [8], the fire and energy release models can be formulated. The steady state fuel consumption rate can be calculated by the HRR/SRH=0.011397 kg/s. All doors are open but no windows are open.

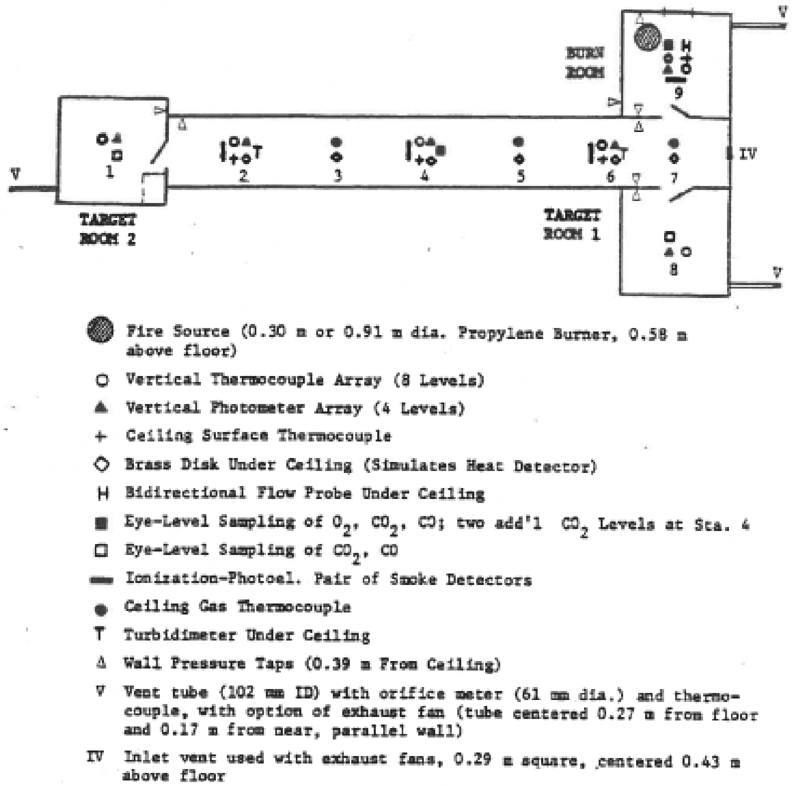

Figure 8. Schematic of FM21 with Instrumentation. Corridor measures 2.44 m x 18.9 m, and each room measures 3.65 m x 3.65 m and ceiling height of 2.44 m [8]

3.2.2. MELCOR Model

The model design for the validation study was influenced by the following hypotheses for modeling the thermal-hydraulic response:

1. Capture the thermal-hydraulic behavior of the fire in the experiment by modeling the fire combustion.
2. Simulate the hot gas layer buildup in the burn room by dividing the room into 3 horizontal control volumes (CVs) and the capture the fire area in the corner of the room. Therefore, 2 vertical CVs were modeled.
3. Capitalize the use of the countercurrent flow model within MELCOR to model the recirculating flow of the hot and cold of the air exchange in the doorway. Thus, the bottom two horizontal volumes connected to the doorway are used to model the air exchange.

To achieve the fire phenomenology described above, the MELCOR model representation of FM21 is shown in Figure 9. As shown in this figure, the burn room (BR) as Compartment 1 is being modeled with 6 CVs. A corner area consists of the fire source in the bottom CV with a total of 3 stacked vertical CVs to represent to allow for stratification (CV10x). The outside of the corner area within the BR also consists of the 3 stacked CVs. A total of 6 CVs are used to represent the BR. The fire source starts at the bottom-most CV (CV101). As mentioned before, MELCOR contains a countercurrent flow model (CCF), which models the flow exchange in a horizontal opening (required 2 flow paths – hot and cold exchange in the doorway). Similarly, the corridor and the connected target rooms (TR1 and TR2) are also represented by 3 stacked CVs (see Figure 4-2). For the corridor, there are 3 connected CVs: near, middle, and far (i.e., +3 and +5 are the boundary locations as shown in Figure 8), which indicates the region closed to the BR and far is connected to TR2. The compartment number in the nodalization is for comparison to CFAST data [8].

Only a one CCF model is used for the air exchange between the corridor and the BR. As described in the CFAST model description, the doorways are fully open during the fire and 33% of the fire energy is radiated to the surfaces in the BR. These values were adapted for the MELCOR model. In MELCOR, each surface in BR will receive the fraction of the fire energy based on its area divided by the total surfaces in the room. Since the FM21 data did not include any specification of heat structures such as walls, ceiling, and floors, the flooring data from the CFAST model is used. The floor is concrete with a thickness of 0.15 m. The walls and ceilings are made of 0.5 in (1.27 cm) thick gypsum board. The gypsum properties from the CFAST input were a heat capacity of 0.9 kJ/kg-C, density of 790 kg/m^3 and thermal conductivity of 0.16 kW/m-C.[1] In addition, we assume that the external surfaces of walls and ceilings include the heat loss to the environment, except the floors which are specified to be adiabatic. The door structures and wood frames were not modeled.

The MELCOR fire model includes the O_2 consumed and the CO_2 and H_2O production according to the combustion reaction. The initial conditions of the rooms and corridor used a humidity of 0.5, an air temperature of 288 K, O_2 and N_2 mole fractions of 0.205 and 0.795, respectively. Note CFAST used O_2 of 0.2165.

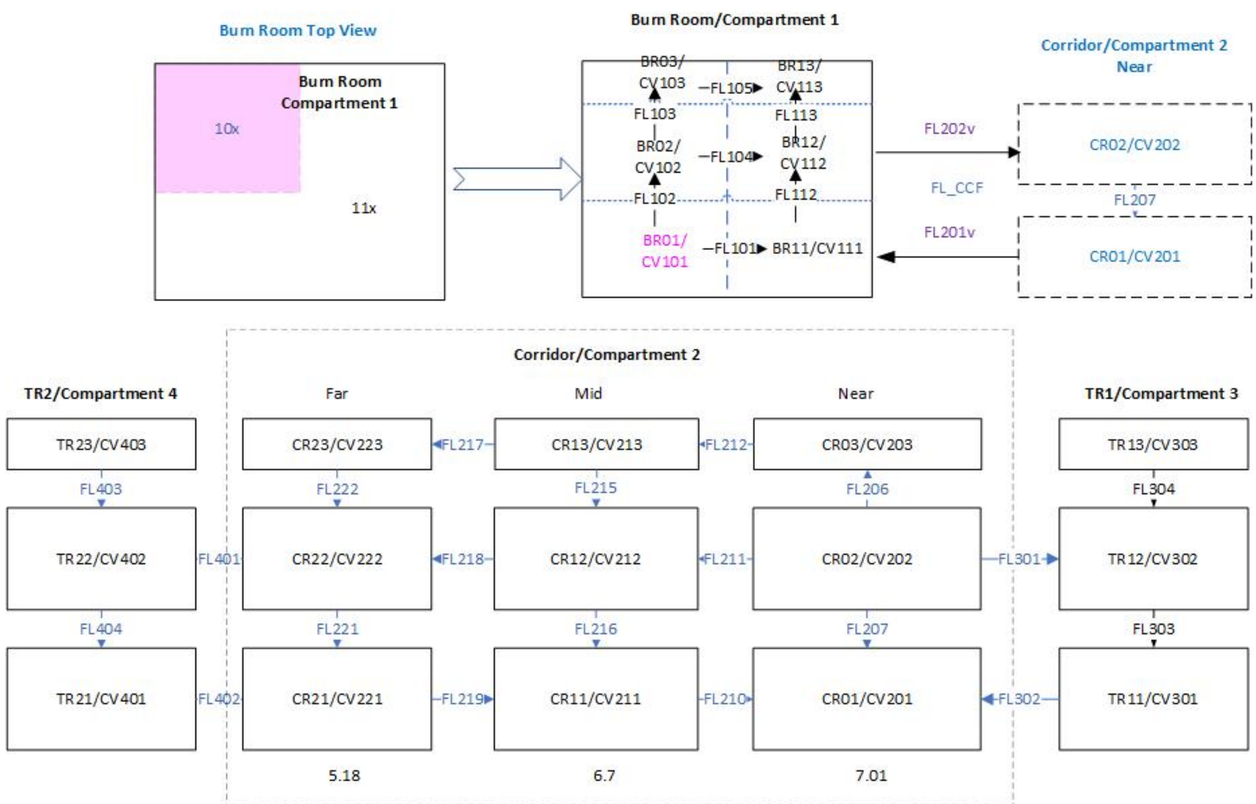

Figure 9. FM21 MELCOR CV and FL Schematics

Countercurrent flow between the fire room and corridor is a well understood phenomenology [9]. Although MELCOR is limited with fixed control volume boundaries, it can model the counter-current flow exchange between the fire room and corridor by the use of the FL_CCF physic package. The CCF model is represented in the following equation as:

[1] https://github.com/firemodels/cfast/blob/master/Validation/FM_NBS/FM21.in

$$Q_{cc} = X_{cc} C_D \sqrt{\frac{l^5 g \Delta\rho}{\bar{\rho}}} \quad (3)$$

Q_{cc}=volumetric flow of pure countercurrent flow (m^3/s), X_{cc}=a coefficient which is a function of the orientation and geometry of the opening, such as square versus round, C_D=discharge coefficient, l=characteristic dimension such as the opening height (m), g= gravity (m^2/s), $\Delta\rho$=density difference (kg/m^3), and $\bar{\rho}$=average density (kg/m^3). X_{cc}=0.3333 for a rectangle doorway. For a perfect exchange of flow in a doorway, the upper flow (generally hot) should be equal to the lower flow (generally cold). Thus, the net flow should be zero. As shown the above equation, the magnitude of the countercurrent flow, Q_{cc}, is a linear function of the discharge coefficient, C_D. The CCF flow is also a function of the donor (or upstream) density.

Only the thermal-hydraulic validation of MELCOR is discussed here. The aerosol transport results from MELCOR for the smoke experimental data is documented in Ref. [7].

3.2.3. Discussion and results

MELCOR (Version 2.2.9541) for the FM 21 simulations. Four calculations were performed to examine the effect of the discharge coefficient, C_D in Equation (3) and the amount of radiation heat loss to the heat structure or surfaces from the combustion. The details of these runs are described in [7]. Here we only show the run that provided the best match to the experimental data. A 33% fire radiative loss heat loss to surfaces is used, which is consistent with the analysis done in the CFAST calculation. The discharge coefficient, C_D=0.5, is CCF in this calculation. Figure 10 shows the gas velocities at doorways. As shown in this figure, the upper flow path of the doorway tends to have a higher velocity compared to the lower flow paths. This explained by the two stream's density differences. However, the mass flow into and out of BR is conserved.

As shown in Figure 11, the mole fraction of oxygen in the BR is slightly decreased. MELCOR closely matched the experimental data, while CFAST is underpredicted the BR mole fraction after the burn has started. This calculation assumed that the combustion remains active when the oxygen mole fraction remains above 0.1. In most many situations, the oxygen volume fraction (or mole fraction if ideal gas) to sustain combustion is >10%. In some cases, as much as > 15% may be required to sustain a burn [6]. Figure 12 and Figure 13 show the BR gas temperature and pressure drop at the BR doorway, respectively. As shown in Figure 12, this calculation closely matches the experiment data and CFAST results. Similarly, the pressure drop result agrees with the experimental data as shown in Figure 13. Any increase of heat loss may not be substantiated. Increasing or decreasing the discharge coefficient from C_D=0.5 did not result a better agreement to CFAST or experimental data; increasing C_D would yield a better BR temperature match only, whereas, decreasing this value yields a much higher BR temperature because of the slower flow.

3.2.4. Summary and conclusion

This section summarizes the validation work on MELCOR for modeling a multiroom fire with a corridor. This validation work demonstrates that MELCOR can be used for modeling a fire source term, even though it lacks a specialized hot gas layer model. Furthermore, the sensitivity studies provide insight on the effect and the use of the CCF model from the FL package for better modeling of the countercurrent flow in the fire room and the adjacent opening area.

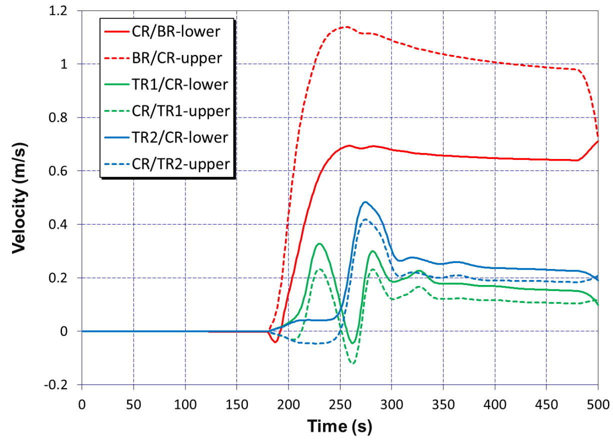

Figure 10. MELCOR Results in Gas Velocities at Doorways. Upper door flows as shown as dashed lines, while lower door flows as solid lines.

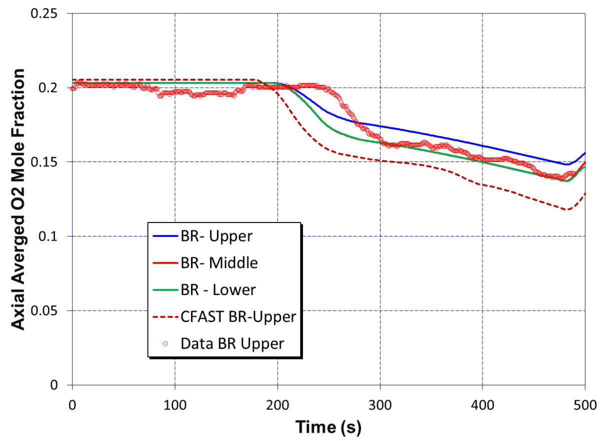

Figure 11. MELCOR Results in O_2 Mole Fraction.

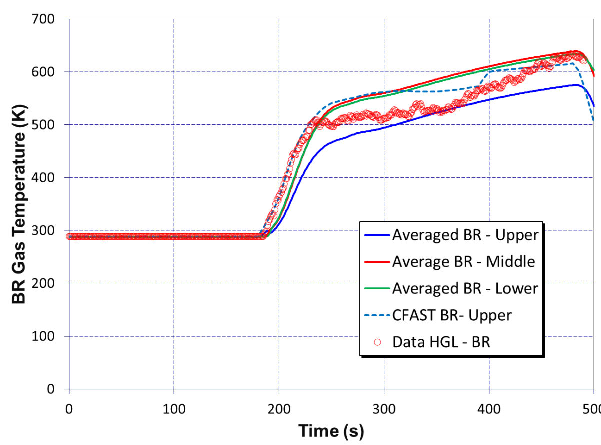

Figure 12. MELCOR Results on BR Gas Temperatures

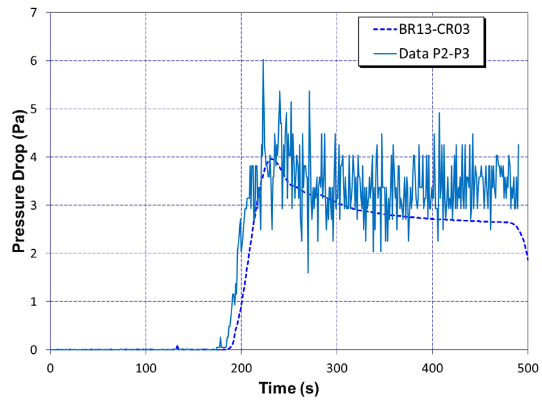

Figure 13. MELCOR Results on Pressure Drop between BR and Corridor.

4. SPENT FUEL REPROCESSING DEMONSTRATION

In the previous section, the validation studies were provided to show that MELCOR can be used to model fire scenarios adequately based on a single and a multi-room fire experiment. Here we are providing a demonstration calculation summary using MELCOR for a spent fuel reprocessing facility, Barnwell Nuclear Fuel Plant (BNFP) [10]. In Ref. [10], it discusses a number of sensitivity studies on both fire and explosion that could occur in an aqueous reprocessing plant such as BNFP. The objective of this study was to develop methods and modeling experience with MELCOR that is applied to non-reactor nuclear facilities, in particularly a large processing facility such as BNFP. The solvent used at the facility can cause chemical fire and red oil explosion, including the fission product source term. However, we only briefly discuss the thermal-hydraulic responses for the fire scenario [10]. The layout of the BNFP is given in Figure 14. As shown in this figure, the BNFP contains a number of rooms, process cells, galleries, and corridors with multiple levels. More detailed layouts are given in [10].

4.1. MELCOR Model

The BNFP MELCOR model uses at least one control volume for each significant room or gallery. Each of the larger rooms or galleries are subdivided into multiple control volumes. For example, the longer piping galleries are subdivided into three control volumes connected lengthwise. The model development focused on the five process cells, the filter niche (FN), and the piping galleries where an accidental release of fission products would most likely occur. The BNFP MELCOR model has 208 control volumes, 354 flow paths, and 294 heat structures. All the connecting passageways and doorways are simulated with flow paths. The doorways are closed but allow leakage flows above and below the door. There are five full height stairwells associated with the main process building. Each of these stairwells are subdivided into vertically stacked volumes corresponding to various floor levels connecting to the stairwell and with doorways connecting each stairwell to each floor level. The BNFP MELCOR model includes control volumes and flow paths to represent key sections of the ventilation ductwork. The main supply airflow enters the ventilation system via the blower station (BS) located on top of an adjacent building. The lower enclosed level of the BS building is the ventilation filter station containing the final exhaust filters. Tuning of the MELCOR model and source term models are not discussed here. Readers should refer to [10] for details.

4.2. Fire Simulation Summary and Conclusion

In this simulation study, many fire scenarios were modeled as a sensitivity study. The organic solvent used in the liquid extraction method is typically composed of 30%/n-dodecane (or kerosene). Kerosene is composed of hydrocarbon chains. MELCOR model includes the control functions to represent the combustion of dodecane for fire scenarios up to 169 MW. Figure 15 shows a temperature response in the HILC during a solvent fire scenario (see the location of HILC in Figure 14). The fire room is subdivided into a number of control volumes to capture the stratification of a fire. Consequently, the fires burn longer at an oxygen-limited rate until the solvent was consumed. The initial rapid heat up of the air from the fire pressurized the hot cell room and failed ventilation dampers to the room.

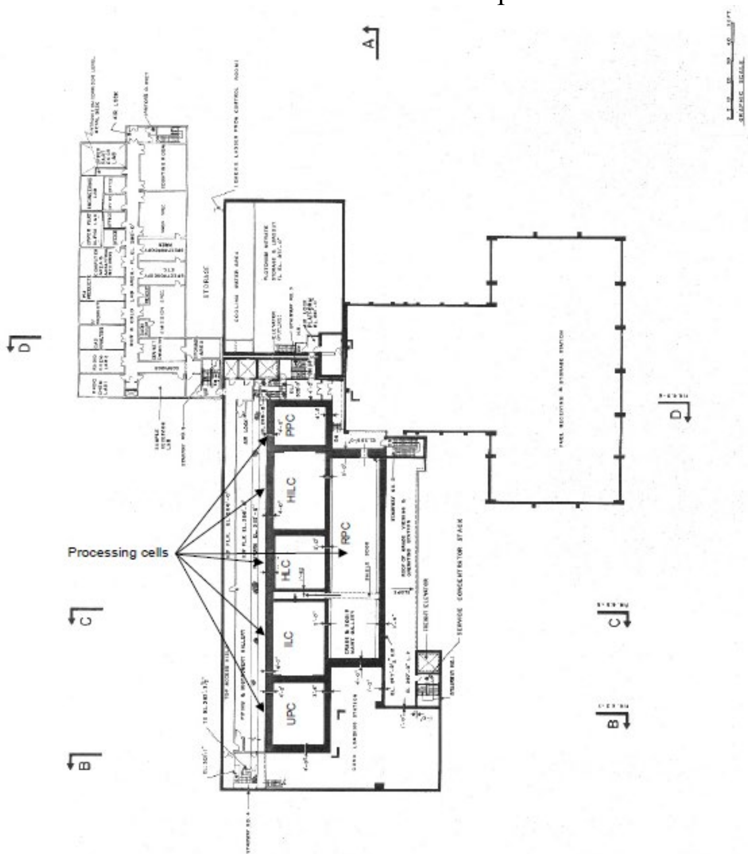

Figure 14. Layout of the BNFP [10]

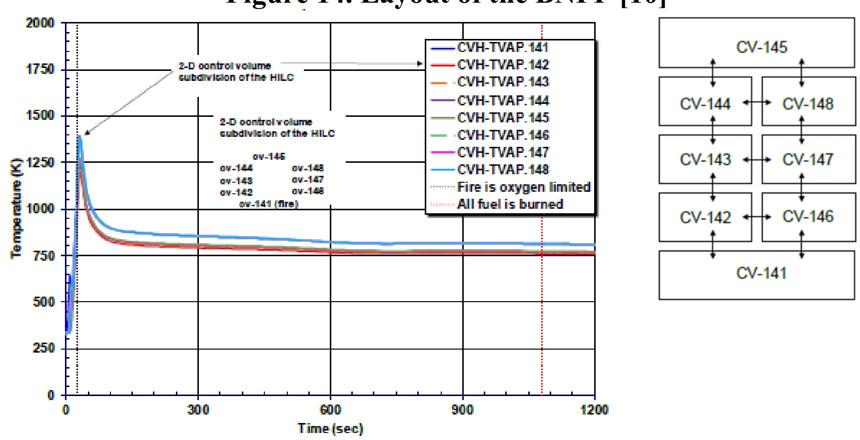

Figure 15. Temperature Distribution in the HILC during Solvent Fire Scenario

5. CONCLUSIONS

This paper presents a range of validation studies used to benchmark MELCOR's capability to characterize fire scenarios at nuclear facilities. The ability to model combustion of flammable material, the progression of a fire, and the depletion of oxygen necessary to maintain a combustion reaction represent important features of MELCOR for application to these types of scenarios. The validation results show that MELCOR can model a multi-room fire well, exhibiting good agreement between simulation results and experimental data. A demonstration calculation for the BNFP has shown that MELCOR can model the most complicated facilities with a large number of rooms and corridors, a severe fire (i.e., large fire sizes), and enable the detailed representation of a complicated ventilation system.

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REFERENCES

1. L.L. Humphries, et al., **MELCOR Computer Code Manuals- Vol.1: MELCOR Primer and Users Guide, Version 2.1 6840 2015**, SAND2015-6691 R, Sandia National Laboratories, Albuquerque, NM, August 2015.
2. L.L. Humphries, et al., **MELCOR Computer Code Manuals-Vol.3: MELCOR Assessment Problems, Version 2.1 6850 2015,** SAND2015-6693 R, Sandia National Laboratories, Albuquerque, NM, August 2015.
3. D.L.Y. Louie, et al., NSRD-10: **Leak Path Factor Guidance Using MELCOR**, SAND2017-3200, Sandia National Laboratories, Albuquerque, NM, March 2017.
4. R.D. Peacock, et al., **CFAST-Consolidated Fire And Smoke Transport (Version 7) Volume 2: User's Guide,** NIST Technical Note 1889v3, CFST Version 7.1.0, GIT Revision: Gitv7.1-0-g7ea5756, U.S. Department of Commerce, National Institute of Standards and Technology, April 2016.
5. R.D. Peacock, et al., **CFAST-Consolidated Fire And Smoke Transport (Version 7) Volume 3: Verification and Validation Guide,** NIST Technical Note 1889v3, CFST Version 7.1.0, GIT Revision: Gitv7.1-0-g7ea5756, U.S. Department of Commerce, National Institute of Standards and Technology, April 2016.
6. NFPA, **The SFPE Handbook of Fire Protection Engineering**, 2nd Edition, National Fire Protection Association, Quincy, MA 1995.
7. D.L.Y. Louie, et. al., "MELCOR Validation Study on Multi-Room Fire," Proceedings of the 2020 Power Virtual Conference, ASME, August 4-5, 2020.
8. G. Heskestad, et .al, **Experimental Fires in Multiroom/Corridor Enclosures, FMRC J.I. 0J2N8.RU**, NBS-GCR-86-502, Factory Mutual Research Corporation, Norwood, MA, October 1985.
9. M. Hurley, **SFPE Handbook of Fire Protection Engineering 5th Edition**. Springer, 2016.
10. K.C. Wagner, et al., **MELCOR Modeling of Accident Scenarios at a Facility for Aqueous Reprocessing Fuel,** NUREG/CR-7266, U.S. Nuclear Regulatory Commission, January 2020.