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MELCOR DEMONSTRATION ANALYSIS OF ACCIDENT SCENARIOS AT A SPENT NUCLEAR REPROCESSING PLANT

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ABSTRACT

The work presented in this paper applies the MELCOR code developed at Sandia National Laboratories to evaluate the source terms from potential accidents in non-reactor nuclear facilities. The present approach provides an integrated source term approach that would be well-suited for uncertainty analysis and probabilistic risk assessments. MELCOR is used to predict the thermal-hydraulic conditions during fires or explosions that includes a release of radionuclides. The radionuclides are tracked throughout the facility from the initiating event to predict the time-dependent source term to the environment for subsequent dose or consequence evaluations. In this paper, we discuss the MELCOR input model development and the evaluation of the potential source terms from the dominated fire and explosion scenarios for a spent fuel nuclear reprocessing plant.

Keywords: MELCOR, reprocessing, fire, aerosol transport, source term

NOMENCLATURE

AFS	Analytical Filter Station
ARF	Airborne Release Fraction
BNFP	Barnwell Nuclear Fuel Plant
FSAR	Final Safety Analysis Report
HILC	High Intermediate Level Cell
HLC	High Level Cell
ILC	Intermediate Level Cell
LPF	Leak Path Factor
NRC	U. S. Nuclear Regulatory Commission
PPC	Plutonium Product Cell
RF	Release Factor
RPC	Remote Process Cell
SCFM	Standard Cubic Feet per Minute
SNL	Sandia National Laboratories
TBP	Tributyl Phosphate
VFS	Ventilation Filter Station

1. INTRODUCTION

Sandia National Laboratories (SNL) under sponsorship by the U.S. Nuclear Regulatory Commission (NRC) has been developing capabilities to simulate accidents in nuclear facilities other than the current fleet of light-water reactors. The work presented in this paper supports the advancement of NRC's safety assessment capabilities in terms of evaluating accidents that could release radioactivity into the environment from a non-reactor nuclear facility with a large inventory of mixed radionuclides, such as a nuclear spent fuel reprocessing facility. Unlike in a reactor facility that includes a containment barrier for a radionuclide release, a reprocessing facility the large inventory of radioactive materials uses administrative controls, a filter and ventilation system, and other safety feature to retain a radionuclide release in the building. Due to the presence of combustible materials and potential explosion accidents, it is important to evaluate the confinement structure that could withstand such accidents. This paper uses the historical facility design basis accidents (DBAs), which were considered serious but credible accidents to determine the effectiveness of various lines of defense within the facility. The DBAs establish and allow assessment of safety-related structures, systems, and components and items important to safety

Previously, SNL characterized accident phenomena related to spent fuel reprocessing, which was documented in NUREG/CR-7232 [1]. The report included the status of past and current reprocessing facilities throughout the world, an overview of the reprocessing plant design and processes, the historical accidents and phenomena, and the models needed to describe the accidents. NUREG/CR-7232 provides the background and concepts needed to construct a computational model to predict reprocessing facility source terms. As part of the previous work, a MELCOR demonstration model was built based on the Barnwell Nuclear Fuel Plant (BNFP) [2]. MELCOR is NRC's fully integrated, engineering level computer code that models the progression of severe accidents in nuclear power plants [3]. The

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BNFP was the first large scale commercial reprocessing facility in the U.S. but was decommissioned before being operated. The MELCOR model was developed using available historical drawings and tested for four postulated fire and explosion accident scenarios. The previous project demonstrated analytical techniques needed to apply the MELCOR code in safety assessments of a large non-reactor nuclear facility with significant radioactive materials. The current project, as described herein builds on the previous MELCOR work to predict the source terms from a range of spent fuel reprocessing fire and explosion accidents that include the DBA from the Barnwell Final Safety Analysis Report (FSAR) [4].

The BNFP MELCOR model simulates the various BNFP pressure zones so that the air flows from the least radioactive (or non-radioactive) areas to the most radioactive areas. The building air flows are sent through a filtration process before being vented into the environment via a tall stack. The model was carefully balanced to accurately represent the room pressures and ventilation flows in the BNFP. The previous MELCOR BNFP accident analyses used trace amounts of radionuclides to estimate conservative leak path factors (LPFs) [5], which is a measured of fraction of radionuclide source term from the facility to the environment [2]. The model was enhanced for the current project to include representative accident radionuclide inventories based on ORIGEN calculations of commercial spent nuclear fuel [6]. The facility models were also expanded to include ventilation, filtration, and structural failures as well as filter degradation due to high temperatures and soot loading. A detailed description of the model is given in Section 3.

The results of the analysis predict the radionuclide activity distributed through the facility and to the environment. The resultant activities can be used as source terms to predict the maximum dose at the site boundary or the offsite dose to the public. Ten accident scenarios were specified to span a range of explosion and fire energies using realistic masses of chemicals and radionuclides (source terms). Five of the accident scenarios were based on the Class 5 Design Basis Accidents from the FSAR, which included three red oil explosions and two solvent fires [1]. The explosion scenarios fell within estimated ranges of historical events (e.g., 50 to 700 MJ) that occurred at reprocessing facilities throughout the world. Three of the remaining five accident scenarios include sensitivity studies on smaller solvent fires. The final two accidents included an induced fire from an initial explosion. A detailed description of the accident scenarios is provided in Section 4. The results of the accident scenarios are summarized in Section 5. The results discuss the source term to the environment, the building decontamination factor, and the distribution of radionuclides in the building. The results of the first five scenarios MELCOR calculations are also compared to the BNFP FSAR results. A summary of the results and findings is provided in Section 6.

The detailed MELCOR results can be coupled to the MACCS code to evaluate the offsite doses [7]. Due to the nature of the initiating events and pathways included in present analysis, only an airborne release is predicted. Furthermore, only respirable size aerosols are transported to the environment (i.e., a long distance to leakage locations and filters). However, the full characterization of the aerosol size distribution is retained for the subsequent variable settling rate in the environment (i.e., the best-estimate methodology using MELCOR and MACCS).

2. BNFP MELCOR MODEL DESCRIPTION

In the previous work associated with NUREG/CR-7323, a MELCOR model of a nuclear fuel reprocessing plant was developed using available historical information of the BNFP [3].

The scope of the BNFP MELCOR model includes all the process cells and the surrounding rooms in the facility as well as the ventilation and filtration system. However, there is no representation of the chemical reprocessing processes and the associated chemical flows in the hot cells and piping galleries. Similarly, off-gassing from the operational chemical processes and the subsequent filtration of those gases are not modeled in the MELCOR model. Instead, the model is designed to simulate radiative release from the accident scenarios associated with the various chemical processes.

The MELCOR model was balanced to simulate the operational airflows and controlled pressure zones through the facility. The BNFP is designed with pressure zones so that the air flows from the least radioactive (or non-radioactive) areas to the most radioactive areas and then through a filtration process to clean the air before it is reintroduced into the environment via a tall stack. A key challenge was the development of the control techniques needed to model the facility airflows and room pressures to match the facility design and/or operational flow and pressure data. Once the model was stabilized to the desired initial conditions, explosion and fire accidents are simulated to evaluate the accident source terms. Some of the special non-reactor facility MELCOR models are described in the following sub-sections.

2.1 BNFP MELCOR Model Description

Figure 1 shows the layout of the BNFP building. The BNFP MELCOR model uses at least one control volume for each significant area or gallery. Each of the larger areas 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 various hot cells are identified in FIGURE 1. Each of the hot cells is a relatively narrow chamber 15.8 m (52-ft) high. The hot cells are subdivided into five vertically stacked control volumes with supply air entering at the top and exiting near the bottom except when simulating an accident. When a scenario included a fire or explosion in a hot cell, the room was further subdivided into a two dimensional control volume nodalization capable of simulating thermally driven countercurrent flows. This included the Intermediate Level Cell (ILC), the High

Intermediate Level Cell (HILC), the Remote Processing Cell (RPC), and the Plutonium Product Cell (PPC).

The outer buildings, including the fuel receiving and storage station (FRSS), the waste tank equipment gallery (WTEG), and the plutonium nitrate storage and load out (PNSL) area used a single control volume representation so their respective airflows could be included in the overall flow networks. 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, except for some portions of Stairwell 4, which was connected to major open areas. A smaller stairwell connected the filter piping and instrumentation gallery (FPIG) to the waste tank pipe vault (WTPV) and another stairwell connecting the lower and upper floors of the hot and cold lab analysis (HCLA) building.

2.2 Model Airflows and Pressures

The supply and exhaust airflow diagrams are shown in FIGURE 2 and FIGURE 3, respectively. The various rooms are colored according to their design pressures (i.e., see the color code in Figure 3). The number beside each room is the supply or exhaust airflow. The emphasis of the model nodalization is the hot cells (UPC, ILC, HLC, HILC, PPC, and RPC), the filter niche (FN), and the supporting piping galleries (FPIG, LPIG, and TPIG). The outer buildings (buildings other than the main process building) used a simpler nodalization so their respective airflows could be incorporated into the overall airflow model. All accident scenarios are initiated inside a hot cell and not expected to significantly involve the outer buildings. The airflows are in standard cubic feet per minute units (scfm), which is effectively mass flow due to the standard density scaling.

The main process building has a large fan that supplies 95,000 scfm. No performance information for the main process building fan was available. Consequently, a constant inlet flow is specified to simulate the supply air, which also simplified overall building flow and pressure balance.

The two main exhaust blower fans are simulated using fan head curves rather than a specified flow. The exhaust fans are part of the final filtration stage, designated as Filters 1 and 2 in FIGURE 3. Filters 1 and 2 are modeled using separate control volumes for the inlet plenum, the ventilation duct between the roughing pre filters and the HEPA filters, and the exhaust plenum between the HEPA filters and the fans. The BNFP design included two parallel banks of filters with two operating fans drawing airflow and a third fan in reserve. The two filter banks and two fans are combined in the model into a single unit. The other filters shown in Figure 3 included a roughing pre-filter and a HEPA filter but did not have a fan. All airflows from the main process building passed through at least two stages of HEPA filters. The exhaust flows from Filters 1 and 2 are combined into a single flow through a long horizontal pipe to a 100 meter stack for discharge into the atmosphere.

2.3 Decay Heat and Radionuclide Inventory

Decay power and inventory information are required input for BNFP source term accident simulations. The ORIGEN-S and Automatic Rapid Processing (ARP) from the SCALE 6.1.3 code package [6] was used to evaluate the required input. The ARP module allows for burnup dependent (i.e., problem dependent) cross sections to be used in the ORIGEN S calculations. The ARP data libraries can be supplied via the TRITON sequence in SCALE. The methodology to obtain the data is described in Reference [8] but slightly adopted for spent fuel rather than a reactor core inventory.

The ORIGEN S calculations used representative PWR fuel with an initial enrichment of 4.5% U 235 by weight. The inventory and decay heat quantities reflect PWR spent fuel with 5 years of decay following the final 500 day irradiation cycle. Two previous irradiation cycles are assumed before the final cycle, which are separated by 30 day decay periods to approximate refueling outages. A 60 GWd/t fuel assembly burn up data was used to conservatively bound current U.S. reactor practices.

The nuclide level inventory used in the analysis includes all nuclides tracked by ORIGEN-S. All stable and radioactive nuclides greater than 10^{-9} g/t after 5 years of decay time are retained. The stable nuclides are included in the list given their significance to MELCOR Radionuclide Package class masses (i.e., most lumped class masses are dominated by stable or long lived nuclides). Since an explosion or fire will release both stable and radioactive nuclides, using both stable and radioactive nuclides better reflect the total released inventory and its impact on the aerosol physics. 323 nuclides are retained from the ORIGEN-S calculations.

The input required for the BNFP safety analysis combines the decay heat, mass, and activity data from the 323 nuclides into MELCOR's 12 radionuclide classes (see Table 1). MELCOR uses the specific decay heat (i.e., W/kg) to predict the radionuclide decay heating. Consequently, the decay heat power in each control volume is determined based on the mass from the 12 radionuclide classes times the specific decay heat per class. Other parametric models apportion the decay heat deposition from the radionuclides to the gas and surfaces in the room. User specified logic was developed to track the activity distribution within and released from the facility.

2.4 Ventilation and Filtration Mechanical failures

High pressure conditions are developed in the accident scenarios due to the explosion or fire. The ventilation and filter systems are robust during normal operating conditions and for a range of accident conditions. However, the Class 5 design basis accidents include large explosions and large fires that challenge the ventilation and filtration system. The filter media and ventilation dampers would experience high pressures and temperatures.

Experimental testing of HEPA filters under simulated tornado conditions was used to develop reasonable criteria for their failure due to large differential pressures [9]. Nuclear grade HEPA filters were tested to failure under large differential pressures. A range of nuclear grade filter designs were considered. The mean break pressure was 2.87 psid with a low value near 1.31 psid. The test results were not sensitive to the pressurization rate or the flow duration. The limiting break pressure with a 95% confidence limit is 3.45 kPa (1.5 psid), which is used in these calculations.

There was very little information available on the roughing filters protecting the HEPA filters in BNFP. It is assumed the BNFP roughing filters failed at the same differential pressure as the HEPA filter. The pressure drop across the roughing filter is considered separately in the MELCOR BNFP model. Consequently, the differential pressure must exceed 1.5 psid across the roughing and HEPA filters separately for their failure.

All filter and ventilation failures described in this section resulted in a fully open pathway where the previous restriction to flow was removed. For example, the flow resistance due to the HEPA material was replaced with an open space. Likewise, the partially open dampers were replaced with an open space. The new configuration reduced the flow resistance and increased flow to downstream locations.

2.5 Thermal Failure of HEPA Filters

The BNFP FSAR had limited information on the design specifications of the filters. Nuclear grade filters have design criteria for pressure drop, temperature range, and humidity range. In a conservative safety analysis, the filter may be considered failed when design limits are exceeded. A best estimate approach was used for the thermal failure criteria.

It was difficult to find thermal HEPA filter testing data. The DOE handbook (DOE-HDBK-3010, [5]) for airborne release from nonreactor nuclear facilities cites tests where HEPA filters resisted temperatures as high as 825°C for tens of minutes before a loss of efficiency and 500°C for more than 45 min [5]. The handbook further cites that the fine diameter glass fiber softens and melts when heated. The hot material tends to retain captured materials adhering to the fibers. The reported thermal airborne release fraction (ARF) at high temperatures is very low (e.g., ARF=10^{-4}). The filters show very low release rates at temperatures below that required to induce failure (up to 400°C).

Based on this limited information from the DOE Handbook, a parametric thermal failure model was developed for the MELCOR model. Each filter in the MELCOR model monitored the gas temperature entering the filter and calculated the cumulative timing to failure.

Once the thermal failure limit is reached, the filter (a) releases some radioactive material (ARF=10^{-4}, [5]), (b) stops capturing aerosols, and (c) has no more flow resistance.

2.6 Plugging of HEPA Filters

Large quantities of soot can be released during fire from the solvent due to an incomplete reaction with oxygen. As soot and radionuclides are released from the fire and transported to the HEPA filter, the accumulation of particles on the filter will increase the flow resistance. The increased flow resistance of a HEPA filter due to particulate loading has been characterized experimentally [10].

The particle dependent flow losses are applied to the HEPA filters in the BNFP model. As the HEPA filters load with radionuclide particulates and soot from a fire, the flow resistance increases. If the increased flow resistance causes the filter pressure drop to exceed the failure pressure of the HEPA filter, then the filter will fail (see Section 2.4). The mechanical failure of the HEPA filter uses the same airborne release fraction as the thermal failure cited in Section 2.5 (i.e., 10^{-4} from Reference [5]).

2.7 HEPA and Rough Filter Effectiveness

The BNFP roughing pre filter and HEPA efficiencies are reported as 80 to 85% and 99.9%, respectively [1]. The cited filter efficiencies in the FSAR did not include a minimum particle size effectiveness. However, the DOE Handbook states HEPA filters have reduced filtering effectiveness for particles smaller than 0.3 micron [5], which is incorporated into the current analysis. Consequently, aerosols smaller than 0.3 microns pass through the HEPA filter.

The BNFP FSAR DBA safety analyses used slightly different assumptions on the HEPA filter effectiveness. The design basis accidents assumed an aerosol transmission factor of 0.0014. The effective retention is the compliment of the aerosol transmission factor, or 0.9986 (i.e., compares well with the documented effectiveness of 99.9%). The effective decontamination factor is the reciprocal of the aerosol transmission factor, or 714.3. The MELCOR analyses use the FSAR HEPA decontamination factor for larger aerosols (i.e., 714.3) and no retention for aerosols smaller than 0.3 microns.

There were very limited design specifications for roughing pre filters. The roughing filters were specified to use an aerosol retention of 0.825, or a decontamination factor of 5.7. It was assumed the roughing filters were ineffective at filtering aerosols smaller than 1 micron.

All radioactive gases are assumed to pass through the filters. This includes noble gases, gaseous iodine, and volatile ruthenium. The FSAR safety analyses estimated 0.1% of the ruthenium is volatile in an explosion and 10% during a fire.

2.8 Building Structural Failures

Explosion Scenarios 1 and 9 included a large pressure rise and shock wave that was assumed to damage the Remote Processing Cell (RPC) wall. The severe consequences from this scenario specification were used to explore the consequences from an explosive event that damaged internal structures in the BNFP but did not breach a direct pathway to the environment. A detailed integrated explosion and structural calculation was beyond the scope of this project. However, a review of the plant drawings showed two viewing penetrations between 270' 6" and 279' to the filter niche region. It was assumed the RPC penetrations breached at these locations at the maximum pressure in the MELCOR simulation.

2.9 Fire Modeling

The fire modeling included the fire heat sources and the associated chemical reactions. The radionuclides and soot were released uniformly with the consumption of the solvent. The large fires in DBA Scenarios 2 and 4 were assumed to start up over a period of 60 seconds. DBA Scenario 2 is a very large fire (50 m^2, with a diameter of 8.0 m) and a maximum power of 85 MW. DBA Scenario 4 is even larger (100 m^2, diameter of 11.3 m) and a maximum power of 169 MW. The remaining fires were considerably smaller (i.e., <17 MW) and were assumed to start up over 10 seconds.

All fires had the potential to consume oxygen below the concentration where the fire could burn at full power. It was assumed that the fire would be oxygen limited according to Equation (2).

$$\dot{\boldsymbol{m}}_{o2} = \dot{\boldsymbol{m}}_{max} * \boldsymbol{min}\left[\frac{(X_{o2}-X_{no\ burn})}{(X_{limited}-X_{no\ burn})}, \mathbf{1}\right] \qquad (2)$$

where,

$\dot{m}_{o2}$	Burn rate as a function of the local oxygen concentration near the fire, X_{o2}
$\dot{m}_{max}$	Maximum burn rate with ample oxygen
X_{o2}	Oxygen mole fraction near the fire
$X_{limited}$	Oxygen mole fraction at which the fire becomes oxygen-limited, assumed to be 11%
$X_{no\ burn}$	Oxygen mole fraction where the fire will extinguish, assumed to be 5%

3. ACCIDENT SCENARIOS

Ten accident scenarios are defined that provide a range of thermal and explosive challenges to the facility. The first five source terms are based on the Class 5 design basis accidents in the BNFP FSAR [4]. The remaining five accident scenarios are sensitivity studies of fire duration and/or combinations of explosions with fires. The explosions assume rapid chemical reactions from the decomposition of tributyl phosphate (TBP) with nitric acid or other constituents at elevated temperatures (i.e., a "red oil" explosion). The fires involve combustion of the solvent used in the reprocessing process.

3.1 Solvent Fires

The organic solvent used in the liquid extraction method is typically composed of 30%/n-dodecane (or kerosene). Kerosene is composed of hydrocarbon chains, which contain 10 to 16 carbon atoms per molecule. A chemical formula for a complete reaction for dodecane is:

$$C_{12}H_{26}(l) + 18.5O_2 \rightarrow 12CO_2 + 13H_2O \qquad (3)$$

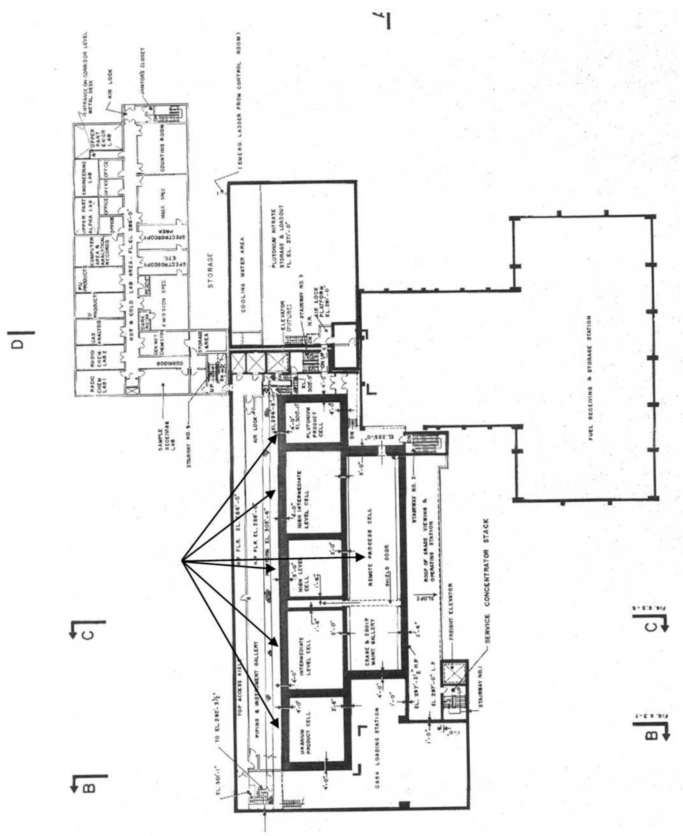

FIGURE 1: TOP VIEW OF OVERALL PROCESS BUILDINGS AT ELEVATIONS 85 M (279'-0") TO 90.5 M (297'-0") (HIGHEST FLOOR LEVEL) [4].

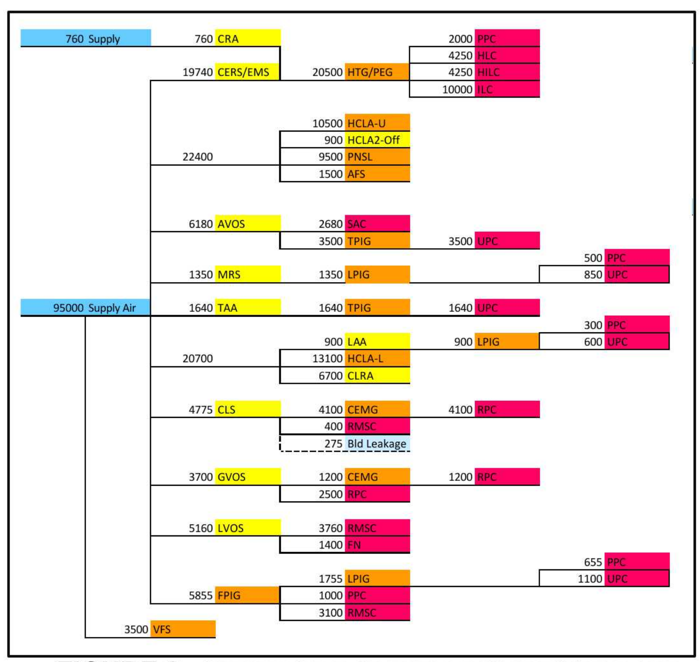

FIGURE 2: SUPPLY SIDE OF BUILDING PRESSURE AND AIRFLOW DIAGRAM [2].[2]

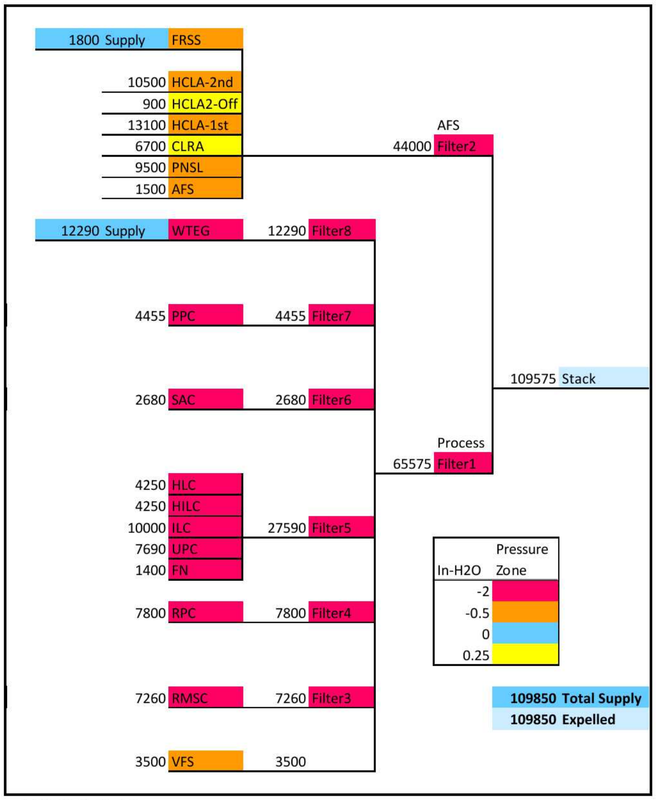

FIGURE 3: EXHAUST SIDE OF BUILDING PRESSURE AND AIRFLOW DIAGRAM [2]. [2]

3.2 Red Oil Explosions

Red oil explosions are a major concern in spent fuel reprocessing plants and other nuclear chemical processing facilities. The Defense Nuclear Facilities Safety Board (DNFSB)'s TECH-33 report [11] describes the importance of red oil explosions following the accident at Tomsk-7 in 1993. The report describes generic controls that are necessary to prevent a red oil explosion. A red oil explosion refers to the decomposition of tributyl phosphate (TBP), a complexing agent used in extraction processes. When TBP interacts with nitric acid or other constituents at elevated temperatures, TBP can decomposed rapidly (i.e., explosively). The gases generated during red oil explosions include CO_2, CO, NO, N_2O, N_2 and NO_2. The primary decomposition product of TBP is n-butanol (C_4H_9OH) from the hydrolysis of TBP. The key chemical can be simplified as,

$$(C_4H_9)_3PO_4 + 3H_2O \rightarrow H_3PO_4 + 3C_4H_9OH \qquad (4)$$

The subsequent reaction of butanol with nitric acid generates gases,

$$C_4H_9OH + 1.81\ HNO_3 \rightarrow 0.42\ C_4H_8O_2 + 0.32\ C_3H_6O_2 + 0.26\ C_2H_4O_2 + 0.75CO_2 + 0.09CO + 0.31N_2O + 0.14N_2 + 1.4NO + 0.24NO_2 + 0.26HNO_2 + 0.17H_2O \qquad (5)$$

The reactions in the previous equations are complicated and the gas products are extensive. There are still many unknowns about the by-products. Reference [12] proposed a complete oxidation of TBP by nitric acid:

$$(C_4H_9)_3PO_4 + 14.4\ HNO_3 \rightarrow 12\ CO_2 + 7.2\ N_2 + 19.2\ H_2O + H_3PO_4 \qquad (6)$$

The temperature during an energetic red oil explosion is expected to be very high. From the results of the hand calculation and informal recommendations from explosive computational specialists at SNL, it is assumed all radionuclides in the concentrate are vaporized in a large explosion. The MELCOR simulations neglect the consumption of the liquids in Equation (6) but include the production of gases (CO_2 and H_2O).

3.3 Scenarios

In the BNFP FSAR [4] six Class 5 (i.e., most severe and limiting) accidents were considered. The first 5 red-oil explosions and solvent fire scenarios for solvent fires and explosions are relevant for this study. The sixth accident is a reactivity accident and beyond the scope of the current effort.

Both volatile and non-volatile fission products as well as the heavy metals, such as Pu, and U are considered in the FSAR DBA analyses whereas the range of nuclides in the ORIGEN-S calculations is used in the present analysis.

The 1975 BNFP FSAR analysis is dated in many respects. Current reactor operations include burn-ups extending towards 60 GWd/MTU. In addition, spent fuel transport would not occur until after five years aging. In contrast, the BNFP FSAR specified a lower burn-up (40 GWd/MTU) typical of the mid-1970s but with only 160 days aging. The FSAR spent fuel aging time is also not realistic for modern regulations for off-site fuel transport, which are a minimum of 5 years. The new inventories include both stable and radioactive nuclides after 5 years of decay time. The stable nuclides are included due to their significance to MELCOR's radionuclide tracking algorithm.

The ORIGEN calculations are used with information from the DBA analysis to specify the initial inventories of the fission products (volatiles, semi-volatiles, inert) and heavy metal, primarily Pu. The characteristics of the fire and explosions and associated releases are specified using the correlations and assumptions described in the previous sections.

The magnitude of the explosion scenario and the resulting damage was not discussed in the BNFP DBA analyses. Depending on the amount of concentrate included in a "red oil" explosion, a maximum complete reaction could destroy the process cell and surrounding structure. Instead, reasonable

[2] The number on FIGURE 2 and FIGURE 3 are in ft^3/min and shown to illustrate the connectivity in the building. The hot cells where the accidents are specified are denoted as PPC, HILC, HILC, UPC, and RPC.

bounds were placed on the completeness of the reaction such that it did not fail the 3-ft thick wall in the process cell rooms. Nevertheless, the magnitude of the explosion is within the lower range estimate for the TOMSK-7 accident, which was the most severe "red oil" explosion [1].[3] The combined explosion and fire scenario descriptions also consider that enough solvent remains after the explosion to allow a subsequent fire.

4. SIMULATION RESULTS

Ten scenarios MELCOR simulations were performed. The first 5 scenarios are DBA scenarios defined in the BNFP FSAR. The remaining five scenarios were derived from the DBA scenarios. Scenarios 6 to 8 are solvent fire sensitivity cases derived from the DBA fire scenarios. Scenarios 9 and 10 simulate combined explosion-induced fires. In one case, the wall of the accident cell/room has been compromised and the fire has then been started. In another case, no wall failure resulted, and fire was started in the same cell/room as the explosion room to study the limitation of oxygen.

In the radionuclide distribution results, the activity results are grouped into the environment, the exhaust system, the hot cells, the support gallery, and other building regions (e.g., the fuel receiving and storage station). The environment corresponds to activity exiting the building. All the released activity is respirable aerosols or gases (i.e., there are no non-respirable aerosols or water-borne releases). The hot cells are the process cells as indicated in FIGURE 1. All the scenarios originate in one of the process cells. The support gallery includes all the regions immediately surrounding the hot cells in the main building. Normally all the exhaust flow goes from the process cells to the exhaust filtration system and the plant stack. Consequently, any radioactive material in the support gallery occurs due to leakages or structural failures. Finally, the most remote locations were grouped into the other category. Similar to the support gallery, no radionuclides from an accident in a processing cell would be expected in the other regions (i.e., shipping and storage station).

4.1 Fire Scenarios

There were two solvent fire scenarios from the BNFP DBA list. Three sensitivity calculations examined the impact of the fire size and duration. Due to space limitations, only the fire in the code-contamination cycle and the two sensitivity calculations identified in Table 1 are discussed.

Scenario 4 is the described in the BNFP FSAR and Scenarios 7 and 8 are sensitivity calculations where the size of the fire is smaller, but they burned longer. All three scenarios specify a leak of 378 liters in a line carrying the organic solvent bearing U, Pu, and some fission products. The fire surface area of DBA Scenario 4 is 100 m^2 (1080 ft^2) with a burn duration of 72.4 seconds at the maximum consumption rate. Scenarios 7 and 8 have a fire surface area of 5 m^2 (53.8 ft^2) and 1 m^2 (10.8ft^2), respectively. The fires take place in the High Intermediate Level Cell (HILC). The airflow from the HILC normally goes through Filter 5 and then Filter 1 before venting through the stack to the environment (see FIGURE 3).

[3] Any current design basis accident for a US reprocessing facility would be governed by the new requirements identified by the DNSFB [11].

TABLE 1 SUMMARY KEY FIRE PARAMETERS FOR THE FIRE ACCIDENT SCENARIOS.

Scenario	Location	Solvent Volume	Fire Size		
			Area	Diameter	Duration
4	Code-contamination Cycle	378 liters	100 m^2	11.3 m	72 sec
7			5 m^2	2.52 m	24 min
8			1 m^2	1.1 m	2.0 hr

The timing of key events for the three sequences are shown in Table 2. The DBA Scenario 4 calculation assumed the spill covered the entire floor. The fire can reach a maximum power of 169 MW at a maximum solvent burn rate. However, the large fire never reached the maximum power before burning all the solvent. In contrast, the smaller surface area fires in Scenarios 7 and 8 have a maximum power of 8.4 MW and 1.7 MW, respectively, and did reach their maximum power. The fires produce the same amount of energy (i.e., in each scenario all 378 liters were burned). The large fire was assumed to build towards the maximum power over 60 seconds whereas the small fires only required 10 seconds (i.e., Scenarios 7 and 8).

TABLE 2 SUMMARY KEY RESULTS FROM THE FIRE SCENARIOS.

Event Timing [s]	Scenario		
	4	7	8
Start of building pressure/flow steady state balance	-10,000	-10,000	-10,000
Start of the solvent fire (14 liters)	0.0	0.0	0.0
Failure of the HILC outlet damper (>10.34 kPa)	4.3	9.4	n/c
Failure of the inlet damper from the HTG&PEG (>10.34 kPa)	10.2	n/c	n/c
High exhaust fan inlet temperature (>121.1 °C)	11.5	49.2	n/c
High Filter 1 ΔP (>33.8 kPa)	14.8	n/c	n/c
Filter 1 damper closes to 10% to protect filter	24.8	n/c	n/c
High Filter 5 ΔP (>33.8 KPa))	992	962	6534
Filter 5 damper closes to 10% to protect filter	1002	972	6544
All solvent is burned	1301	1575	7266
Filter 1 ΔP <33.8 kPa	1305	n/c	n/c
Filter 1 damper opens to 100%	1305	n/c	n/c

n/c = not calculated

The Scenario 4 fire reaches 75 MW before reducing due to inadequate oxygen. The oxygen concentration near the floor dropped to a minimum of 5% rapidly. The fire burned at a very low oxygen-limited rate until all the solvent was consumed (i.e., <10 MW at an oxygen limited rate). The room gas temperatures approach 760 °C (1400°F) as the fire reached its maximum power but rapidly cooled thereafter when the fire became oxygen limited. The fire continued at an oxygen limited rate until all the solvent was burned at 1301 s. As noted in Table 2, the flow of hot gases from the HILC increased the exhaust fan inlet temperature above 250°F by 11.5 s.

The rapid heating from the large fire pressurized the HILC, which caused failures of inlet and exhaust dampers to the room. During the pressurization in the hot cell from the fire, there was radionuclide leakage into the surrounding rooms as well as through the normal exhaust to Filter 5. The differential pressure across Filter 1 exceeded 33.8 kPa at 14.8 sec, which automatically caused the Filter 1 dampers to close 10 seconds later (see Section 4.4.7). However, the differential pressures across the Filter 1 and 5 components remained well below their estimated failure pressures of 1.5 psid (see Figure 5 12).

Considerably later at 992 seconds, the differential pressure drop across Filter 5 also exceeded 33.8 kPa, which closed the isolation damper 10 s later. The isolation of Filter 5 was due to the large build-up of soot on the filter as the fire progressed. Most of the mass loading on Filter 5 was due to soot. Since Filter 5 remained intact, it captured much of the soot and radioactive material leaving the HILC. The downstream loading on Filter 1 was very small. This is important because Filters 1 and 2 are the final filtration prior to the stack. Consequently, the final filters were not severely challenged, which contributed to the low environmental release.

In Scenarios 7 and 8, the smaller fires caused fewer structural failures since they burned the solvent more slowly (see Table 2. Neither scenario included failures of the back-flow protected inlet dampers to the HILC. However, the fire in Scenario 7 failed the outlet damper and heated the gas going to the fan inlet above 121.1 °C (250°F) by 49.2 s. All the solvent was burned by 1575 s (26.3 min) and 7266 s (2.02 hr) for Scenarios 7 and 8, respectively.

The radionuclide activity released during the fire is spread throughout the BNFP due to the cell pressurization and associated back flow damper failures. The radionuclides are discharged to the adjacent rooms as well as through the normal exhaust to Filter 5. FIGURE 4 shows the distribution of the activity through various regions in the facility (i.e., included in the Hot Cell group). Most of the released activity is captured in the exhaust filtration system and primarily Filter 5. Filter 5 normally filters all the exhaust from the HILC and is located before the final exhaust filter (i.e., Filter 1) and the stack. Due to the room pressurization during the fire, some radionuclide activity is discharged outside of the HILC. Filter 7 also captured some of the released activity but a negligible amount was captured by Filter 2. Any activity that passes Filter 5 to Filter 1 is only small aerosols (i.e., filter performance assumption). The primary pathway to the environment was through the stack. Most of the aerosols going to the stack through Filter 1 and 2 were pre-filtered by the other filters. Consequently, the final stack filters (Filters 1 and 2) were less effective at capturing any more activity.

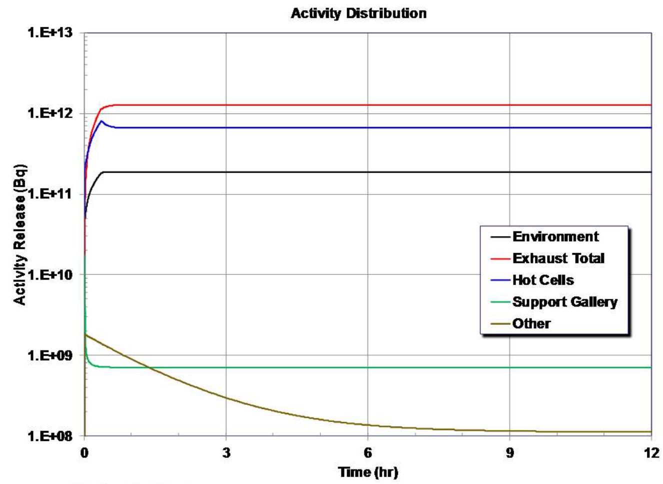

FIGURE 4: ACTIVITY DISTRIBUTION IN SCENARIO 4.

DBA Scenario 4 included fission products, so the fire released many types of radionuclides (see FIGURE 5). The highest releases were from the radionuclide class containing cesium, followed by ruthenium and cerium (i.e., the cerium group includes Pu). The ruthenium class includes volatile gaseous ruthenium, which is not captured on the filter. The environmental release in Scenario 4 (1.94×10^{12} Bq) was about 65% larger than Scenario 2 (1.17×10^{12} Bq). Scenario 4 occurred in the code contamination cycle with 0.039 MTU of the fuel inventory with the leaked solvent. The Scenario 4 radionuclide inventory included volatile fission products such as ruthenium and cesium. Gaseous ruthenium is released in the Scenario 4 fire that passes through the HEPA filters. Similarly, cesium has a relatively high vapor pressure, which also forms a gas in a hot fire. The Scenario 4 environmental release was dominated by cesium due to its volatile gaseous properties and high inventory in the spill (see FIGURE 5). 85% of the activity released to the environment during the fire was cesium group elements versus 10.9% and 4.5% for the ruthenium and cerium groups, respectively.

The total source term to the environment for Scenario 7 was 1.79×10^{11} Bq. Scenario 8 had 1.79×10^{10} Bq, while for Scenario 4, as mentioned above, the total source term was 1.94×10^{12} Bq. The results of Scenarios 7 and 8 were similar to DBA Scenario 4 because all key portions of the filtration system remained intact (i.e., Filters 1, 2, and 7). Consequently, most of the released radionuclides were transported to the filters and Filter 7 captured most of the radionuclide mass and soot from the fire.

4.2 Red Oil Explosion Scenarios

There were three red oil explosion scenarios from the BNFP DBA list. Two other sensitivity calculations examined the impact of an induced fire following the explosion. Due to space limitations, only the fire in the Plutonium Concentrator Explosion (Scenario 3) is discussed.

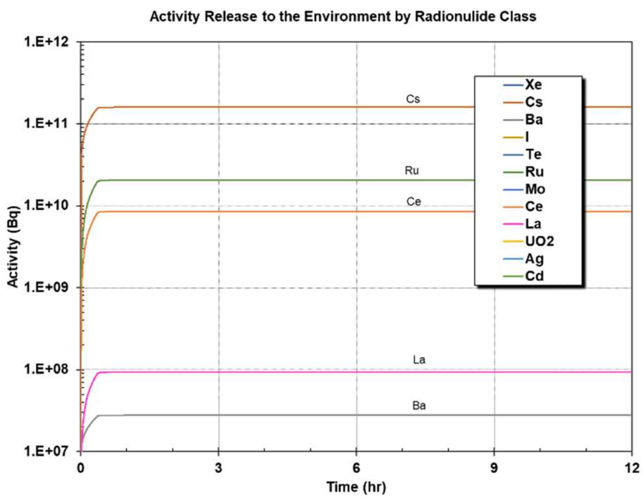

FIGURE 5: ACTIVITY RELEASE IN SCENARIO 4.

Scenario 3 is a "red oil" explosion in the plutonium concentrator in the PPC. The concentrator is assumed to rupture due to the explosion and expels its entire contents into the cell. The scenario specifies 25% of the TBP in the concentrator is involved in the explosion. The resulting explosion has a Trinitrotoluene (TNT) equivalent weight of 27.2 kg (60 lb). The explosion has an energy of 1.28×10^{8} J, which is released over 10 milliseconds. The explosion is expected to fail the connecting ventilation system but not damage the cell walls. Onsite power is available for the exhaust fans and automatic safety controls.

The timing of key events is in Table 3. The explosion caused a large pressure rise that failed all dampers connected to the room. The dedicated pre- and HEPA filters in the Filter 4 compartment also failed. Other than the immediate ventilation and the Filter 4 failure, the high pressure from the explosion was mainly absorbed by the PPC cell walls. The static room pressurization immediately dropped to less than 10 psi and decreased quickly as the hot gases vented from the room. The hot gases led to a high temperature reading at the exhaust fan inlet by 2.8 s (i.e., see Figure 34), high pressure at the Filter 1 compartment at 3.3 s, and a low fan inlet pressure at 5.4 s.

FIGURE 6 shows the pressure response across the Filter 7 HEPA, the Filter 1 HEPA, and the gauge pressure in the AFS and VFS. The explosion immediately failed the Filter 7 HEPA but the longer-term static depressurization also caused failure of the Filter 1 HEPA at 11.9 s. The high-pressure flow towards Filter 1 is assisted by the exhaust fans, which are discharging to the plant stack. No other structural failures were predicted.

The radionuclide behavior for DBA Scenario 3 is shown in FIGURE 7. The activity released during the explosion is spread into the surrounding regions of the BNFP due to the cell pressurization and connecting ventilation failures. Most of the released activity is either captured in the filtered exhaust system (which is labeled as Exhaust Total in FIGURE 7) or released to the environment. The airborne activity in the support gallery and other (loading area) steadily decreases as the regions are filtered. The HEPA filters on the primary pathway from the PPC to the environment failed, which leads to a large source term to the environment.

TABLE 3 SUMMARY KEY RESULTS FROM THE RED OIL EXPLOSION SCENARIO.

Event Timing [s]	Time
Start of building pressure/flow steady state balance	-10,000
Explosion	0.0
PPC outlet damper to Filter 7 fails (>1.5 psid)	<0.01
PPC inlet damper from the FPIG fails (>1.5 psid)	<0.01
Pre-filter 7 fails (>1.5 psid)	<0.01
HEPA filter 7 fails	<0.01
PPC inlet damper from the LPIG fails (>1.5 psid)	<0.01
Explosion ends	0.01
PPC inlet damper from HTG&PEG fails (>1.5 psid)	0.02
High exhaust fan inlet temperature (>250°F)	2.8
High HEPA filter 1 ΔP (>10" inH_2O)	3.3
Low fan ΔP (<44" inH_2O, monitored only) [A]	5.4
HEPA filter 1 fails	11.9

n/c = not calculated

Notes:

A The differential pressure generated by the fan is not a control signal identified in the BNFP FSAR but often monitored in other DOE facilities. The low differential pressure condition indicates an abnormal condition with possibly excessive exhaust flow.

Although the HEPA in filter compartment 1 failed, the pre-filter remained intact following the explosion. BNFP reports the pre-filter has an aerosol capture efficiency between 80–85%. Most of the activity released in the accident was captured by the pre-filter in the Filter 1 compartment. The pre-filter has limited effectiveness because the plutonium was released as a vapor, which quickly condenses into very small aerosols. The pre-filter is assumed to only capture aerosols larger than 1 micron. The other filters captured smaller amounts of radionuclides.

The fans quickly restored a negative pressure in the building after the explosion. Consequently, essentially all the activity released to the environment exited through the stack. The failure of both HEPA filters between the PPC to the stack was critical for the very high activity release to the environment.

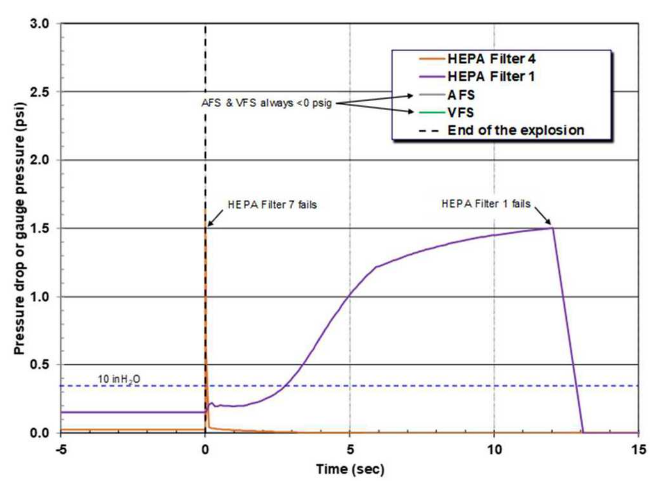

FIGURE 6: FILTER AND COMPARTMENT PRESSURE RISE IN SCENARIO 4.

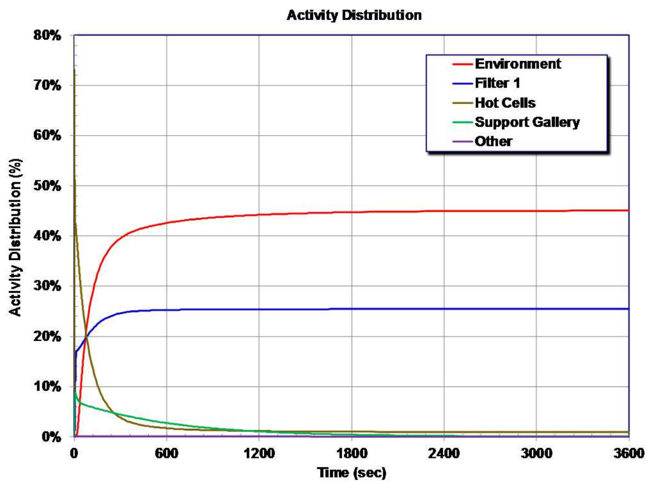

FIGURE 7: RADIONUCLIDE DISTRIBUTION IN SCENARIO 3.

5. CONCLUSION

This paper has demonstrated that MELCOR can be used to evaluate the potential source term release from a nuclear spent fuel reprocessing facility due to fire and explosion accident scenarios. In contrast to the LPF used in the BNFP FSAR calculations, the MELCOR best-estimate modeling includes,

- complete radionuclide inventories characteristic of modern practices,
- thermal and mechanical filter degradation and failure,
- no filtration of very small aerosols,
- building leakage,
- structural failures,
- aerosol physics for agglomeration and deposition within the building,
- radionuclide dispersion throughout the building due to the pressurization from the explosion or fire,
- the radionuclide vapor pressure (e.g., converts some radionuclides to a gaseous form in high temperatures and condenses in cooler regions), and
- chemical reactant and product generation associated with explosions and fires (e.g., oxygen consumption and soot production)

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