



NUREG/CR-7266

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MELCOR Modeling of Accident Scenarios at a Facility for Aqueous Reprocessing of Spent Nuclear Fuel

Manuscript Completed: September 2019

Date Published: January 2020

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ABSTRACT

The work presented in this report applies the MELCOR code to evaluate potential accidents in non-reactor nuclear facilities, focusing on Design Basis Accidents. Ten accident scenarios were modeled using NRC's best-estimate severe accident analysis code, MELCOR 2.2. The accident scenarios simulated a range of explosions and/or fires related to a nuclear fuel reprocessing facility. The objective was to evaluate the radionuclide source term to the environment following initiating explosion and/or fire events. The simulations were performed using a MELCOR model of the Barnwell Nuclear Fuel Plant, which was decommissioned before beginning reprocessing operations. Five of the accident scenarios were based on the Class 5 Design Basis Accidents from the Final Safety Analysis Report. Three of the remaining accident scenarios include sensitivity studies on smaller solvent fires. The final two accidents included an induced fire from an initial explosion. The radionuclide inventory was developed from ORIGEN calculations of spent PWR fuel with an initial enrichment of 4.5% U-235 by weight. The fuel aged for five years after a final 500-day irradiation cycle. The burn-up was conservatively increased to 60 GWd/MTU to bound current US operations. The results are characterized in terms of activity release to the environment and the building decontamination factor, which is related to the leak path factor used in Department of Energy safety analyses. The MELCOR 2.2 results consider adverse consequences to the filters, ventilation system, and structures as a result of the explosions and fires. The calculations also include best-estimate models for aerosol transport, agglomeration, and deposition. The new calculations illustrate best-estimate approaches for predicting the source term from a reprocessing facility accident.

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EXECUTIVE SUMMARY

The work presented in this report enhances 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. The approach centers on the concept of design basis accidents (DBAs), which are intended 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. Ten accident scenarios were modeled using NRC's best-estimate severe accident analysis code, MELCOR 2.2. The accident scenarios simulated a range of explosions and/or fires related to nuclear fuel reprocessing. The objective of the project was to evaluate radionuclide releases within the facility and to the environment following initiating explosion and fire events.

The simulations were performed using a MELCOR model of the Barnwell Nuclear Fuel Plant (BNFP), a facility that never operated. Five of the accident scenarios were based on the Class 5 Design Basis Accidents from the BNFP Final Safety Analysis Report [1]. Three of the remaining accident scenarios include sensitivity studies on smaller solvent fires. The final two accidents included an induced fire from an initial explosion. The explosion scenarios fell within estimated ranges of historical events (e.g., 50 to 700 MJ) that occurred at reprocessing facilities throughout the world. There were two very large fire scenarios from the FSAR that also caused some ventilation system damage and three sensitivity calculations of smaller fires.

The radionuclide inventory was developed from ORIGEN calculations of spent PWR fuel with an initial enrichment of 4.5% U-235 by weight. The fuel aged for five years after a final 500-day irradiation cycle. The burn-up was conservatively increased to 60 GWd/MTU to bound current US operations. The results are characterized in terms of activity release to the environment and building decontamination factor, which is related to the leak path factor (LPF) used in Department of Energy safety analyses. The present calculations predict the full source term to the environment rather than the LPF. New radionuclide tracking features were added to predict the distribution of radionuclide activity within the facility and to the environment.

The MELCOR BNFP model monitors for the potential adverse consequences to the filters, ventilation system, and structures as a result of the explosions and fires. The calculations also include best-estimate models for aerosol transport, agglomeration, deposition, and radionuclide compound vapor pressure. The key modeling features of the MELCOR calculations are,

- complete radionuclide inventories characteristic of modern fuel practices,
- filter degradation and failure,
- no capture of very small aerosols by the HEPA or roughing pre-filter,
- building leakage,
- 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 them in cooler regions),
- structural failures,
- chemical reactant and product generation associated with explosions and fires (e.g., oxygen consumption and soot production)

The two largest explosions caused damage to the ventilation dampers connected to the hot cell in which the explosion took place. As the high pressure from the explosion dissipated outside

the hot cell, the HEPA filters between the hot cell and the environment were predicted to fail. The penetrations between the processing cell and an adjacent low radioactivity region also failed as a consequence of the largest explosion. The source terms from the explosion scenarios were very large (i.e., 1.04×10^{15} Bq, or 28,151 curies for the largest explosion and 1.71×10^{15} Bq, or 46,316 curies for the second largest explosion). Nonintuitively, the smallest explosion had the highest percentage of the released activity getting to the environment. Due to the relatively small amount of inventory released from the smallest explosion, there was significantly less agglomeration and deposition of the very small aerosols formed in the explosion. The small aerosols (i.e., many below the capture efficiency of the HEPA filters) passed through the filters to the environment. Consequently, the magnitude and constituents of the source term to the environment is highly dependent on (a) the amount of material involved in the accident, (b) the efficiency of the physical deposition and agglomeration processes, and (c) the filter efficiency.

Two of the FSAR DBA accident scenarios were very large fires (i.e., 84 MW and 169 MW maximum fire power). However, the BNFP MELCOR model considered oxygen availability, which limited the fires from reaching their maximum power. Consequently, the fires burn longer at an oxygen-limited rate until the solvent was consumed. The initial rapid heatup of the air from the fire pressurized the hot cell room and failed ventilation dampers to the room. Similar to the explosion results, the fire scenarios had releases to the environment due to very small aerosols passing through the filters. Unlike the large explosions, there were two intact HEPA filters between the fire in the hot cell and the stack that captured most of the activity. However, the net retention was much lower than the filter efficiency due to the filtration bypass mechanisms, primarily the presence of very small aerosol particles that passed through the filters.

The MELCOR results were compared to the BNFP FSAR building decontamination factors. The conservative decontamination factors from the FSAR for the explosion DBA scenarios range from 416.7 to 714.3. The MELCOR calculations include the benefits of aerosol retention in the building but also consider consequential failures of filter elements and ineffective filtering of small aerosols or gaseous forms of the radionuclides. The calculated explosion DFs ranged from almost 1 (i.e., no retention) to 21, which was much smaller than FSAR values. The differences are due to the HEPA filter failures for the two large explosions and ineffective capture of very small aerosols for the smallest explosion. In these cases, there is a substantially greater release predicted by MELCOR than by the FSAR calculations.

The two fires had better agreement with the FSAR building decontamination factors than the explosion scenarios. The conservative decontamination factors from the FSAR for the DBA scenarios range from 9.1 for ruthenium up to 100 for aerosols. The MELCOR results for aerosol retention ranged from 4 to 50. There were no HEPA failures in the fire scenarios, but very small aerosols or gases were not captured. Consequently, the calculated building decontamination factors for fires were lower than the rated filter efficiency. Overall, the calculated building decontamination factors in the two large fire scenarios had closer agreement to the FSAR values than the explosion scenarios. This is also due to the lower filter efficiency used in the FSAR analysis for fire scenarios (i.e., 99% versus 99.98% for the rated performance).

ACKNOWLEDGMENTS

This work was funded by the U.S. Department of Energy, Office of Nuclear Energy, under Interagency Agreement DE AI01 07NE24496/0015 and a memorandum of understanding between NRC and DOE (Agency-wide Documents Access and Management System (ADAMS) Accession No. ML071210153). Activities conducted under the Interagency Agreement are consistent with and support DOE's "Nuclear Energy Research and Development Roadmap".

The authors gratefully acknowledge the contributions from Clint Shafer (ARES) for the development of the Barnwell MELCOR model. Nate Bixler, Fred Gelbard, David Louie, and Jesse Phillips provided the technical methods for the analysis of reprocessing accidents from the previous NUERG/CR-7232 project. Mark Fuhrmann provided valuable technical guidance and comments as the Nuclear Regulatory Commission Contracting Officer's Representative (NRC COR).

ABBREVIATIONS AND ACRONYMS

AFS	Analytical Filter Station
ARF	Airborne Release Fraction
AVOS	Analytical Viewing and Operating Station
BNFP	Barnwell Nuclear Fuel Plant
BS	Blower Station
CCFH	Contact Cell Filter Housing
CCS	Cold Chemical Station
CEMG	Crane and Equipment Maintenance Gallery
CERS	Contact Equipment Removal Station
CLRA	Change and Lunch Room Area
CRA	Control Room Area
CSA	Chemical Storage Area
DR	Damage Ratio
EMS	Equipment Maintenance Station
FDS	Fire Dynamics Simulator
FN	Filter Niche
FP	Fission Products
FPIG	Filter Piping and Instrument Gallery
FRSS	Fuel Receiving and Storage Station
FSAR	Final Safety Analysis Report
GVOS	Grade Viewing and Operating Station
HA	High Activity
HAN	Hydroxylamine Nitrate
HAP	High Activity Process
HAW	High-activity Waste
HCLA	Hot and Cold Lab Area
HILC	High Intermediate Level Cell
HLC	High Level Cell
HS	Heat Structures
HTG	Head Tank Gallery
ILC	Intermediate Level Cell
LAA	Lower Access Aisle
LAW	Low-activity Waste
LPF	Leak Path Factor

LPIG	Lower Piping and Instrumentation Gallery
LVOS	Lower Viewing and Operating Station
MAR	Material at Risk
MRS	Manipulator Repair Station
NRC	U. S. Nuclear Regulatory Commission
OFPT	Other Fission Products and Transuranium Elements
PEG	Pulser Equipment Gallery
PMMA	Polymethyl Methacrylate
PNSL	Plutonium Nitrate Storage and Load-out
PPC	Plutonium Product Cell
RF	Release Factor
RMSC	Remote Maintenance and Scrap Cell
RPC	Remote Process Cell
SAC	Sample and Analytical Cell
SCFM	Standard Cubic Feet per Minute
SCG	Service Concentrator Gallery
SNL	Sandia National Laboratories
TAA	Top Access Aisle
TBP	Tributyl Phosphate
TPIG	Top Piping and Instrumentation Gallery
UPC	Uranium Product Cell
VFS	Ventilation Filter Station
WTEG	Waste Tank Equipment Gallery
WTPV	Waste Tank Pipe Vault

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 report 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. The approach centers on the use of design basis accidents (DBAs), which are serious but credible accidents intended 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.

In this work, SNL characterized accident phenomena related to spent fuel reprocessing, which was documented in NUREG/CR-7232 [2]. 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 2.1 demonstration model was built based on the Barnwell Nuclear Fuel Plant (BNFP) [3]. The BNFP was the first large-scale commercial reprocessing facility in the U.S. but was decommissioned before being operated. The MELCOR 2.1 model was developed using available historical drawings and tested for four postulated accident scenarios. The project demonstrated analytical techniques needed to apply the MELCOR code in safety assessments of a large non-reactor nuclear facility. The current project 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 Design Basis Accidents from the Barnwell Final Safety Analysis Report (FSAR).

The MELCOR code is NRC's fully integrated, engineering-level computer code that models the progression of severe accidents in nuclear power plants. A broad spectrum of severe accident phenomena is treated in MELCOR in a unified framework, which includes the thermal-hydraulic response in the reactor coolant system, reactor cavity, containment, and confinement buildings; core heatup, degradation, and relocation; core-concrete attack; hydrogen production, transport, and combustion; fission product release and transport behavior. Current uses of MELCOR include estimation of severe accident source terms and their sensitivities and uncertainties in a variety of applications, including non-reactor nuclear facilities (e.g., [4]). For facility analyses, MELCOR includes basic physics models to predict operational and accident-driven airflows throughout a facility. MELCOR's radioactive aerosol and vapor models track the transport of fission products (FP) and other radionuclides from their point of release to their final deposition or release from the facility into the environment.

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) [3]. The model was enhanced for the current project to include representative accident radionuclide inventories based on ORIGEN calculations of commercial spent nuclear fuel. New radionuclide tracking features were added to predict the distribution of radionuclide activity within the facility and to the environment. 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.

MELCOR Version 2.2 was used for these analyses [5]. A detailed description of the model is given in Section 3.

The BNFP model is used to predict radionuclide releases from explosions and/or fires related to nuclear fuel reprocessing. 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. Detailed descriptions of the accident scenarios are 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.

2 DEPARTMENT OF ENERGY SOURCE TERM APPROACH

In the context of (a) this report, (b) other Department of Energy (DOE) nonreactor facility analyses, and (c) most reactor severe accident analyses, the source term is defined as the amount of radioactive material released offsite to the surrounding environment. The source term can be further characterized as an airborne, a water-borne, or a respirable radioactive release. DOE-STD-1027-2018 identifies the airborne pathway having the primary interest for nonreactor nuclear facilities [6]. Similarly, NRC Reference [7] states that (a) the airborne pathway has the greatest interest for fuel cycle and other radioactive material licenses and (b) the dose from the inhalation pathway will dominate the (overall) dose.

The DOE guidance for evaluation of the airborne source term is typically estimated using a five-component linear equation [8]:

$$\text{Source Term} = \text{MAR} \times \text{DR} \times \text{ARF} \times \text{RF} \times \text{LPF} \quad (1)$$

where:

MAR	Material-at-Risk (curies or grams),
DR	Damage Ratio,
ARF	Airborne Release Fraction,
RF	Respirable Fraction, and
LPF	Leak Path Factor.

The source term to the environment is the product of the five factors. The material-at-risk (MAR) is the amount of radionuclides (in grams or curies of activity for each radionuclide) available to be acted on by a physical stress. For facilities, processes, and activities, the MAR is a value representing some maximum quantity of radionuclide present or reasonably anticipated for the process or structure being analyzed.

The Damage Ratio (DR) is the fraction of the MAR impacted by the accident conditions. DOE facility source guidance describes a degree of interdependence between the definitions of MAR and DR. If it is predetermined that certain types of material would not be affected by a given accident, the DR is used to modify the amount of material identified in the MAR.

The Airborne Release Fraction (ARF) is the coefficient used to estimate the amount of a radioactive material suspended in air as an aerosol or gas as a result of the initiating event. The ARF is the fraction of material available for transport due to a physical stress from a specific accident. If the released material deposits quickly and is not an aerosol suspended in air that transports away from the MAR, then it is not included in the MAR.

The Respirable Fraction (RF) is the fraction of airborne radionuclides as particles that can be transported through air and inhaled into the human respiratory system and is commonly assumed to include particles 10- μm Aerodynamic Equivalent Diameter (AED) and less. In the DOE handbook, the highest RF values are often associated with the smallest ARFs.

The Leak Path Factor (LPF) is the fraction of the suspended material that is released out of a facility to the environment. The LPF may include pathways through filters and building leakage. When multiple leak paths are involved, their cumulative effect is often expressed as one value.

At the DOE facilities, the concern is the release of radioactive airborne materials (such as PuO_2) from a nuclear explosive, nuclear waste, or process facilities as a result of accident conditions

such as spills, fires, or explosions. The LPF cannot be obtained from handbooks because it is a strong function of the energy source, ventilation flows, building leakage rates, coincidental damage, and filtration efficiency. Furthermore, the release characteristics of each postulated accident can progress differently.

An LPF value less than 1 represents some retention of the radioactive release within the facility. The amount of radioactive retention is greatly dependent upon the initial accident event. The major accident events found across the DOE complex include explosion, fire, inadvertent criticality, and spill. Earthquakes can induce many of these accident events, such as explosion and fire. DOE nonreactor nuclear facility ventilation systems include a filtering subsystem that captures much of the particulates in the exhaust stream. Thus, the filter subsystem is important to minimize the release of particulates.

The LPF is usually evaluated independently in DOE nonreactor nuclear safety analyses without including the full airborne radionuclide inventory from the MAR, DR, ARF, and RF evaluations. The LPF is evaluated by releasing a trace airborne aerosol source. The fraction of the trace release that progresses to the environment is the LPF. The independent LPF evaluation using a trace species does not include best-estimate aerosol physics such as agglomeration and deposition. In contrast, the present analysis includes an integrated evaluation of the full source term from the initiating event. Using the aerosol distribution from the released inventory (i.e., MAR x DR), MELCOR's best-estimate aerosol physics solution is used to calculate the source term to the environment. The integrated source term evaluation includes the quantity of each radionuclide, the phase (i.e., gas or aerosol), the time-varying aerosol size distribution, the release by location, and the energy of the release. The time-varying history of all these quantities is tracked at each leakage location.

The detailed MELCOR results can be coupled to the MACCS code to evaluate the offsite doses [9]. 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).¹ 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).

¹ The initial aerosol size distribution for fires was 2.4 μm and the explosions assumed all releases started as a vapor. Natural deposition processes or filters limited the transport of large aerosols to building leakage locations or through filters. Consequently, any aerosols that transported to the environment were in the respirable range (i.e., <10- μm). Nevertheless, MELCOR tracks the time-dependent aerosol size for input to MACCS from every leakage location, including the stack. MACCS subsequently calculates the deposition in the environment based on many factors including the building wake effects, the plume loft, the weather stability, and any rain washdown [9].

3 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 model was used to predict the leak path factors (i.e., the LPF) for two explosions and two solvent fires. The goal of these analyses was to develop and demonstrate the analytical techniques needed for a probabilistic safety assessment of a spent nuclear fuel reprocessing facility.

MELCOR is a generalized building-block code that is well suited for facility analysis. The basic geometry of the facility model is constructed using control volumes for the rooms, hot cells, and ventilation ducting; flow paths are used to connect control volumes, including controlled paths to simulate dampers or failures; there are also specialized flow path models for filters and fans; and heat structures represent walls, floors, ceilings, and equipment. A flexible radionuclide model can release aerosols and vapors based on user-specified physics. MELCOR's radionuclide physics models calculate vapor and aerosol interactions, transport, condensation and vaporization, deposition and resuspension, and decay heating. An explosion or fire can be represented using energy sources with mass sources and sinks to represent chemical reactions (e.g., the consumption of oxygen or generation of carbon-dioxide). Consequently, MELCOR contains the basic models to represent radionuclide release accidents in non-reactor facilities. The building-block construction and generalized control functions allow flexible specification and uncertainty analysis of a wide range of scenarios.

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. The previous accident analyses used trace (unit) radionuclide releases to estimate conservative leak path factors (LPFs) [3].² In contrast, the current model uses realistic inventories and radionuclide releases to predict source terms.

Sections 3.1 and 3.2 summarize the BNFP MELCOR model description from Reference [3]. Section 3.3 summarizes the improved radionuclide modeling for the current analyses, which includes new spent fuel radionuclide inventory calculations. The facility filter models were

² DOE facility safety analyses use a five-factor formula to calculate the accident source term. The LPF is one of the five factors [8]. For design basis safety analysis, the LPF is determined using a trace amounts of very small aerosols to conservatively minimize natural aerosol retention mechanisms such as agglomeration and gravitational settling.

enhanced to include (a) mechanical and thermal failure models, (b) plugging by soot from fires, and (c) release of captured radionuclides following the filter failure.

3.1 Model Development References and Limitations

The information available for modeling the Barnwell facility was primarily obtained from the Final Safety Analysis Report (FSAR) [1]. While information on the facility was limited, as detailed below, the objectives of the project were not impacted since they were not intended to represent any specific facility, but to provide an understanding of the model's capacity to evaluate a non-reactor facility with a very large inventory of mixed radionuclides.

The best electronic copy of the FSAR was quite incomplete. Some critical pages from the design basis safety analysis were re-printed from archival microfiche from NRC document archives. However, the microfiche version was unknown during the original MELCOR model development [3]. A few building layout drawings were included in the FSAR (e.g., selectively reproduced in Appendix A of NUREG/CR-7232 and in Figure 3-1 through Figure 3-3 in this report). However, most of the words and numbers in the figures were unreadable. The building and room dimensions were scaled based on readable values to determine the many dimensions needed to deduce lengths, areas, and volumes. Specific data such as door dimensions, door gaps, and ventilation system ductwork were completely missing. Often, such detailed geometric data can only be obtained from a plant walkdown or contractor reports, which was not possible.

Some building ventilation system flows and room pressures were obtained from text descriptions in the FSAR. However, much of the comprehensive data from key ventilation process figures in the FSAR was not readable. With the airflow numbers included in the text and some partially readable numbers on the diagram, a plausible airflow layout was developed. Missing airflows were estimated based on relative volumes receiving the airflows.

A few room pressures were provided in the text. The five hot cells (UPC, ILC, HLC, HILC, PPC) and the remote process /scrap cells (RPC, RMSC) pressures were maintained at a negative 2 inH₂O with respect to the outside. At least one room, the crane and equipment maintenance gallery (CEMG) was maintained at a negative 0.5 inH₂O. It was assumed that other areas and galleries that potentially contained irradiated equipment and/or employed the use of airlocks were also maintained at a negative 0.5 inH₂O. The control room area (CRA) was maintained slightly positive at 0.25 inH₂O with respect to the outside. All other normally accessible areas and stations were assumed to be positive 0.25 inH₂O.

Another difficulty is modeling leakages between rooms. The leakages are important for the spread of contamination outside the normal filtered ventilation pathways. Doors and piping penetrations may have some leakage around the perimeter. In contrast, an airlock double set of doors is designed to reduce any nominal leakage to negligible amounts. The FSAR did not describe the smaller leakage airflows. During the development of the BNFP MELCOR model, the smaller leakage airflows could alter the building airflows and room pressures significantly. The primary ventilation model was developed assuming the flow through the small leakage paths was negligible.

The FSAR did not include detailed manufacturer performance data for the supply and exhaust fans. However, a few fan performance data points (i.e., head versus airflow) were obtained from the FSAR text descriptions. The data points were fit to a fan head curve for the main process building and the analytical building exhaust air blowers.

In summary, the references and data used to develop the MELCOR model are reasonably characteristic of the BNFP. However, some assumptions and estimates were required to develop the model. While there was incomplete information to develop the model of the BNFP,

this does not impact results of the project. The objective is to develop methods and modeling experience with MELCOR that is applied to non-reactor nuclear facilities. It was not meant to evaluate results of a specific facility.

3.2 BNFP MELCOR Model Description

Figure 3-1 through Figure 3-3 show 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 3-1 and Figure 3-2. A vertical cross-section is shown in Figure 3-3. Each of the hot cells is a relatively narrow chamber 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.

3.2.1 Model Airflows and Pressures

The supply and exhaust airflow diagrams are shown in Figure 3-4 and Figure 3-5, respectively. The various rooms are colored according to their design pressures (i.e., see the color code in Figure 3-5). 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.

There are four supply airflows. The main supply airflow supplies the main process building with approximately 95,000 scfm³. The control room area (CRA) has an independent air recirculation system with a small independent make-up airflow from the outside of 760 scfm and discharges its exhaust air into the upper level of the main process building. The CRA, FRSS, and WTG recirculation systems are not simulated. A portion of their exhaust flows are recirculated into the room supply flow. A small building leakage flow of 275 scfm from the cask loading station (CLS) is included. There are other leakage locations or intakes when the building is operating at negative pressure but the large cask transfer door into the CLS is a likely location.

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 3-5. 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 3-5 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.

³ All airflows are in standard cubic feet per minute (scfm) units based on the standard outside air density.

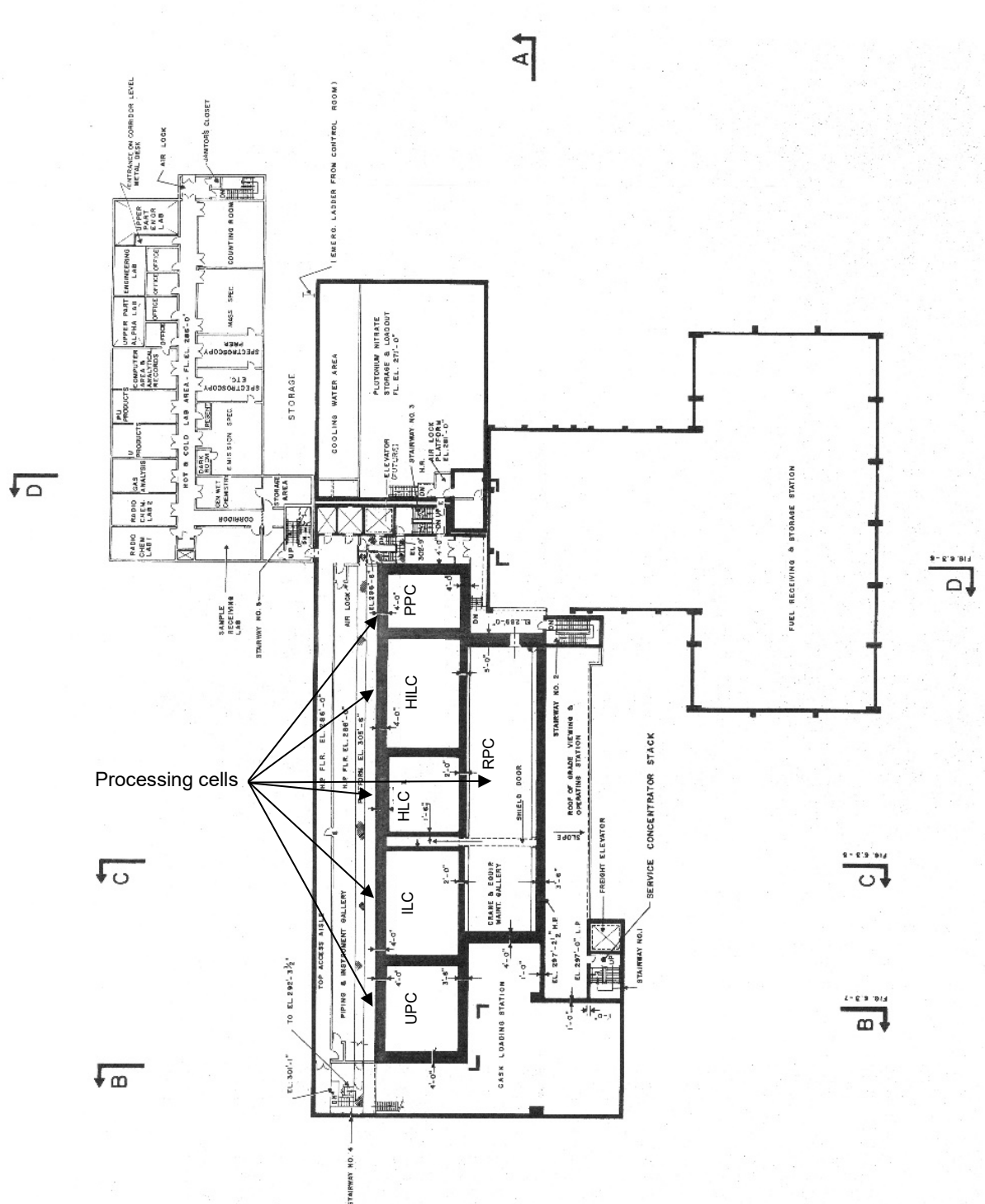


Figure 3-1 Top View of Overall Process Buildings at Elevations 279'-0" to 297'-0" (Highest Floor Level) [1]

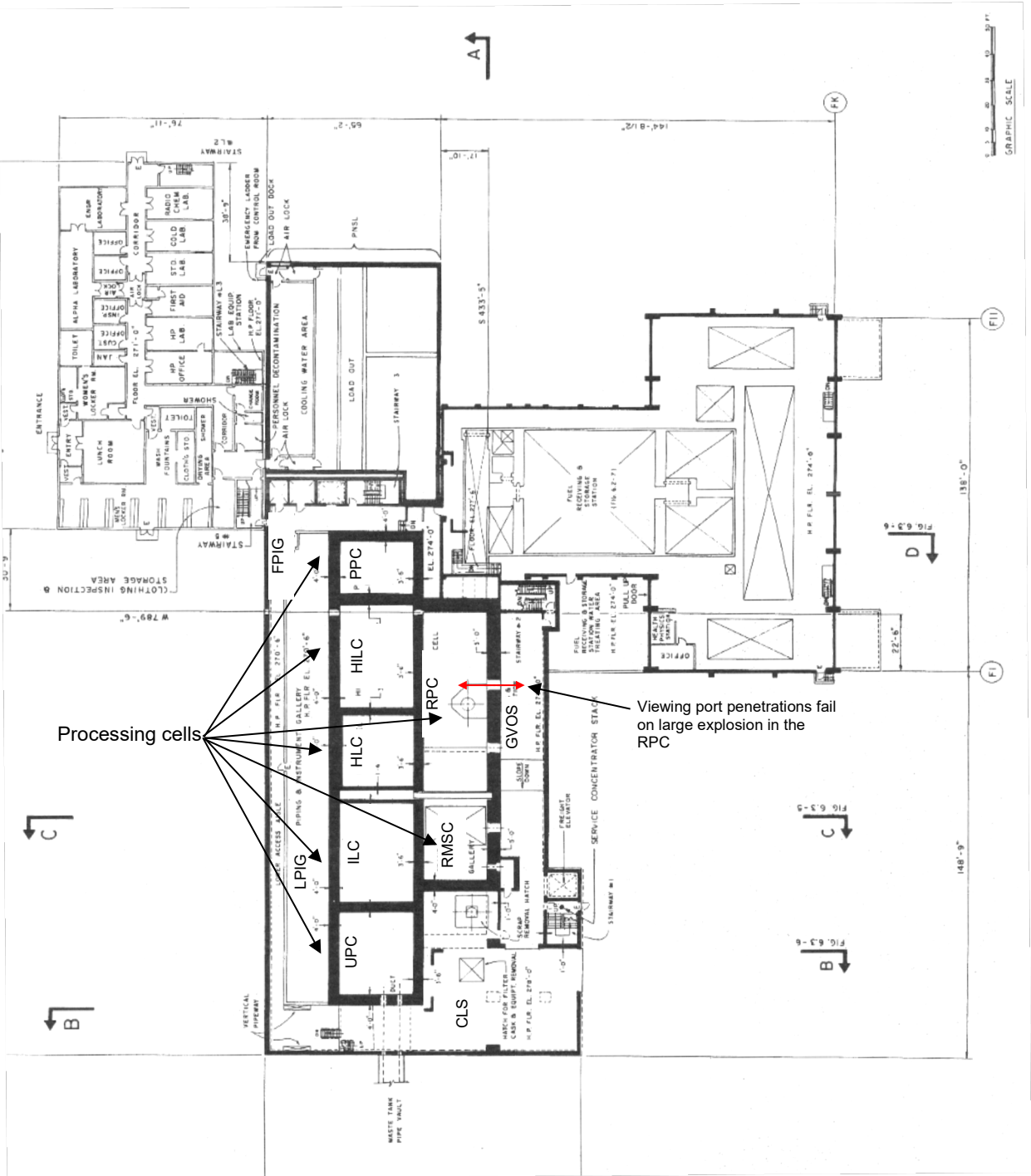


Figure 3-2 Top View of Overall Process Buildings at Elevations 279'-0" to 297'-0" (Lowest Floor Level) [1]

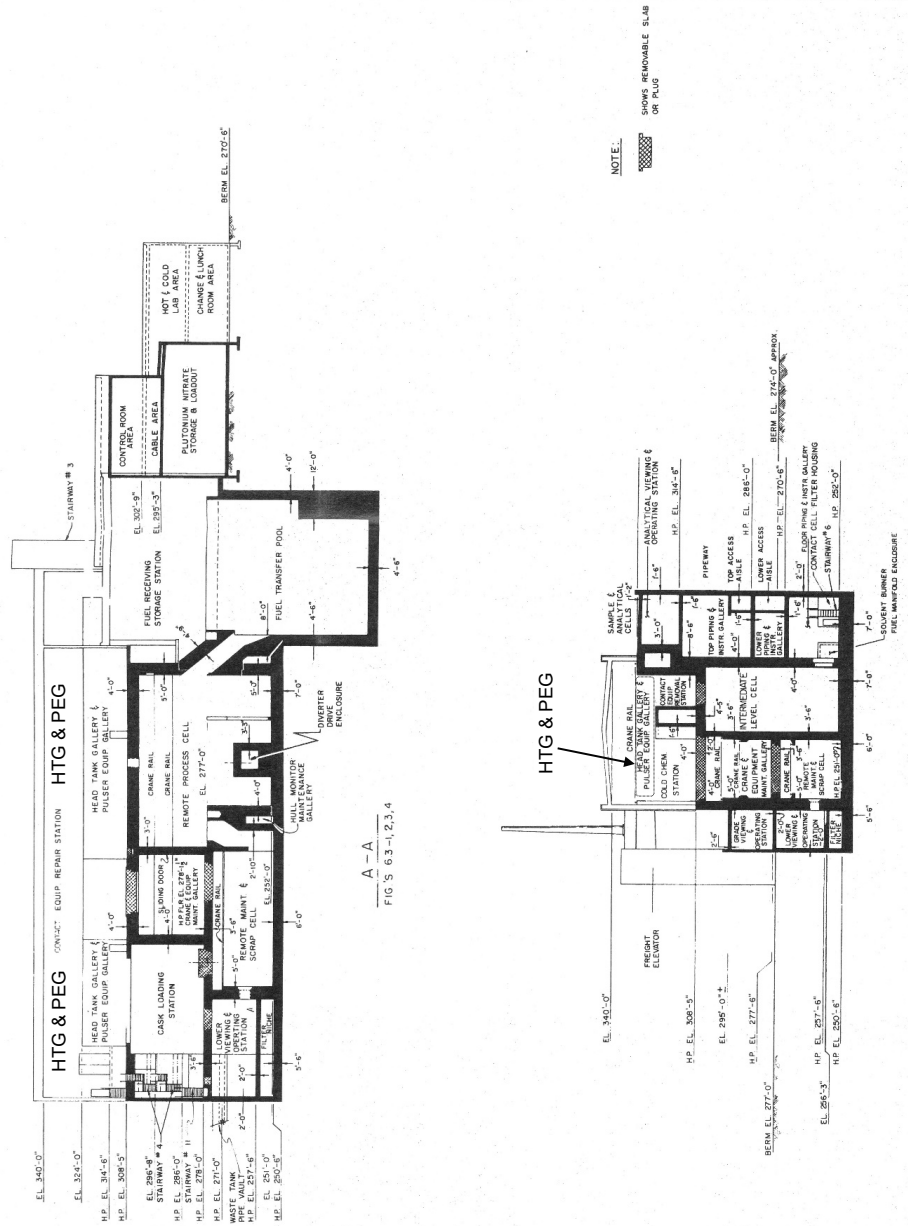


Figure 3-3 Side View of Overall Process Buildings at A-A and C-C Planes [1]

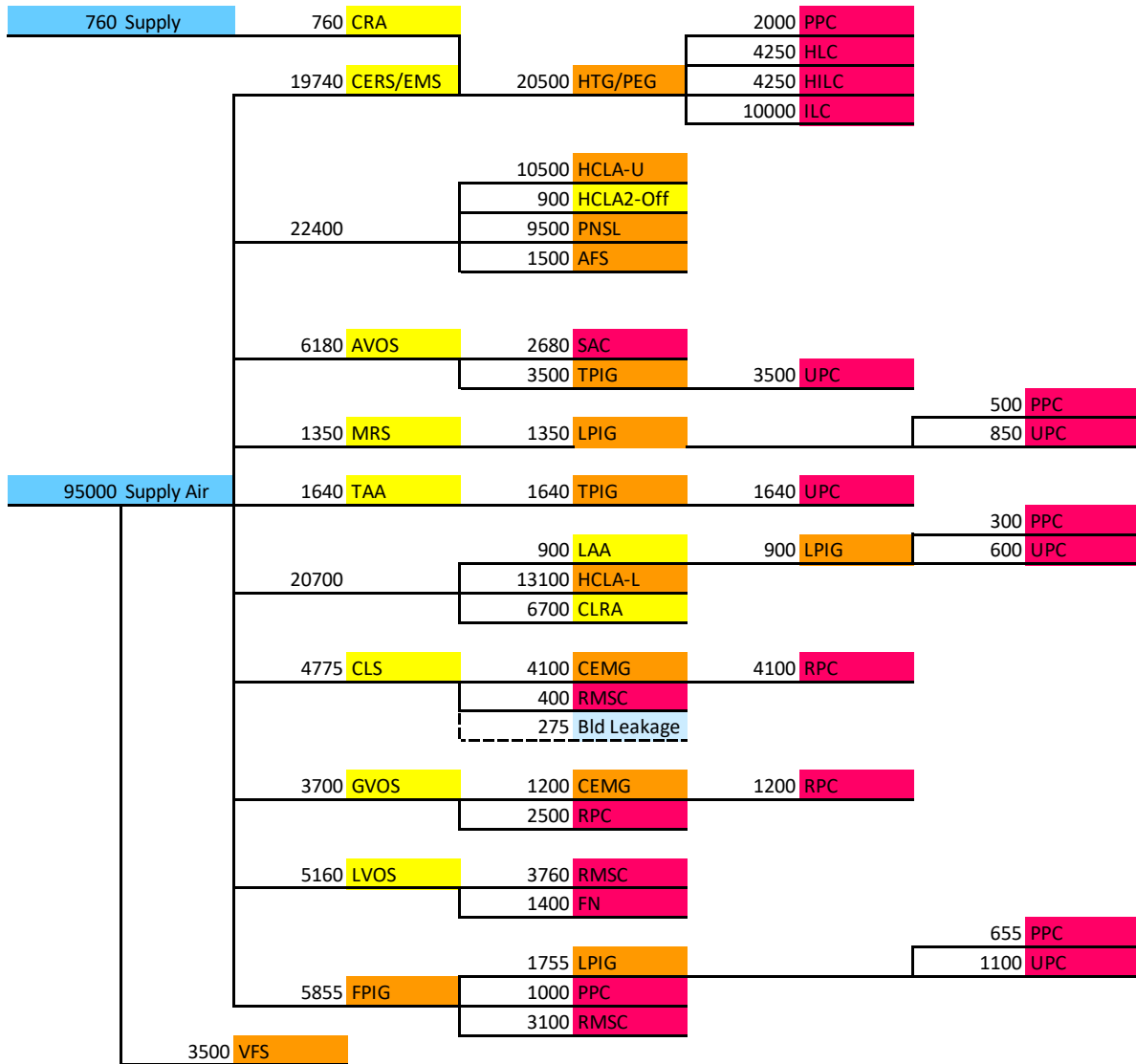


Figure 3-4 Supply Side of Building Pressure and Airflow Diagram [3]

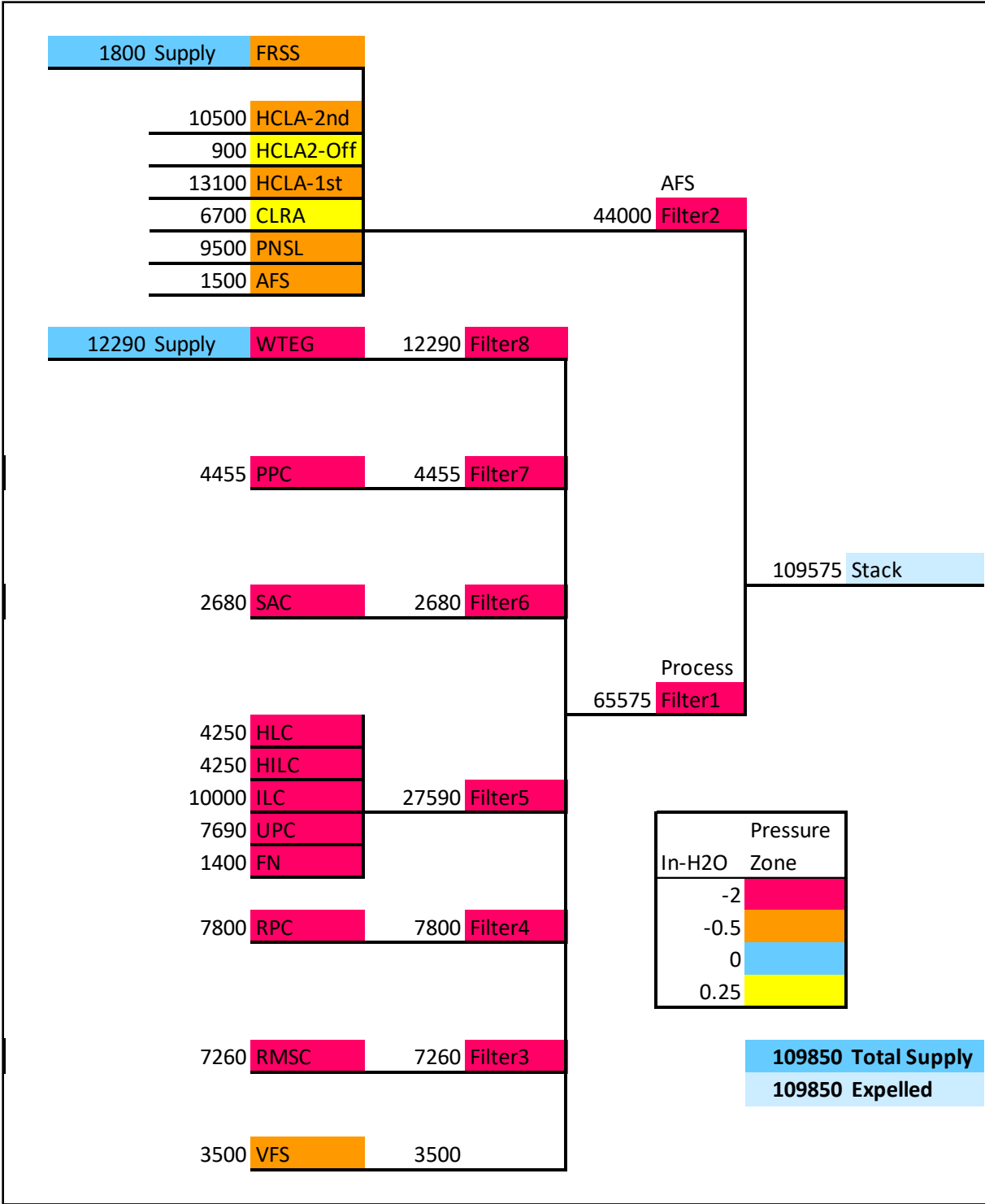


Figure 3-5 Exhaust Side of Building Pressure and Airflow Diagram [3]

There are several individual sample and analytical cells (SAC) located on the upper floor of the process building. These cells are combined into a single volume due to their low importance for accident scenarios originating in the hot cells. There are also many glove boxes for handling radioactive materials throughout the facility that are not explicitly modeled. The scope of the current accident analyses only included large fires and explosions and their associated source terms. However, the BNFP model could be updated to simulate less severe glove box accidents.

The various rooms in the BNFP are maintained at three different pressure zones. The most radioactive areas are modeled to maintain a negative 2 inH₂O. These areas include the five individual hot cells, the RPC and RMSC cells, the FN, and the SAC. The high radiation areas are designated in Figure 3-4 and Figure 3-5 with bright red boxes. The RPC and RMSC cells handle the mechanical cutting of the spent fuel rods, the dissolving of the fuel, and the disposal of the scrap. The chemical processing occurs in the hot cells. The FN contains the off-gassing filtration system. The SAC system is designed to handle highly radioactive samples. The WTEG, which supports the transfer of radioactive wastes into the waste storage tank, is included in the negative 2 inH₂O pressure zone.

The CEMG operating pressure is maintained at a negative 0.5 inH₂O, designated as orange in the figures. The piping galleries (FPIG, LPIG, and TPIG) supporting the operations inside the hot cells that have controlled access through airlocks are assumed to operate at a negative 0.5 inH₂O. The other locations maintained at negative 0.5 inH₂O include (a) the HTG/PEG enclosure above the hot cells, (b) the enclosures for the final filtration (i.e., the VFS and the AFS), (c) the outer facility buildings of the FRSS, the PNSL, and (d) the lab portions of the hot and cold laboratory analysis building. The remainder of the facility is controlled to a positive 0.25 inH₂O pressure, which is denoted with yellow shading. Facility staff would occupy the yellow areas and the orange areas as needed but would rarely enter the red areas during normal operation. Some activity is expected in the red FN region to perform routine filter inspections and maintenance.

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 (VFS) containing the final exhaust filters (Filter 1 in Figure 3-5) and the exhaust blowers for both the main process building exhaust and the analytical filter exhaust. An airflow of 3500 scfm is directed downward from the supply blower exhaust plenum into the VFS where it exits that station into the Filter 1 inlet plenum. From the BS supply, the supply air flows across to the main process building via an apparent overhead conduit. The airflow is subsequently distributed via manifolds to different locations throughout the building as illustrated in Figure 3-6.

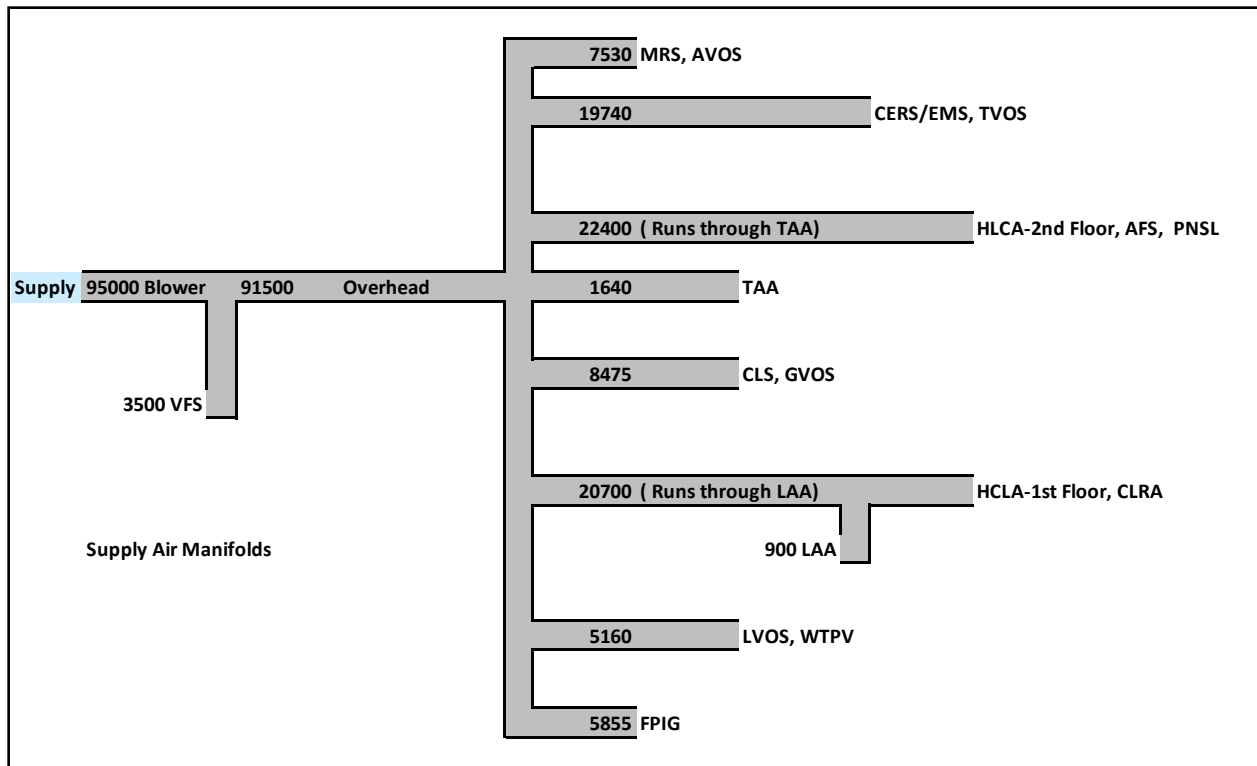


Figure 3-6 Supply Ventilation Distribution Diagram

The air supplies to the hot cells enter near the top of the room and exit near the bottom. Some airflow likely enters the hot cells via the supporting piping galleries via leakage around the pipe penetrations. Much of the airflow into the CEMG, RPC, and RMSC also enters from side galleries. The exhaust filters in the main process building are located at the lowest level of the process building, either in the FN or the CCFH, which is a small side room located inside the FPIG. Filter 1 is in the VFS; Filter 2 is in the AFS (located on top of the HCLA building); and Filter 8 is located inside the WTEG building. Filters 3 and 4 are in the FN; and Filters 5, 6, and 7 are assumed to be in the CCFH located inside the FPIG.

3.2.2 Heat Sources and Heat Structures

There is little information on the room heat loads. FSAR Table 11.5-1 provides a set of hot cell temperatures that are presumably either typical or the maximum operating temperatures [1]. These temperatures are 143°F, 135°F, 130°F, 140°F, and 140°F for the UPC, ILC, HLC, HILC, PPC, respectively. Although, there would be some radionuclide decay heat, the primary source of heating would be steam used in the chemical processes. An appropriate heat load is added to each of these cells such that these respective temperatures are maintained during a steady state calculation.

Since most of the heat structures (HSs) in this model consist of a relatively thick concrete wall (with or without a liner or layer of paint), the wall heat transport inside of one cell, for example due to an explosion, would almost certainly not affect flow in the next cell unless it is an extraordinarily long accident scenario. Rather, the HSs primarily serves as radionuclide deposition surfaces. All HS temperatures are initialized to steady state conditions for their respective locations.

The ventilation ductwork would be constructed using sheet metal. The HS modeling for the metal ductwork is modeled as adiabatic on the outside. The rationale is that the ductwork likely

does not run through either the cells or the piping galleries where an accident might be postulated.

3.2.3 Flow Dampers and Fans

The flow through the facility and the associated pressure control is balanced using dampers. The BNFP MELCOR model included 54 internal and filter compartment dampers. The internal dampers are adjusted to achieve the target airflows and pressures shown in Figure 3-4 and Figure 3-5 and fixed at those positions for accident simulations [3].

The FSAR identifies dampers around the main exhaust blowers and the filter compartments that include manual and automatic control from the control room. In automatic control, the dampers around the filters automatically close to 10% when the pressure drop across the HEPA exceeds 10 inH₂O for more than 10 seconds. When pressure ahead of the final filters is not sufficiently negative (i.e., assumed to be less than 0 inH₂O), the process building supply fan is shut down.

The exhaust blowers have backup electrical power whereas the supply fan does not. In the event of a power failure, an exhaust blower connected to the emergency power system will automatically restart. The exhaust dampers modulate to maintain negative pressure.

3.3 Radionuclide Modeling

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 [10] 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 [11] 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. Five sets of data were generated where the overall burnup was varied parametrically from 20 GWd/t to 60 GWd/t. Two previous irradiation cycles are assumed before the final cycle, which are separated by 30-day decay periods to approximate refueling outages. The 60 GWd/t fuel assembly burn-up data are selected 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. Overall 323 nuclides are retained from the 60 GWd/t calculations. ORIGEN/S-ARP calculations were also done for 50 GWd/t, 40 GWd/t, 30 GWd/t, and 20 GWd/t burn-ups.

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 3-1). 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. The radionuclide mass and activity data are shown in Table 3-2. The values are based on 1 MTU.

Table 3-1 MELCOR Radionuclide Classes

Class	Class Name	Chemical Group	Representative	Member Elements
1	XE	Noble Gas	Xe	He, Ne, Ar, Kr, Xe, Rn, H, N
2	CS	Alkali Metals	Cs	Li, Na, K, Rb, Cs, Fr, Cu
3	BA	Alkaline Earths	Ba	Be, Mg, Ca, Sr, Ba, Ra, Es, Fm
4	I2	Halogens	I ₂	F, Cl, Br, I, At
5	TE	Chalcogens	Te	O, S, Se, Te, Po
6	RU	Platinoids	Ru	Ru, Rh, Pd, Re, Os, Ir, Pt, Au, Ni
7	MO	Early Transition Elements	Mo	V, Cr, Fe, Co, Mn, Nb, Mo, Tc, Ta, W
8	CE	Tetravalent	Ce	Ti, Zr, Hf, Ce, Th, Pa, Np, Pu, C
9	LA	Trivalent	La	Al, Sc, Y, La, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Cm, Bk, Cf
10	UO ₂	Uranium	UO ₂	U
11	CD	More Volatile Main Group	Cd	Cd, Hg, Zn, As, Sb, Pb, Tl, Bi
12	AG	Less Volatile Main Group	Ag	Ga, Ge, In, Sn, Ag

Table 3-2 PWR 60 GWd Spent Fuel Activity and Mass per MTU after 5 years Aging

MELCOR RN class	MELCOR Class Mass (g)	Class Activity (Bq)
Noble Gases (Xe)	1.043E+04	4.569E+14
Alkali Metals (Cs)	5.035E+03	8.535E+15
Alkaline Earths (Ba)	4.649E+03	9.928E+15
Halogens (I)	3.753E+02	1.713E+09
Chalcogens (Te)	9.746E+02	3.237E+13
Platinoids (Ru)	7.764E+03	1.464E+15
Early Transition Elements (Mo)	7.381E+03	3.763E+13
Tetravalent (Ce)	2.018E+04	4.492E+15
Trivalent (La)	1.514E+04	7.015E+15
Uranium (U)	9.278E+05	1.637E+11
More Volatile Main Group (Cd)	2.499E+02	1.322E+14
Less Volatile Main Group (Ag)	2.334E+02	3.843E+12

4 ACCIDENT SCENARIOS

This section describes the development of the accident scenarios for the Barnwell reprocessing plant. 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 Final Safety Analysis Report (FSAR) [1]. 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. Section 4.1 discusses the key assumptions used to develop the accident scenarios. Section 4.2 provides a description of the accidents and key modeling parameters used to specify the accident source terms. Section 4.3 summarizes the specifications for the ten accident source terms.

4.1 Key Methodology Assumptions

Both fires and explosions have historical importance for fuel reprocessing. For example, Reference [12] describes the solvent fire accidents in fuel reprocessing plants. Similarly, the Defense Nuclear Facility Safety Board (DNFSB) Tech-33 document [13] describes the history of the “red oil” explosions in the fuel reprocessing facilities. The present analysis will focus on “red oil” explosions and solvent fires as postulated in the design basis accidents in the FSAR.

The following assumptions were used to characterize the accident scenarios,

- The accident analysis is based on available drawings and information for the Barnwell Nuclear Fuel Plant (BNFP). A MELCOR model [3] of the BNFP was constructed that simulates key features of the facility. The model is lacking in geometry specifics due to limited availability of information. There is no significant operational data since the facility was decommissioned before operating. The results of the present analysis should be considered demonstrative rather than predictive of BNFP DBA source terms.
- The first five accident scenarios are based on Class 5 accidents identified in the BNFP’s final safety analysis report (FSAR) [1]. The Class 5 design basis accidents (DBA) were defined to be an upper limit challenge to the facility. The accident descriptions provided the activities, location, and chemical materials associated with the fire and explosion scenarios.
 - Three explosion scenarios were modeled – high/low fission product (FP) activity processes and a plutonium concentration process
 - Two solvent fire scenarios were modeled – high FP activity and a plutonium concentration process
- The five DBAs define specific locations of the accidents within the BNFP.
 - DBA 1 - Explosion in the high-activity waste concentrator in the Remote Process Cell (RPC)
 - DBA 2 - Solvent fire in the plutonium extraction cycle in the Plutonium Product Cell (PPC)
 - DBA 3 - Explosion in the plutonium product concentrator in the PPC
 - DBA 4 - Solvent fire in the codecontamination cycle in the High-Immediate Level Cell (HILC)
 - DBA 5 - Explosion in the low-activity waste concentrator in the Intermediate Level Cell (ILC)
- Three of the remaining five accidents include sensitivity calculations for the fire duration and magnitude. The final two scenarios include an explosion that starts a fire.

- The accident analysis uses modern methods to specify the radionuclide release and the fire and explosion dynamics rather than the accident progression parameters specified in the BNFP FSAR (e.g., release quantity, transport effectiveness, and radionuclide inventory).
- The BNFP DBA analysis did not include the structural consequences from the fire and explosion initiating events but the current calculations include filtration, ventilation, and structural failures.
- The radionuclide inventory is specified using modern methods. High burn-up ORIGEN (60 GWd/MTU) calculations of spent fuel were performed to define radionuclide inventory and decay heat after five years aging. The BNFP FSAR assumed lower burn-up spent fuel (40 GWd/MTU) that was typical of the mid-1970s but with only 160 days cooling after last fission operation. The FSAR cooling time is not realistic for modern regulations for off-site fuel transport.
- The fire scenarios use the same amount of the combustibles (such as solvent) described in each DBA. The fires are modeled as solvent fires (i.e., kerosene).
- The explosion scenarios use “red oil” chemical reactions. The explosion does not fail the hot cell walls unless the description of the DBA indicates otherwise.

4.2 **Accident Models**

This section describes the release models for solvent fires and red oil explosions. To complete the specification of the accident, additional assumptions and data are required, which will be described in Section 4.3. Section 4.2.1 discusses solvent fire correlations and Section 4.2.2 discusses “red oil” explosion correlations. The solvent fire discussion includes methods to specify the solvent burn rate, the smoke particle release, and the radioactive aerosol generation. Similarly, the explosion section discusses methods to specify the explosive energy and radionuclide release. The radionuclides are released as vapors from the explosion but subsequently cool to form aerosols.

4.2.1 **Solvent Fire**

Ballinger [12] provides a description of the aerosol release model during a solvent fire from various experimental programs. The small- and large-scale solvent fire tests at Kernforschungszentrum Karlsruhe (KfK), Pacific Northwest National Laboratory (PNNL) and at Japan Atomic Energy Research Institute (JAERI) are relevant to the specification of solvent fires. The following descriptions and conclusions are drawn from the relevant experimental programs.

At KfK:

- Experimental specifications and measurements include
 - Solvent fires in a kerosene, tributyl phosphate (TBP) and nitric acid mixture
 - Burning rates in open air and closed containments
 - Aerosol formation rates and particles sizes
 - Radioactive particle release rates
- Key findings
 - The burning rate is determined by the solvent vapor pressure and the oxygen diffusion to the evaporating solvent. Large fires develop strong turbulent mixing flows that enhance the burning rate.
 - The burning rate flux is higher for an open environment than a closed containment.
 - The fire can extinguish in a closed containment because of limited oxygen. Large fires begin to extinguish at an oxygen concentration between 11% to 17.5%

- Soot formation occurs due to the incomplete burning of the kerosene. The size of the average soot particle is larger (up to 0.45µm) for closed containment and spray fires than the open environment fires (~0.22 µm).
- The contaminant release rate is proportional to contaminant concentration in the solvent.

At PNNL:

- 10 fire experiments were conducted to study the combustion of 30% TBP in normal paraffin hydrocarbon (NPH).
- The radionuclide concentrations ranged from 101 g/liter uranium in solvent to 188 g/liter uranium in acid.
- Findings
 - The smoke production is highest near the end of combustion after most of the volatile NPH has been consumed.
 - The aerosol formation rate is higher for Kerosene/TBP (70/30%), than for pure kerosene.
 - The total uranium release is between 0.2 to 7% of the mass originally in the solvent.
 - Up to 9% of the organic layer was converted into smoke. The aerodynamic mass median diameter of 0.6 µm and geometric standard deviation of 3.1 is estimated for the uranium-bearing smoke from the experiments.
 - The following non-volatile release correlation was developed,

$$dU/dt(g/s) = 1.38(dS/dt)C_u, \quad (2)$$

where,

dS/dt = smoke generation rate (g/s) and
 C_u = uranium concentration (g U/g combustible liquid).

At JAERI:

- The tests at JAERI focused on the fire and filter behavior.
 - The combustibles included 100% n-dodecane or 30 vol% TBP/n-dodecane on water.
 - Cross winds between 120 to 600 m³/h simulated the ventilation system.
 - The burn pan area varied from 0.0768 to 1.84 m².
- Findings:
 - The rate of solvent mass loss from the pan is higher than the burning rate of the solvent.
 - The solvent n-Dodecane with 30% TBP has a constant burn rate flux, which is independent of surface area and the ventilation area.
 - Complex combustion product formation was observed in these tests.
 - The smoke production rate is related to the burn rate at a constant value of 0.05.
 - The entrainment rate of the contaminant is proportional to the burn rate of the solvent.

Additional information is needed to generate a contaminant release rate for non-volatile and volatile fission products. For the non-volatile fission products, the contaminant release rate (\dot{m}_r) is given by:

$$\dot{m}_r = e_{ARF} \dot{m}_b R \quad (3)$$

where,

- e_{ARF} the airborne release fraction (ARF) entrainment fraction for non-volatile radionuclides, such as Pu or U,
- \dot{m}_b the burn rate,
- R the ratio of the mass of the contaminant in the solvent mass for the fire based on the ARF calculated for the beaker fire experiments as described in [4], and
- e_{ARF} specified as a constant value of 0.002 for UO_2 if no other data is available.

In addition to the contaminant release rate, the particle size and its distribution are required, which is discussed in Section 4.2.1.1.

For the volatile fission products (i.e., iodine, cesium, and ruthenium), the correlation from Reference [14] was used:

$$\dot{m}_r = \frac{0.84 W_r}{t_b} \quad (4)$$

where,

- t_b burn time
- W_r mass of volatile fission products in the solvent

Note that Equation (3) and Equation (4) can be used to estimate the non-volatile radionuclide release rate. Equation (2) requires the knowledge of the smoke rate, which is approximately 0.05 times the burn rate as described in Reference [12]. For Equation (4), the volatile fission product release rate occurs at a constant release rate over the burning of the fire, assuming all volatile fission product could be released completely during the fire. This is a reasonable assumption since volatiles tends to release when the fluid near a fire condition is very hot. The volatile fission products include xenon, krypton, ruthenium, tritium and carbon-14.

4.2.1.1 Solvent Fire Source Term

The previous correlations require additional information to predict the fission product release rate and establish the size distribution of the airborne particulates. The size distribution is greatly dependent on the accident characteristics and the radionuclide inventory. For example, the various ARF values for a fire of contaminated combustible liquid are shown in Table 4-1. Table 4-1 also includes the airborne particle size and distribution range, which are necessary for accident specifications.

Table 4-1 ARF Values for Burning of Combustible Liquid [2]

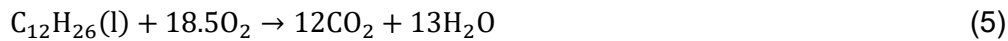
Release Mechanism	Airborne Release Fraction	Airborne Particle Size	
		AMMD (µm)	GSD
Burning of contaminated combustible liquids			
U or Pu liquid (Combustible liquid is spilled over large amount of radioactive material, then ignited)	0.114	2.4	3.8
U or Pu nitrate	0.003	2.4	3.8
Non-volatiles other than U or Pu	0.0077	2.4	3.8
Semi-volatiles	0.01	2.4	3.8
Volatiles	0.843	2.4	3.8

AMMD = Aerodynamic Mass Median Diameter

GSD = Geometric Standard Deviation

4.2.1.2 Solvent Fire Chemistry

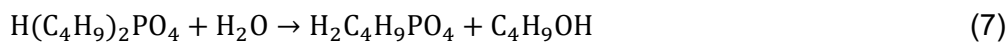
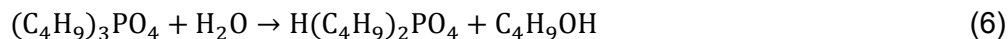
The organic solvent used in the liquid extraction method is typically composed of 30%/n-dodecane (or kerosene). Kerosene is composed of hydrocarbon chains, which contain 10 to 16 carbon atoms per molecule. A chemical formula for a complete reaction for dodecane is:



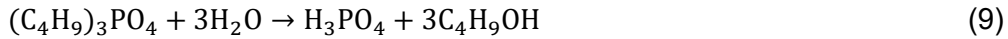
The combustion energies for dodecane and kerosene are about same (i.e., approximately 43.2 MJ/kg). The kerosene burn rate is 0.039 kg/m²-s [15]. The density of dodecane (i.e., 750 kg/m³) is slightly lower than kerosene (i.e., 820 kg/m³).

4.2.2 Red Oil Explosion

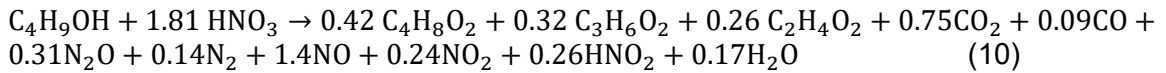
Red oil explosions are a major concern in spent fuel reprocessing plants and other nuclear chemical processing facilities. The Defense Nuclear Facilities Safety Board (DNFSB)'s TECH-33 report [13] describes the importance of red oil explosions following the accident at Tomsk-7 in 1993. The report describes 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 be decomposed rapidly (i.e., explosively). The gases generated during red oil explosions include CO₂, CO, NO, N₂O, N₂ and NO₂. The primary decomposition product of TBP is n-butanol (C₄H₉OH) from the hydrolysis of TBP. The key chemical reactions are [13]:



Equations (6-8) can be simplified as,

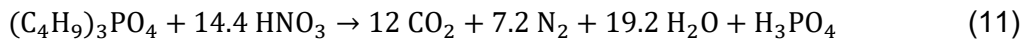


The subsequent reaction of butanol with nitric acid generates gases,



The heat energy for a red oil explosion ranges from 6.7407×10^6 to 7.6618×10^6 J/mole-TBP, assuming the reaction taking place at 25°C. At 120°C, the heat energy is about 4.4158×10^6 J/mole. The molecular weight of TBP is taken to be 266.32 g/mole or 0.26632 kg/mole. Thus, the specific heat energy is 1.5868×10^7 J/kg TBP. One mole of TBP would generate 1 mole of H_3PO_4 and 3 moles of butanol. Thus, one mole of TBP would yield 2.25 moles of CO_2 , 0.27 mole of CO , 0.93 mole of N_2O , 0.42 mole of N_2 , 4.2 moles of NO , and 0.72 mole of NO_2 .

The reactions in the previous equations are complicated and the gas products are extensive. There are still many unknowns about the by-products. Reference [16] proposed a complete oxidation of TBP by nitric acid:



The temperature during an energetic red oil explosion is expected to be very high. To determine the explosion temperature (T_{exp}), the following equation is used:

$$T_{exp} = T_o + \frac{q_{exp}}{C_{p_{product}}} \quad (12)$$

where

T_{exp}	Sum of the heat capacities of each by-product weighted by their mole fraction.
T_o	ambient temperature
q_{exp}	specific explosion energy (J/kg or J/mole)
$C_{p_{product}}$	heat capacity of the by-product

Using the by-products generated in Equation (12), T_{exp} is estimated to be greater than 3000°C. 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.

4.3 Scenarios

In the BNFP FSAR, Section 15 and Appendix J (previous version published in 1970, see Reference [1]), 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.

The source activity related to these DBAs is for the pressurized water reactor (PWR) fuel with a burnup of 40 gigawatt day (GWd)/metric ton of uranium (MTU) (specific power = 50 kW/kg) and cooled for 160 days. 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.

Only the MTU involved in the accident 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, where any nuclide with greater than 1×10^{-9} gram/MTU is included. The stable nuclides are included due to their significance to MELCOR's radionuclide tracking algorithm.

The new 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 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.⁴ The combined explosion and fire scenario descriptions also consider that enough solvent remains after the explosion to allow a subsequent fire.

The following subsections describe details of the 10 scenarios selected for the MELCOR simulations. The summary of these accidents is shown in Table 4-2. As shown in this table, 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.

⁴ Certainly, any current design basis accident for a US reprocessing facility would be governed by the new legal requirements identified by the DNSFB [13].

Table 4-2 Summary of Key Specifications for the Ten Accident Scenarios

No	Scenario Description	Accident Location	Energy Source 1		Energy Source 2		ARF	Initial Failure Due to Explosion		Source Term Type	Fuel Mass Inventory (MTU)
			Energy	Duration	Energy	Duration					
1	DBA – HAW Concentrator Explosion	RPC	4.27x10 ⁸ J	10 ms			ARF=1.0 is assumed due to the high explosion temperature. Assume all radionuclides are vaporized in the explosion.	Supporting structure failed	Ventilation failed	Volatile, Semi-volatile, heavy metal	0.106
2	DBA – Solvent Fire in Plutonium Solvent Extraction Cycle	PPC	4.536x10 ⁸ J	6 s			ARF for Pu assumed to be that of Table 4-1, which is 0.114, AMD=2.4, GSD=3.8	None	None	Pu	0.034
3	DBA – Plutonium Concentrator Explosion	PPC	1.28x10 ⁸ J	10 ms			ARF=1.0 is assumed due to the high explosion temperature. Assume all radionuclides are vaporized in the explosion.	No support structure failure	Ventilation failed	Pu	0.625

Table 4-2 Summary of Key Specifications for the Ten Accident Scenarios (continued)

No	Scenario Description	Accident Location	Energy Source 1		Energy Source 2		ARF	Initial Failure Due to Explosion		Source Term Type	Fuel Mass Inventory (MTU)
			Energy	Duration	Energy	Duration					
4	DBA – Codecontamination Cycle Solvent Fire	HILC	1.225x10 ¹⁰ J	72.5 s			Apply Table 4-1 here: Pu/U ARF=0.114, other inert ARF=0.008, Semi-volatile ARF=0.01, volatile ARF=0.843, AMD=2.4, GSD=3.8	None	None	Volatile, Semi-volatile, heavy metal	0.085
5	DBA – LAW Concentrator Explosion	ILC	1x10 ⁸ J	10 ms			ARF=1.0 is assumed due to the high explosion temperature. Assume all radionuclides are vaporized in the explosion.	No support structure failure	Ventilation failed	Volatiles, Semi-volatiles, and heavy metal: Pu	0.35
6	Same as 2 above, except small fire pool area	PPC	4.536x10 ⁸ J	32.2 s			ARF for Pu from Table 4-1, which is 0.114, AMD=2.4, GSD=3.8	None	None	Pu	0.034

No	Scenario Description	Accident Location	Energy Source 1		Energy Source 2		ARF	Initial Failure Due to Explosion		Source Term Type	Fuel Mass Inventory (MTU)
			Energy	Duration	Energy	Duration					
7	Same as 4 above, except small fire pool area to 5 m ²	HILC	1.225x10 ¹⁰ J	1,454 s			Apply Table 4-1 here: Pu/U ARF=0.114, other inert ARF=0.008, Semi-volatile ARF=0.01, volatile ARF=0.843, AMD=2.4, GSD=3.8	None	None	Volatile, Semi-volatile, heavy metal	0.085
8	Same as 4 above, except small fire pool area to 1 m ²	HILC	1.225x10 ¹⁰ J	7,269 s			Apply Table 4-1 here: Pu/U ARF=0.114, other inert ARF=0.008, Semi-volatile ARF=0.01, volatile ARF=0.843, AMD=2.4, GSD=3.8	None	None	Volatile, Semi-volatile, heavy metal	0.085
9	Same as 1 above, add fire (explosion-induced fire)	RPC	4.0x10 ⁸ J	10 ms			ARF=1.0 is assumed due to the high explosion temperature. Assume all radionuclides are vaporized in the explosion.	Supporting structure failed	Ventilation failed	Volatile, Semi-volatile, heavy metal	0.106

Table 4-2 Summary of Key Specifications for the Ten Accident Scenarios (continued)

Table 4-2 Summary of Key Specifications for the Ten Accident Scenarios (continued)

No	Scenario Description	Accident Location	Energy Source 1		Energy Source 2		ARF	Initial Failure Due to Explosion		Source Term Type	Fuel Mass Inventory (MTU)
			Energy	Duration	Energy	Duration					
	Scenario 9 continued				1.3×10^{10} J	807 s	Pu/U ARF=0.114, other inert ARF=0.008, Semi-volatile ARF=0.01, volatile ARF=0.843, AMD=2.4, GSD=3.8 (see Table 4-1)			Volatile, Semi-volatile, heavy metal	0.74
10	Same as 3 above, except add fire (explosion induced fire)	PPC	1.28×10^8 J	10 ms			ARF=1.0 is assumed due to the high explosion temperature. Assume all radionuclides are vaporized in the explosion.	No support structure failure	Ventilation failed	Pu	0.625
					1.63×10^9 J	969 s	ARF for Pu is 0.114, AMD=2.4, GSD=3.8 (see Table 4-1)	None	None	Pu	1.875

4.3.1 DBA Scenario 1 – HAW Concentrator Explosion

Scenario 1 is a “red oil” explosion in the high-activity waste (HAW) concentrator, which is in the remote process cell (RPC, see Figure 3-2). The HAW concentrator holds 600 liters of concentrate (5'-3" [1.6 m] diameter and 18'-0.25" [5.49 m] high [1]). The volume of the RPC is about 2850 m³. The density of the concentrate is 1.4 kg/liter. The concentrate to uranium ratio is 567 liter/MTU.

Comments/Assumptions:

1. The entire content of 600 liters in the concentrator is involved in the accident.
2. Density of concentrate is 1.4 kg/l.
3. RPC has a volume of 2850 m³ and is assumed to be surrounded by concrete structure at about 3.5-ft (1 m) thick. The standoff distance is assumed to be the half of the cube root of the volume, which is 7 m.
4. Assume 30-vol% of concentrate is TBP, which results in 180 liters of TBP in the spill.
5. Using a TBP density of 1430 kg/m³, and its molecular weight of 0.26632 kg/mole, there are 966 moles of TBP is in this scenario. A value of 4.42x10⁶ J/mole is used for the TBP decomposition, which generates 4.27x10⁹ J for 966 moles of TBP.
6. Assume only 10% of the TBP is involved in the explosion, which gives 4.27x10⁸ J. The resulting explosion has a TNT equivalent weight of 200 lb. Using the explosion correlation in Table 5-6 in NUREG/CR-7232 [2], the side-on pressure is >100 psig, and reflected pressure is twice as much. According to Table 4-5 in NUREG/CR-7232, this pressure would create a crater. Note the TOMSK-7 explosion's energy was about 1x10⁸ J to 1x10¹¹ J. All connecting ventilation fails in the explosion. However, it is assumed the walls and roof remain intact. Two penetrations are assumed to fail.
7. Assume the form of the chemical reaction in Equation (11) and the explosion vaporizes all radionuclides in the participating TBP mixture (i.e., 10%).
8. Assume only 10% of the radionuclide inventory is released in the explosion (i.e., assumed to scale with the percentage of concentrate participating).

Summary of Scenario:

1. The explosion energy is 4.27x10⁸ J, which is released over 10 milliseconds.
2. The connected ventilation systems are expected to fail. However, it is assumed the walls and roof remain intact. Two penetrations are assumed to fail (see Figure 3-2).
3. 10% of the concentrate is assumed to participate in the explosion, which is assumed to vaporize 10% of the radioactive inventory present in 0.106 MTU.⁵
4. The radionuclide inventory includes volatile, semi-volatile and heavy metals. All materials involved in the explosion are vaporized and released (i.e., ARF=1).

4.3.2 DBA Scenario 2 – Solvent Fire in Plutonium Solvent Extraction Cycle

Scenario 2 is a solvent fire in the PPC where the plutonium solvent extraction cycle is located, (see Figure 3-2). The scenario specifies a spill from the 3AP stream, which carries the organic

⁵ The inventory released in the MELCOR calculation is determined by using the MTU involved in the scenario times the mass or activity for the relevant radionuclides in Table 3-2 (i.e., the Table 3-2 values are based on 1 MTU). Each scenario includes either (a) all radionuclides (i.e., except the Noble gases) or (b) only Pu (e.g., DBA Scenarios 2 and 3). The noble gases are assumed to be removed during the initial processing phases, including chopping of the spent fuel assemblies. Also see Footnote 7 for scenarios with primarily Pu.

stream with the highest plutonium content. Fourteen liters (0.014 m³) of organic solvent leaks, ignites, and is completely consumed by the fire. The amount of solvent released is equivalent to a 10-minute leak at the normal flow rate. The solvent to uranium ratio is 409 liter/MTU,⁶ which is based on the processing rate of 0.208 MTU/hr and the 3AP normal flow of 85 liters/hr (i.e., 85 liter/hr / 0.208 MTU/hr).

Comments/Assumptions:

1. The organic solvent is primarily composed of 30%TBP/n-dodecane (or kerosene).
2. The chemical formula for a complete reaction for dodecane is shown in Equation (5). The combustion energy for dodecane and kerosene are similar. A value of 43.2 MJ/kg is used.
3. The kerosene burn rate is 0.039 kg/m²-s for a large pool [15]. The burn rate is assumed to remain constant until all solvent is consumed within the constraints of the fire start-up (i.e., 60 sec) and oxygen availability (see Section 4.4.6).
4. All 14 liters are involved in the accident and the liquid spans the entire floor (i.e., 540 ft²).

Summary of Scenario:

1. The integral fire energy is 4.536x10⁸ J in 6 seconds based on Assumptions 2-4 above.
2. The 14 liters of the solution is primarily Pu after processing 0.034 MTU of spent fuel inventory.⁷
3. The ARF and the particle size/distribution from Table 4-1 for a liquid Pu spill are used, 0.114, 2.4 μm, and 3.8, respectively.

4.3.3 DBA Scenario 3 – Plutonium Concentrator Explosion

Scenario 3 is a red-oil explosion in the Plutonium Product cell (PPC), see Figure 3-2. This scenario postulates that the explosion occurs in the plutonium concentrator (i.e., the 3P concentrator at the BNFP, see Table A-6 of NUREG/CR-7323 [2]). The concentrator is assumed to rupture due to the explosion and expels its entire contents into the cell. The combined dimension of this concentrator is 4'-6" (1.37 m) x 13'-9" (4.19 m). The final aqueous Pu concentration ranges from 60 g/L up to 350 g/liter. According to Table 2.2-3A of Appendix J [1], the concentrator contains 72 liters of concentrate. The organic solvent consists of 30% TBP, which corresponds to 21.6 liters of TBP (i.e., 30% x 72 liters). The ratio of concentrate to original uranium fuel inventory is 29 liter/MTU.⁷

Comments/Assumptions:

1. 21.6 liters of TBP are available for the explosion, which is about ~30 kg (~114 moles) of TBP. The maximum possible explosion energy is 5x10⁸ J. However, it is assumed only 25% of the TBP participates in the explosion (i.e., 5.16 liters).
2. 25% of the maximum amount of energy is involved in the explosion, which is 1.28x10⁸ J. The energy from the explosion creates an overpressure of 124 psig on the wall (~3 to

⁶ Alternatively, the ratio of uranium to solvent is 2.445 kg-U per liter. Also see Footnote 7.

⁷ The radionuclide material is assumed to be primarily Pu after completing the intermediate reprocessing steps to the plutonium solvent extraction phase. However, the inventory is scaled from the mass of uranium prior to the fuel burn-up and subsequent reprocessing (i.e., scaled to the original mass of uranium in the fuel). For example, Table 3-2 shows 1 MTU of spent fuel has 9.278E+05 g of U after a 60 GWD burn-up and 5 years of aging. The corresponding amount of Pu that is created in the process (i.e., the MELCOR Class Ce) is 2.018E+04 g.

5 ft walls) assuming a standoff distance of 4.6 m. The explosive yield is equivalent to 27.3 kg (60 lb) of TNT. The overpressure is assumed not to cause any wall failures but would damage the connecting ventilation systems.

3. Only 25% of the Pu is released in the explosion (i.e., assumed to scale with the percentage of concentrate participating).⁸

Summary of Scenario:

1. The explosion energy is 1.28×10^8 J, which is released over 10 milliseconds.
2. There are no wall failures, but the connecting ventilation systems are expected to fail.
3. The total MTU in this scenario is 2.5. However, only 25% of volume is involved in the accident, which reduces the participating inventory to 0.625 MTU.
4. The radioactive inventory in the 3P concentrator is primarily Pu. All Pu involved in the explosion (i.e., 25%) is vaporized and released (i.e., ARF=1).

4.3.4 DBA Scenario 4 – Codecontamination Cycle Solvent Fire

Scenario 4 is a solvent fire in the High Intermediate Level Cell (HILC, see Figure 3-2), where a leak is developed in the HAP line carrying the organic solvent bearing U, Pu and some fission products between the HA contractor and the HS scrub column. A total accumulation of 378 liters (0.38 m³) of organic solvent leaks out, which subsequently burns. The dimensions of the HILC is 40' (12.19 m) x 27' (8.23 m) x 52' (15.85 m). According to Table 2.2-4A of Appendix J [1], the floor area is 1080 ft² (100.34 m²) and 100 gallons (378 liters) of solvent are burned. The solvent to uranium ratio is 4431 liter/MTU [1].

Comments/Assumptions:

1. The organic solvent is primarily composed of 30% TBP/n-dodecane (i.e., assumed to have the properties of kerosene).
2. The dodecane reacts completely as specified in Equation (5). The combustion energy of kerosene is used, which is approximately the same as dodecane (i.e., 43.2 MJ/kg is used).
3. The maximum kerosene burn rate is 0.039 kg/m²-s for a large pool [15]. The burn rate is assumed to remain constant until all solvent is consumed within the constraints of the fire start-up (i.e., 60 sec) and oxygen availability (see Section 4.4.6).
4. The 378 liters spread across the entire HILC floor area and burn. The fire duration at the maximum burn rate would be 72.4 seconds.

Summary of Scenario:

1. The fire energy and duration are 1.225×10^{10} J and 72.5 seconds, respectively, using Assumptions 1-4 above.
2. The radioactive inventory is based on 0.085 MTU in 378 liters of solvent.
3. The radioactive inventory includes volatile, semi-volatile and heavy metals. Using the guidance in Table 4-1 for burning liquids, the ARFs for Pu, other inert, semi-volatile, and volatile elements are 0.114, 0.008, 0.01 and 0.843, respectively. The released aerosols have the following characteristics: AMMD=2.4 μm and GSD=3.8.

⁸ Although ORIGEN calculates 6 nuclides of Pu in the spent fuel inventory, the activity is dominated by ²⁴¹Pu (92.5%) and ²³⁸Pu (7.2%). Trace amounts of ²³⁶Pu, ²³⁹Pu, ²⁴²Pu, and ²⁴⁴Pu are also present.

4.3.5 DBA Scenario 5 – LAW Concentrator Explosion

DBA Scenario 5 is a red oil explosion in the Intermediate Level Cell (ILC), see Figure 3-2. The explosion occurs in the low-activity waste (LAW) concentrator, which is postulated to rupture and expel its entire contents into the cell. The concentrator is 7'-10" (2.387 m) in diameter and 20'-8" (6.3 m) high. The ILC cell dimensions are 27' (8.23 m) × 38' (11.58 m) × 52' (15.84 m). Table 2.2-5A/B of Appendix J [1] gives the cell volume of 1500-1510 m³. 1500 liters (1.5 m³) of concentrate are available for the explosion. The density of the concentrate is 1.3 kg/liter. The concentrate to uranium ratio is 432 liters/MTU.

Comments/Assumptions:

1. The concentrate volume is 1500 liters. If the concentrate is 30 vol% TBP, then the TBP volume is 450 liters (~650 kg of TBP or 2450 moles of TBP) using the assumptions described in Section 4.3.1.
2. If all the concentrate participated in the explosion, then the maximum explosion energy would be ~10¹⁰ J. Such a large explosion is unlikely and would cause significant damage to the facility. This scenario assumes 1% (i.e., 15 liters) of the concentrate participates, which releases 1.1x10⁸ J.
3. Similarly, only 1% of the radioactive inventory is released in the explosion (i.e., assumed to scale with the percentage of concentrate participating).
4. The room and wall structures are assumed to remain intact using the same assumptions as in Section 4.3.3. However, the connecting ventilation systems are expected to fail.

Summary of Scenario:

1. The explosion energy is 1x10⁸ J, which is released over 10 milliseconds.
2. No walls fail but the connecting ventilation systems may fail.
3. The ratio of concentrate to uranium is 432 liters/MTU and the volume is 15 liters, which yields 0.035 MTU for this scenario.
4. The radioactive materials include volatile, semi-volatile and heavy metal. All materials involved in the explosion are vaporized and released (i.e., ARF=1).

4.3.6 Scenario 6 – Small Solvent Fire in Plutonium Solvent Extraction Cycle

Scenario 6 is derived from DBA Scenario 2 in Section 4.3.2. However, this scenario assumes a smaller pool area but greater depth.

Comments/Assumptions:

1. All 14 liters of organic solution are consumed, but the floor area is reduced to 8.36 m² (90 ft²) versus 540 ft² for DBA Scenario 2.
2. All other assumptions in Section 4.3.2 apply.

Summary of Scenario:

1. The fire energy of 4.536x10⁸ J is unchanged from Section 4.3.2 but the burn time at the maximum rate increases to 32.2 seconds. The maximum burn rate is constrained by the fire start-up time (i.e., 10 sec) and oxygen availability (see Section 4.4.6).
2. The inventory is based on 0.034 MTU in the 14 liters of solution.
3. The ARF and the particle size/distribution from Table 4-1 for Pu spill as liquid are used, 0.114, 2.4 μm, and 3.8, respectively.

4.3.7 Scenario 7 – Small Codecontamination Cycle Solvent Fire

Scenario 7 is derived from DBA Scenario 4 in Section 4.3.4. However, this scenario assumes a smaller pool area than that in Section 4.3.4 but greater depth.

Comments/Assumptions:

1. All 378 liters of solvent are consumed, but the floor area is reduced to 5 m² versus 1080 ft² (i.e., 100 m²) in DBA Scenario 4.
2. All other assumptions in Section 4.3.4 apply.

Summary of Scenario:

1. The fire energy of 1.225x10¹⁰ J is unchanged from Section 4.3.4 but the burn time at the maximum rate increases to 1454 seconds. The maximum burn rate is constrained by the fire start-up time (i.e., 10 sec) and oxygen availability (see Section 4.4.6).
2. The inventory is based on 0.085 MTU in 378 liters of solvent.
3. The radioactive inventory includes volatile, semi-volatile and heavy metals. Using the guidance in Table 4-1 for burning liquids, the ARFs for Pu, other inert, semi-volatile, and volatile elements are 0.114, 0.008, 0.01 and 0.843, respectively. The released aerosols have the following characteristics: AMMD=2.4 µm and GSD=3.8.

4.3.8 Scenario 8 – Smallest Codecontamination Cycle Solvent Fire

Scenario 8 is derived from DBA Scenario 4 in Section 4.3.4 However, this scenario assumes a smaller pool area than that in Sections 4.3.4 and 4.3.7 but a greater depth.

Comments/Assumptions:

1. All 378 liters of solvent are consumed, but the floor area is reduced to 1 m² (10.8 ft²) versus 100 m² (1080 ft²) in DBA Scenario 4.
2. All other assumptions in Section 4.3.4 apply.

Summary of Scenario:

1. The fire energy of 1.225x10¹⁰ J is unchanged from Section 4.3.4 but the burn time at the maximum rate increases to 7269 seconds. The maximum burn rate is constrained by the fire start-up time (i.e., 10 sec) and oxygen availability (see Section 4.4.6).
2. The inventory is based on 0.085 MTU in 378 liters of solvent.
3. The radioactive inventory includes volatile, semi-volatile and heavy metals. Using the guidance in Table 4-1, the ARFs for Pu, other inert, semi-volatile, and volatile elements are 0.114, 0.008, 0.01 and 0.843, respectively. The released aerosols have the following characteristics: AMMD=2.4 µm and GSD=3.8.

4.3.9 Scenario 9 – HAW Concentrator Explosion with an Induced Fire

Scenario 9 is the explosion identified in Section 4.3.1 with a subsequent fire. There are two parts to this scenario. Part 1 specifies the explosion from Section 4.3.1. Part 2 specifies the induced fire.

Comments/Assumptions:

1. The explosion assumptions are described in Section 4.3.1.
2. All 420 liters of solvent from the 600 liters of concentrate are available for the fire.⁹
3. The explosion ignites the 420 liters (or 315 kg) and the fire generates 1.3x10¹⁰ J.

⁹ There is 420 liters of solvent in the HAW (i.e., 600 liters – 180 liters of TBP). All the solvent was assumed to be available for the fire (i.e., neglecting whether it was ignited or dispersed during the explosion).

4. The solvent spreads across 10 m². The maximum kerosene burn rate is 0.039 kg/m²-s for a large pool [15]. The burn rate is assumed to remain constant until all solvent is consumed within the constraints of the fire start-up (i.e., 10 sec) and oxygen availability (see Section 4.4.6).

Summary of Scenario:

Part 1:

1. The explosion energy is 4x10⁸ J, which is released over 10 milliseconds.
2. The connected ventilation systems are expected to fail. However, it is assumed the walls and roof remain intact. Two penetrations are assumed to fail (see Figure 3-2).
3. The available concentrate is 600 liters; and the ratio of TBP to uranium is 567 liter/MTU. However, only 10% participates in the explosion, which yields 0.106 MTU for this scenario.
4. The radioactive inventory includes volatile, semi-volatile, and heavy metal elements. All materials involved in the explosion are vaporized and released (i.e., ARF=1).

Part 2:

1. The fire energy is 1.36x10¹⁰ J with an 807 s burn duration at the maximum burn rate. The maximum burn rate is constrained by the fire start-up time (i.e., 10 sec) and oxygen availability (see Section 4.4.6).
2. There is 0.74 MTU in 420 liter concentrate based on a concentrate to uranium ratio of 567 liter/MTU.⁹
3. The source term consists of volatile, semi-volatile and heavy metals. The ARFs for Pu, other inert, semi-volatile, and volatile elements are 0.114, 0.008, 0.01 and 0.843, respectively. The aerosols are released with the following characteristics: AMMD=2.4 μm and GSD=3.8.

4.3.10 Scenario 10 – Plutonium Concentrator Explosion with an Induced Fire

Scenario 10 is the explosion identified in DBA Scenario 3 in Section 4.3.3 with a subsequent fire. There are two parts to this scenario. Part 1 specifies the same explosion described in Section 4.3.3. Part 2 specifies the induced fire.

Comments/Assumptions:

1. Assumptions in Section 4.3.3 apply for this scenario.
2. It is assumed that the explosion temperature is high enough to ignite a fire with 51 liters¹⁰ (or 38 kg) of kerosene/dodecane at about 1.63x10⁹ J with a burn rate of 0.039 kg/m²-s and a pool area of 1 m².
3. It is assumed that the 50.4 liters of solvent (i.e., 70%) are part of 72 liters of concentrate. 21.6 liters of TBP (i.e., 30%) are available for the explosion as in DBA Scenario 3.

Summary of Scenario:

Part 1:

1. The explosion energy is 1.28x10⁸ J, which is released over 10 milliseconds.

¹⁰ There are 50 liters of solvent in the Plutonium Concentrator (i.e., 72 liters - 22 liters of TBP = 50 liters of solvent). All the solvent was assumed to be available for the fire (i.e., neglecting whether it was ignited or dispersed during the explosion).

2. There are no wall failures, but the connecting ventilation systems are expected to fail.
3. The total MTU in this scenario is 2.48. However, only 25% of volume is involved in the accident, which reduces the participating inventory to 0.621 MTU (see Footnote 7).
4. The radioactive inventory in the 3P concentrator is only Pu. All Pu involved in the explosion (i.e., 25%) is vaporized and released (i.e., ARF=1).

Part 2:

1. The fire energy is 1.63×10^9 J with a 969 s burn duration at the maximum burn rate. The maximum burn rate is constrained by the fire start-up time (i.e., 10 sec) and oxygen availability (see Section 4.4.6).
2. There is 0.214 MTU in the 20.4 liter concentrate based on a concentrate to uranium ratio of 409 liters per MTU.¹¹
3. The ARF and the particle size/distribution from Table 4-1 for a Pu spill are 0.114, 2.4 μ m, and 3.8, respectively.

4.4 Additional Modeling Boundary Conditions

Several additional boundary conditions were implemented to complete the specifications of the ten accident scenarios. The additional boundary conditions include ventilation system failures (Section 4.4.1), HEPA thermal failures (Section 4.4.2), HEPA filter plugging (Section 4.4.3), filter performance (Section 4.4.4), structural failures following a large explosion (Section 4.4.5), fire modeling (Section 4.4.6), and BNFP safety system actuation (Section 4.4.7).

4.4.1 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. Based on scoping calculations of the scenarios described in Section 4.3, the filter media and ventilation dampers would experience high pressures and temperatures. Due to the lack of specific design information on the systems planned for the BNFP, related DOE facility filter testing was used for the filter media. Similarly, no design information was available for the BNFP damper strength. Consequently, a reasonable value was selected that limited the room pressurization.

If the BNFP were built today the BNFP filtration system would likely be governed and designed using applicable Department of Energy (DOE) Office of Environment, Health, Safety and Security (EHS&S) standards (e.g., References [17] and [18]) and the DOE Handbook for Nuclear Air Cleaning [8]. The DOE standards and handbooks include requirements for design performance. The primary requirements for the current accident analysis include an estimate of the mechanical performance in the BNFP Class 5 design basis accidents, which include mechanical and thermal loadings well beyond normal operations. The assumed criteria for filter failure are described next.

¹¹ The 409 liter/MTU solvent to uranium ratio was erroneously taken from DBA Scenario 2, which is the fire in the PPC solvent extraction cycle (see Section 4.3.2). The appropriate value should be 29 liter/MTU, which is the concentration in the PPC plutonium concentrator cycle. Consequently, the fire only generated 7% of the Pu desired. There are other conservatisms in the scenario (e.g., all the Pu in the explosion vaporized and 100% of the solvent burns in the fire).

Experimental testing of HEPA filters under simulated tornado conditions was used to develop reasonable criteria for their failure due to large differential pressures [19]. 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 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.

The ventilation system includes dampers to regulate flow between regions. The dampers were identified as a structure that could fail due to pressurization events. Like the roughing and HEPA filters, it was assumed the dampers would fail fully open when the differential pressure exceeded 1.5 psi.

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.

4.4.2 Thermal Failure of the 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. Like the HEPA pressure failure criteria described in Section 4.4.1, a best-estimate approach was used for the thermal failure criteria.

It was difficult to find thermal HEPA filter testing data. The DOE handbook 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 [20]. 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 factor (ARF) at high temperatures is very low (e.g., ARF=1x10⁻⁴). 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 (see Table 4-3). A few assumed values were inserted to provide a transition between data points from the handbook. The temperature of the gas entering each filter in the MELCOR model was monitored and the cumulative timing to failure was calculated using Equation (13).

$$\int_t = 1/\tau(T_{filter\ inlet}) dt \quad (13)$$

where,

$\tau(T_{filter\ inlet})$	Time to failure from Table 4-3 as a function of the filter inlet temperature
$T_{filter\ inlet}$	Inlet gas temperature into the filter

Table 4-3 Parametric Model for Thermal Failure of HEPA Filters

Temperature (K)	Time to Failure (min)	Reference
<150°C	No failure	Reference [20], Sect 5.4.1, pp 5-30.
150°C	360	Assumed.
175°C	240	Assumed.
200°C	120	Assumed.
400°C	60	Reference [20], Sect 5.4.1, pp 5-30.
500°C	45	Reference [20], Sect 5.4.1, pp 5-30.
825°C	20	Reference [20], Sect 5.4.1, pp 5-30.
850°C	1	Assumed.

Once the thermal failure limit is reached, the filter (a) releases some radioactive material (ARF=1x10⁻⁴, [20]), (b) stops capturing aerosols, and (c) has no more flow resistance.

4.4.3 Plugging of HEPA Filters

Large quantities of soot can be released during fires 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 [21]. The flow resistance increases based on a quadratic fit of the particulate mass on the filter,

$$S_{laminar} = \frac{d_H^2}{2\mu v L} * (0.0019 * W^2 + 0.1943 * W + 227.01) \quad (14)$$

where;

- $S_{laminar}$ laminar flow loss multiplier to the inverse of the HEPA Reynolds Number,
- d_H hydraulic diameter in the HEPA, nominally 0.00105 m,
- μ viscosity of the gas [N-s/m²], nominally 1.777x10⁻⁵ N-s/m²,
- v velocity of the gas through the filter [m/s], nominally 1.270 m/s,
- L filter dimension in the direction of flow [m], nominally 0.3848 m, and
- W mass of particulate on filter [g].

The nominal resistance settings are from the Reference [21] experimental test program. It is assumed the correlation is applicable to the BNFP filters. 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 4.4.1). The mechanical failure of the HEPA filter uses the same airborne release fraction as the thermal failure cited in Section 4.4.2 (i.e., 1x10⁻⁴ from Reference [20]).

4.4.4 HEPA and Roughing 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 [20], 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 current 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. The MELCOR analysis only models the total ruthenium. Consequently, the effective ruthenium transmission through the filter is estimated as the volatile transmission plus the non-volatile transmission. This can be expressed as follows,

$$T_{Ru,total} = T_{Ru,volatile} + T_{Filter}(1 - T_{Ru,volatile}) \quad (15)$$

where;

$T_{Ru,total}$	Total HEPA ruthenium transmission
T_{Filter}	Nominal filter aerosol transmission (i.e., 0.0014)
$T_{Ru,volatile} = 0.001$	Volatile fraction of total ruthenium release in an explosion [1]

The effective ruthenium transmission factor in an explosion is,

$$T_{Ru,total} = 0.001 + 0.0014(1 - 0.001) = 0.0024 \quad (16)$$

and the effective decontamination factor is,

$$DF_{Ru,total} = 1/T_{Ru,total} = 417 \quad (17)$$

Similarly, the effective ruthenium transmission factor in a fire is,

$$T_{Ru,total} = 0.1 + 0.0014(1 - 0.1) = 0.1013 \quad (18)$$

where;

$T_{Ru,volatile} = 0.1$	Volatile fraction of total ruthenium release in a fire [1]
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and the effective decontamination factor is,

$$DF_{Ru,total} = 1/T_{Ru,total} = 9.9 \quad (19)$$

It is also assumed that the roughing pre-filter was not effective at filtering ruthenium so that the magnitude of the volatile release is more accurately calculated.

4.4.5 Structure 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.¹²

4.4.6 Fire Modeling

The fire modeling included the heat sources described in Section 4.3 and the chemical reaction described in Equation (5) from Section 4.2.1.2. 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 m², with a diameter of 8.0 m) and a maximum power of 85 MW. DBA Scenario 4 is even larger (100 m², 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 (see Section 4.2.1). It was assumed that the fire would be oxygen-limited according to Equation (20).

$$\dot{m}_{o_2} = \dot{m}_{max} * \min \left[\frac{(X_{o_2} - X_{no\ burn})}{(X_{limited} - X_{no\ burn})}, 1 \right] \quad (20)$$

where,

\dot{m}_{o_2}	Burn rate as a function of the local oxygen concentration near the fire, X_{o_2}
\dot{m}_{max}	Maximum burn rate with ample oxygen
X_{o_2}	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%

4.4.7 Building Safety Systems

The BNFP FSAR included information on the ventilation safety system controls. The following plant automatic controls are identified,

1. If the pressure at the suction side of the analytical filters (75-K-703 A/B)¹³ approaches atmospheric, then the spare analytical blower starts automatically.

¹² MELCOR does have physics models for a shock wave, the associated pressure impulse, and structural damage during an explosion. A simplified approach was used to simulate the assumed consequences from an explosion. A failure flow path breach was opened when the static pressure rise reached a maximum. The radionuclides released in the explosion could flow directly from the RPC to the filter niche room, which has fewer filtration protections relative the processing cells.

¹³ Identified as Filter 1 on Figure 3-5.

2. When on automatic control, the filter dampers will close if the filter pressure drop exceeds 10 inH₂O. The dampers will stop at 10% to always allow some flow. The signal is delayed by 10 seconds to prevent closure due to short term flow fluctuations. The dampers will re-open when the pressure drop reduces below 10 inH₂O.
3. The process building and analytical exhaust blowers are interlocked with the process building ventilation supply blower. Failure to either maintain a minimum flow (as shown on a flow recorder in the CRA) in the process or laboratory ventilation systems or a rise in pressure above a preset value at the inlet plenum of the Ventilation Filter Station (VFS) or Analytic Filter Station (AFS) shuts down the process building ventilation supply blower (75-G-725).¹⁴ The pressure shutdown function has a 10-second time delay to accommodate system pressure fluctuations.

The signal from the automatic plant control to start a third fan (i.e., number 1 above) was not implemented in the model. There was no design information how a third fan would impact the exhaust flow. Furthermore, the pressure at Analytic Filter Station (75-K-703 A/B) was not expected to be significantly impacted in the design basis accident scenarios. Consequently, only two fans are modeled.

Automatic plant controls 2 and 3 from above were implemented into the BNFP MELCOR model. The dampers closed to 10% if the HEPA filter pressure drop remained above 10 inH₂O for 10 seconds. It was assumed that the dampers would automatically open if the pressure drop subsequently decreased below 5 inH₂O.

The automatic shutdown of the ventilation supply blower (75-G-725) was also implemented into the BNFP MELCOR model. The fan is turned off when the pressure at the fan inlet for the VFS or AFS rose above +0 inH₂O for 10 seconds.¹⁵ The supply blower is assumed to restart when the pressure subsequently dropped below -10 inH₂O. Note that the supply fan shutoff based on high pressure at the AFS would likely be preceded by starting a third exhaust fan (i.e., plant automatic control #1), which was not implemented.

There are two other plant safety systems that were not credited. First, two emergency diesel generators automatically start within 10 seconds following a loss of onsite power. The exhaust fans and main control room instrumentation are connected to the emergency diesel generators. Second, the process cells are protected by a halon fire suppression system. The system is activated by a protection system that monitors for smoke, a rate-of-temperature rise, or high temperature conditions. The halon system is assumed to be unavailable in the accident scenarios.

¹⁴ Identified as 95000 Supply Air on Figure 3-4.

¹⁵ The VFS is identified as Filter 1 and the AFS is Identified as Filter 2 on Figure 3-5.

5 ACCIDENT SOURCE TERM EVALUATIONS

The updated BNFP MELCOR model was used to calculate the accident progression and radionuclide source term for ten accident scenarios. There were two solvent fire scenarios from the BNFP DBA list. Three sensitivity calculations examined the impact of the fire size and duration (see Table 5-1). The fire scenario results are presented in Section 5.1.

Table 5-1 Summary of Key Fire Parameters for the Fire Accident Scenarios

Scenario	Location	Solvent Volume	Fire Size		
			Area	Diameter	Duration
DBA 2	Plutonium Solvent Extraction Cycle	14 liters	50.2 m ²	8.0 m	5.4 sec
Scenario 6			8.36 m ²	3.2 m	32 sec
DBA 4	Codecontamination Cycle	378 liters	100 m ²	11.3 m	72 sec
Scenario 7			5 m ²	2.52 m	24 min
Scenario 8			1 m ²	1.1 m	2.0 hr

There are three “red oil” explosion scenarios. The results of the explosion scenarios are discussed in Section 5.2. Finally, two scenarios are initiated with an explosion that induced a fire. The results of the combined explosion and fire scenarios are presented in Section 5.3. The first five scenarios prescribed in Section 4.3 were based on the Class 5 Design Basis Accident evaluations from the FSAR. Although the FSAR and current calculations released different amounts of radioactive materials, the overall building and filtration decontamination factors can be compared.

As described in Section 2, the present analysis differs from the five factor DOE approach. It also differs from the historical BNFP FSAR approach. The present approach models the full inventory of radionuclides released from the initiating event and tracks its transport through the building to the environment. MELCOR’s best-estimate aerosol physics models predict rates of agglomeration and deposition. Since the material at risk (MAR) and the airborne release fraction (ARF) were updated for the present analysis, it is not meaningful to compare the activity source term to the environment (i.e., different burn-up and aging assumptions, see Section 3.3). However, it is interesting to compare the transport from the initiating event (i.e., the fire or explosion) to the environment (i.e., the LPF). Rather than using the LPF as the figure of merit, it is more customary to use an effective building decontamination factor. The effective building decontamination factor is simply the reciprocal of the LPF (i.e., 1/LPF). In the present analysis, it includes all leakage, bypass, and filtered releases. In the historical BNFP analysis, the LPF only considered filtered releases. The source term formula from the BNFP FSAR is similar to the 5 factor DOE approach but used slightly different nomenclature. Section 5.4 discusses the BNFP FSAR source term formula and presents a comparison of the calculated MELCOR building decontamination factor to the results from the FSAR.

In the radionuclide distribution results presented in Section 5, 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 subsequent transport of the activity outside the building is outside the scope of a MELCOR calculation. The exhaust system includes the filters and associated ducting to the plant stack. The hot cells are the process cells as indicated in Figure 3-1 and Figure 3-2. 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).

5.1 Fire Scenarios

Results of the solvent fire accident scenarios in the solvent extraction cycle and codecontamination cycle are presented in Sections 5.1.1 and 5.1.2, respectively.

5.1.1 Solvent Fire in the Plutonium Solvent Extraction Cycle

The initial and boundary conditions for the solvent fire in the solvent extraction cycle are described in Section 4.3.2, which is identified as DBA Scenario 2 from the BNFP FSAR [1]. Scenario 6 is a sensitivity calculation where the size of the fire was smaller, but it burned longer. Both scenarios specify a 14 liter spill from the 3AP stream, which carries the organic stream with the highest plutonium content. The fire surface area of DBA Scenario 2 is 540 ft² with a burn duration of 5.4 seconds at the maximum consumption rate. Scenario 6 has a fire surface area of 90 ft² and a burn duration of 32.2 seconds at the maximum consumption rate.¹⁶ The fires take place in the Plutonium Processing Cell (PPC). The airflow from the PPC normally goes through Filter 7 and then Filter 1 before venting through the stack to the environment (see Figure 3-5).

The timing of key events for the two sequences is shown in Table 5-2. The DBA Scenario 2 calculation assumed the spill covered the entire floor (540 ft²). The fire can reach a maximum power of 85 MW at the maximum solvent burn rate. However, the large fire never reached the maximum power before burning all the solvent. In contrast, the smaller surface area fire in Scenario 6 has a maximum power of 14 MW and did reach its maximum power. Both fires produce the same amount of energy (i.e., both burned 14 liters).

Figure 5-1 shows the buildup of the fire versus the oxygen concentration near the floor of the PPC cell for the large fire (i.e., DBA Scenario 2). The fire reaches 35 MW before consuming all the solvent. The oxygen concentration near the floor dropped to a minimum of 11% rapidly when the fire burned out. If the fire continued longer, then the magnitude of the fire would become oxygen-limited (see modeling discussion in Section 4.4.6). The room gas temperatures reached >1250°F as the fire reached its maximum power (see Figure 5-3) but rapidly cooled thereafter. All the solvent was burned by 25.4 s. As noted in Table 5-2, the flow of hot gases from the PPC increased the exhaust fan inlet temperature above 250°F by 15.7 s.

The rapid heating from the large fire pressurized the PPC and caused failures of inlet and exhaust dampers to the PPC as indicated in Table 5-2. During the pressurization in the PPC from the fire, there was radionuclide leakage into the Head Tank Gallery (HTG), the Pulsar Equipment Gallery (PEG), the Lower Piping and Instrumentation Gallery (LPIG), and the Filter Piping and Instrument Gallery (FPIG) as well as through the normal exhaust to Filter 7. The differential pressure across Filter 7 exceeded 10 inH₂O at 16.7 sec, which automatically

¹⁶ The fires included a start-up period as they linearly increased to the maximum solvent burn rate. It is assumed that the large fires (i.e., Scenarios 2 and 4) build towards the maximum power over 60 seconds whereas the smaller fires (i.e., Scenarios 6, 7 and 8) only require 10 seconds. If the fire becomes oxygen-limited, then it will burn slower than the maximum rate and take longer to consume the solvent (see Section 4.4.6 for additional details).

caused the Filter 7 dampers to close 10 seconds later (see Section 4.4.7). However, the differential pressures across the Filter 1 and 7 components remained well below their estimated failure pressures of 1.5 psid (see Figure 5-3).

In Scenario 6, the smaller fire had fewer structural failures since it burned more slowly (see Table 5-2). The heating of the air in the PPC over-pressurized the inlet damper from the HTG&PEG after it closed to prevent backflow. However, there were no other failures as the normal exhaust path to Filter 7 and the increased leakage to the HTG&PEG subsequently reduced the pressure in the PPC. All the solvent was consumed by 37.2 s.

Table 5-2 Summary of Key Event Timings for the Solvent Fire in the Plutonium Solvent Extraction Cycle

Event Timing [s]	DBA Scenario 2	Scenario 6
Start of building pressure/flow steady state balance	-10,000	-10,000
Start of the solvent fire (14 liters)	0.0	0.0
Failure of the PPC outlet damper (>1.5 psid)	5.0	5.0
Failure of the inlet damper from the HTG&PEG (>1.5 psid)	9.7	9.7
Failure of the inlet damper from the FPIG (>1.5 psid)	12.9	n/c
Failure of the inlet damper from the LPIG (>1.5 psid)	12.9	n/c
High exhaust fan inlet temperature (>250°F)	15.7	21.7
High Filter 7 ΔP (>10 inches)	16.7	n/c
All solvent is burned	25.4	37.2
Filter 7 damper closes to 10% to protect filter	26.7	n/c
Filter 7 ΔP <10 inches	28.2	n/c

n/c = not calculated

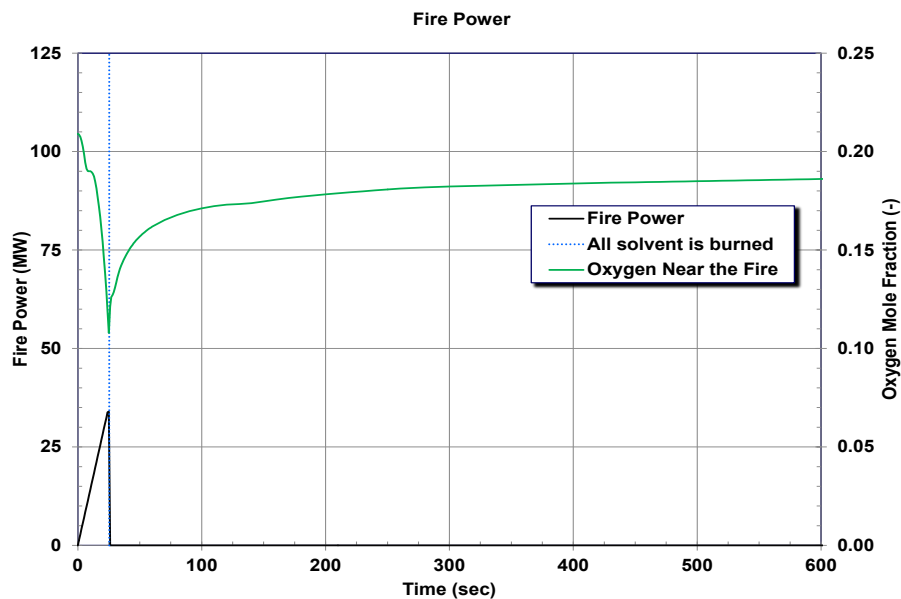


Figure 5-1 Fire Power and Oxygen Concentration near the Fire

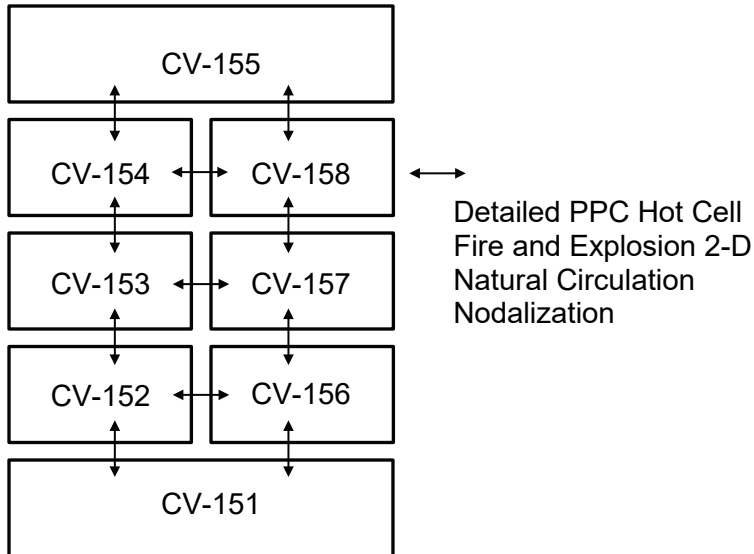
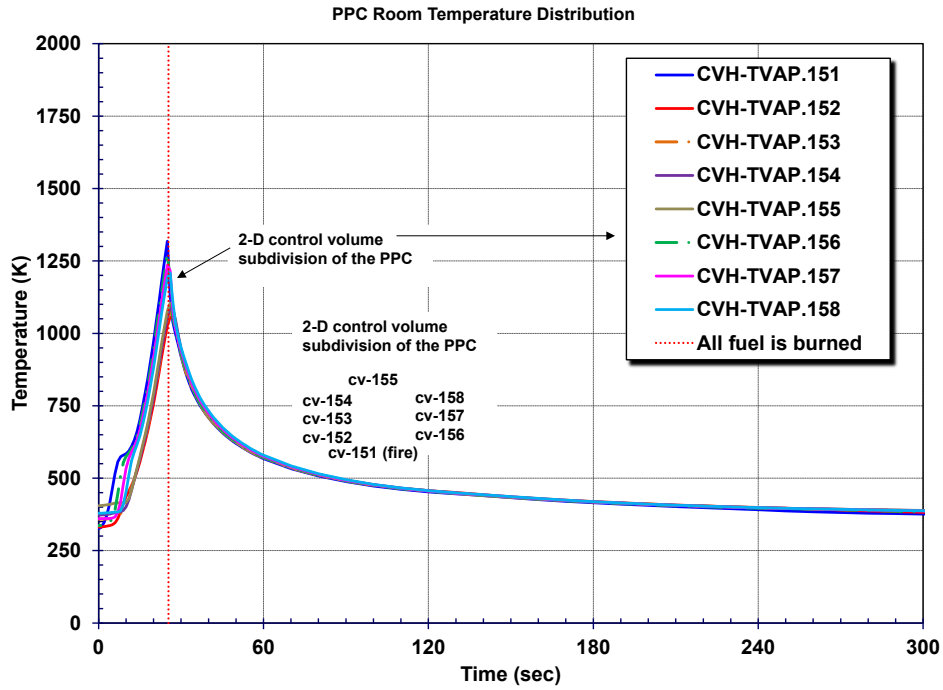


Figure 5-2 Temperature Distribution in the PPC during Solvent Fire Scenario 2, with a Representation of the Modeled Sub-divisions within the PPC Control Volume

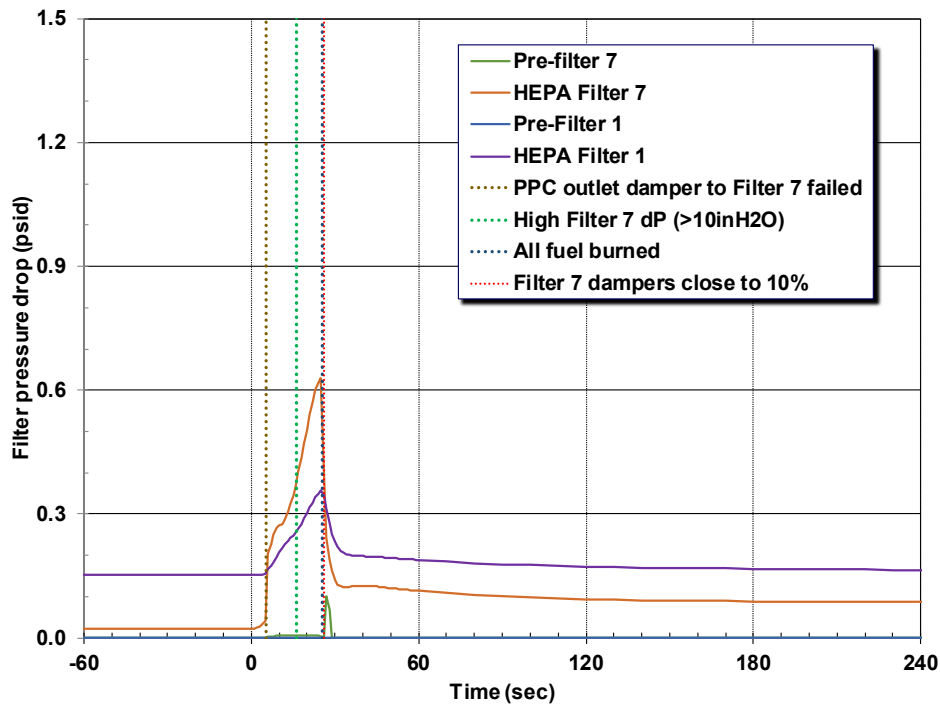


Figure 5-3 Filter Pressure Drops during Solvent Fire Scenario 2

The radionuclide behavior for DBA Scenario 2 is shown in Figure 5-4 through Figure 5-7. The 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 HTG, the PEG, the LPIG, and the FPIG as well as through the normal exhaust to Filter 7. Figure 5-4 shows the distribution of the activity through various regions in the facility as it leaves the PPC (i.e., included in the hot cell group). Most of the released activity is captured in the exhaust filtration system, especially Filter 7 (see Figure 5-5). Filter 7 filters the exhaust from the PPC and is placed 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 PPC. Figure 5-5 shows Filters 2 and 5 also capture some of the released activity. Any activity that bypasses Filters 3 through 8 is also filtered by Filters 1 and 2 (see filtration diagram, Figure 3-5). However, much of the activity transported to final filters are very small aerosols that are not captured efficiently (see Section 4.4.4 for the filtration effectiveness versus particle size).

Figure 5-6 shows that very little activity was released from the building leakage pathways. Essentially all the activity released to the environment went through Filters 1 and 2 to the plant stack. Since the filters were intact, the released activity consisted of very small particles that are not captured in HEPA filters (i.e., see filter performance assumptions in Section 4.4.4). All the released activity was plutonium (i.e., DBA Scenario 2 occurred in the plutonium solvent extraction cycle, see Figure 5-7).

Figure 5-4 shows the total source term to the environment for DBA Scenario 2 was 1.17×10^{12} Bq, or 31.6 curies. The filtration system captured 1.54×10^{13} Bq, or 415 curies. A very much smaller quantity (i.e., 9,200 Bq) was released from other unfiltered leakage pathways to the environment. 1.73×10^{12} Bq or 46.8 curies were spread throughout the building.

Figure 5-8 shows activity distribution for a smaller and longer duration fire (i.e., Scenario 6) but with the same amount of released activity (see the scenario description in Section 4.3.6). The total source term to the environment for Scenario 6 was 7.33×10^{11} Bq, or 19.8 curies. The results of Scenario 6 were similar to DBA Scenario 2 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 and captured on the filters. Filter 7 captures most of the radionuclide mass and soot from the fire (see Figure 5-9). The filtration system captured 1.46×10^{13} Bq as shown in Figure 5-7, or 396 curies. A very much smaller quantity (i.e., 2,300 Bq) was released from other unfiltered leakage pathways to the environment. 2.02×10^{12} Bq or 54.7 curies were spread throughout the building.

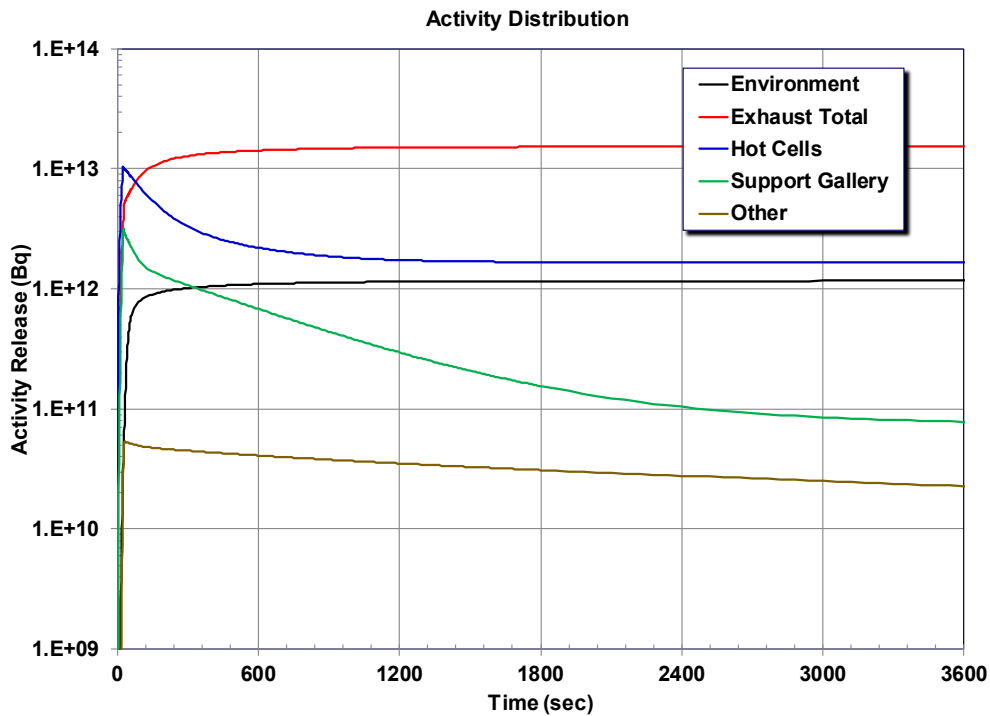


Figure 5-4 Activity Distribution within the BNFP during Solvent Fire Scenario 2

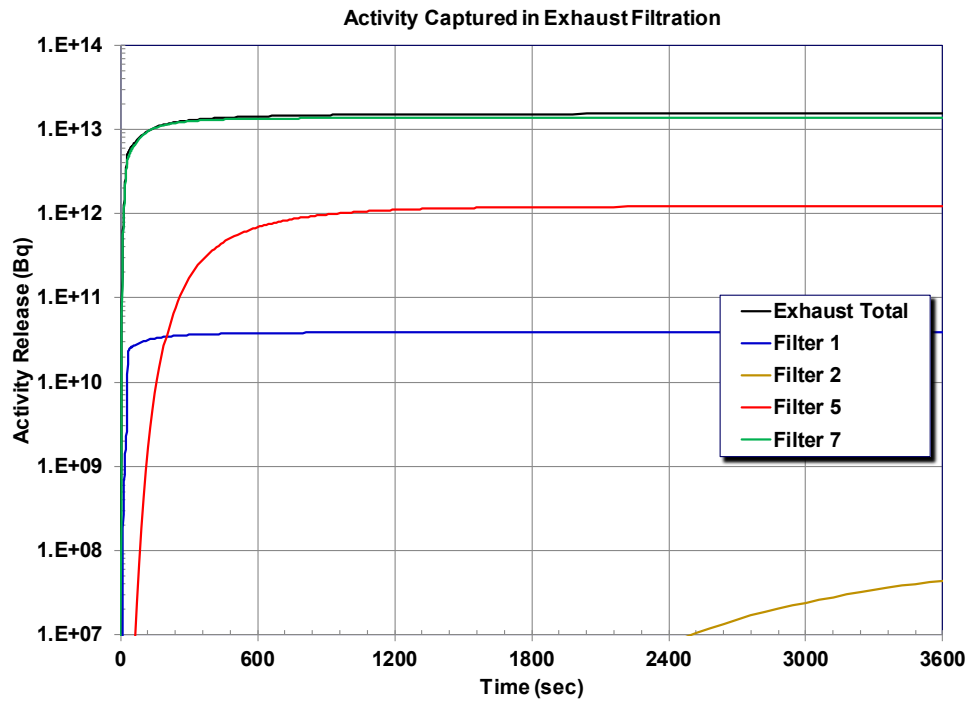


Figure 5-5 Activity Captured in the BNFP Filtration System during Solvent Fire Scenario 2

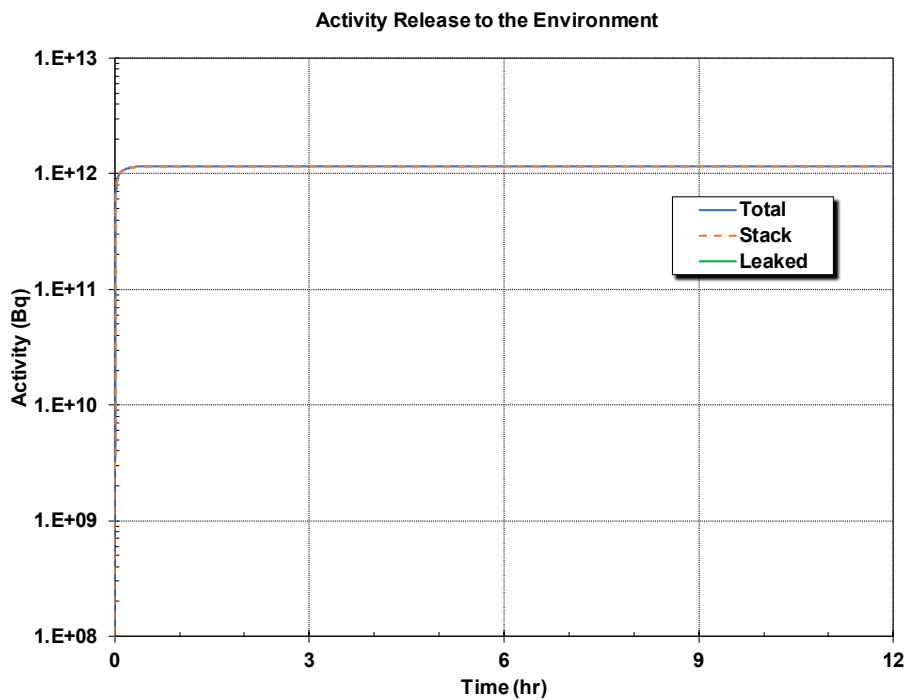


Figure 5-6 Comparison of Activity Vented through the Stack versus Unfiltered Building Leakage Paths during Solvent Fire Scenario 2

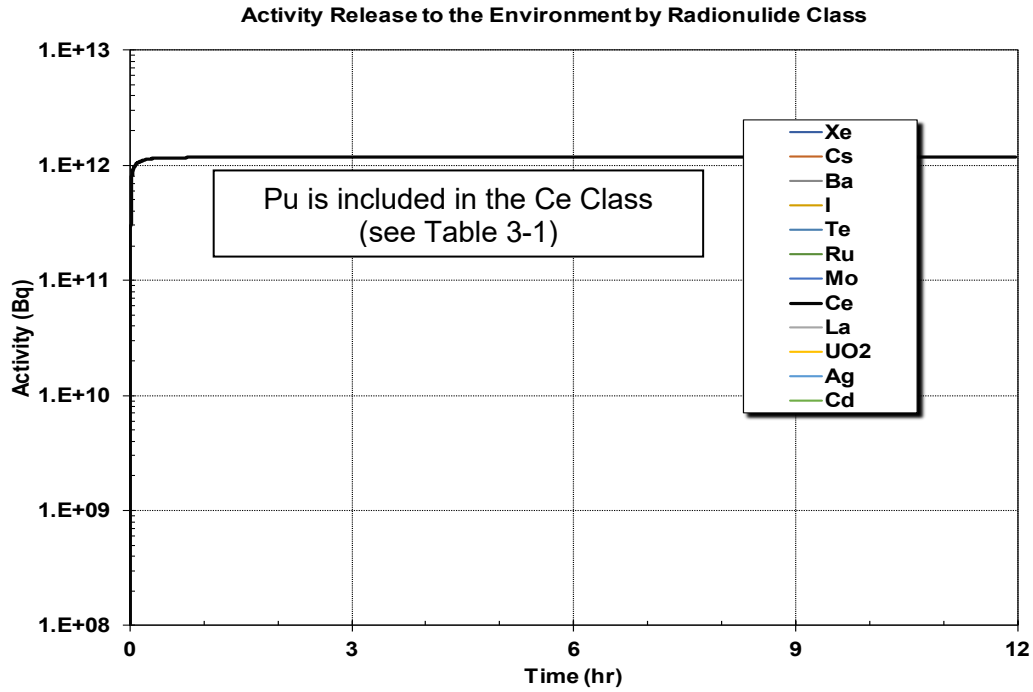


Figure 5-7 Radionuclide Composition of the Activity Released to the Environment during Solvent Fire Scenario 2

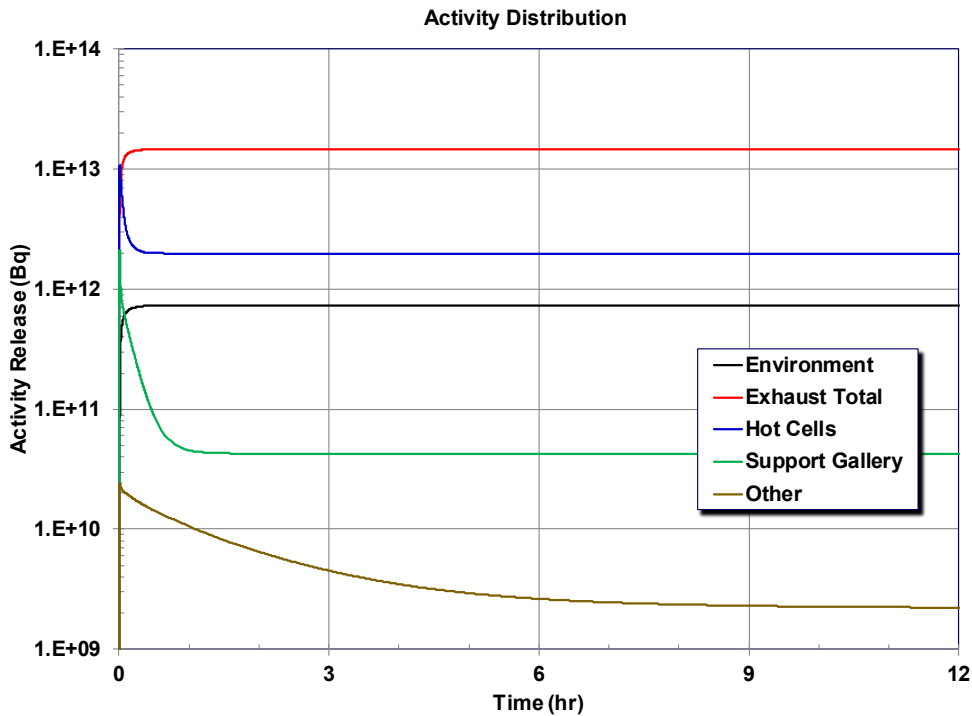


Figure 5-8 Activity Distribution within the BNFP during Solvent Fire Scenario 6

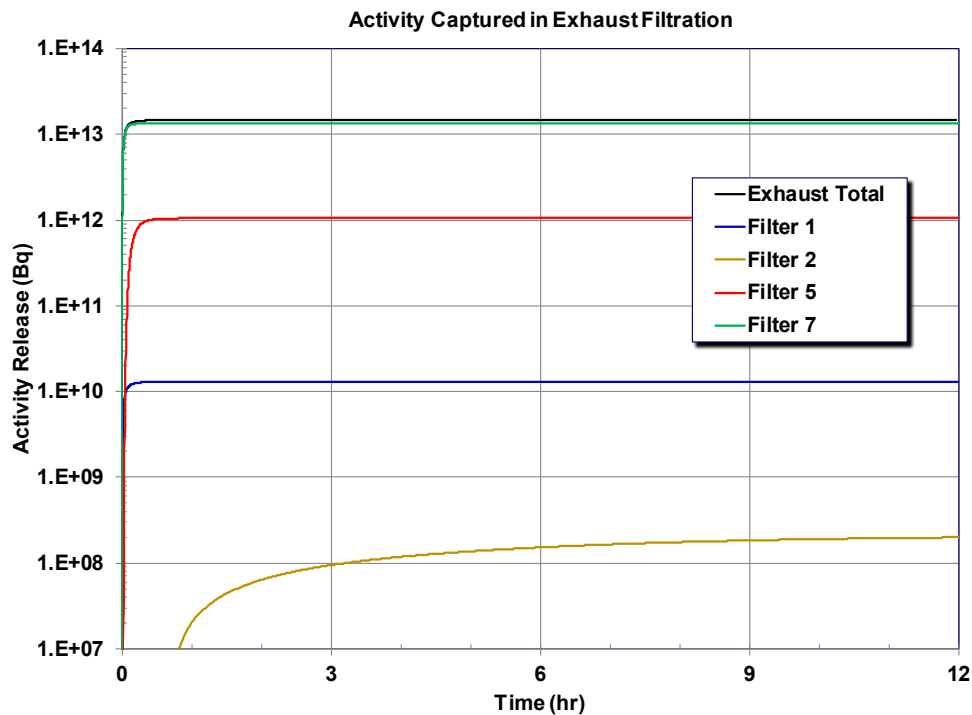


Figure 5-9 Aerosol Capture on the Filters during Solvent Fire Scenario 6

5.1.2 Solvent Fire in the Codecontamination Cycle

The initial and boundary conditions for the solvent fire in the solvent extraction cycle are described in Section 4.3.4, which is identified as DBA Scenario 4 from the BNFP FSAR [1]. 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 the HAP line carrying the organic solvent bearing U, Pu, and some fission products between the HA contactor and the HS scrub column. The fire surface area of DBA Scenario 4 is 1080 ft² (100 m²) with a burn duration of 72.4 seconds at the maximum consumption rate.¹⁷ Scenarios 7 and 8 have a fire surface area of 53.8 ft² (5 m²) and 10.8ft² (1 m²), 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 3-5).

The timing of key events for the three sequences are shown in Table 5-3. 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 is assumed to build towards the maximum power over

¹⁷ If the fire becomes oxygen-limited, it will burn slower than the maximum rate and take longer to consume the solvent (see Section 4.4.6 for additional details).

60 seconds whereas the small fires only required 10 seconds (i.e., Sensitivity Scenarios 7 and 8).

Figure 5-10 shows the buildup of the fire and the oxygen concentration near the floor of the HILC for the large fire. The 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, see Section 4.4.6). The room gas temperatures approach 1400°F as the fire reached its maximum power (see Figure 5-11) 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 5-3, 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 HILC from the fire, there was radionuclide leakage into the HTG and the PEG as well as through the normal exhaust to Filter 5. The differential pressure across Filter 1 exceeded 10 inH₂O 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 10 inH₂O, 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. As shown in Figure 5-13, 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 5-3). 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 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.

Table 5-3 Summary of Key Event Timings for the Solvent Fire in the Plutonium Solvent Extraction Cycle

Event Timing [s]	DBA Scenario 4	Scenario 7	Scenario 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 (>1.5 psid)	4.3	9.4	n/c
Failure of the inlet damper from the HTG&PEG (>1.5 psid)	10.2	n/c	n/c
High exhaust fan inlet temperature (>250°F)	11.5	49.2	n/c
High Filter 1 ΔP (>10 inches)	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 (>10 inches)	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 <10 inches	1305	n/c	n/c
Filter 1 damper opens to 100%	1305	n/c	n/c

n/c = not calculated

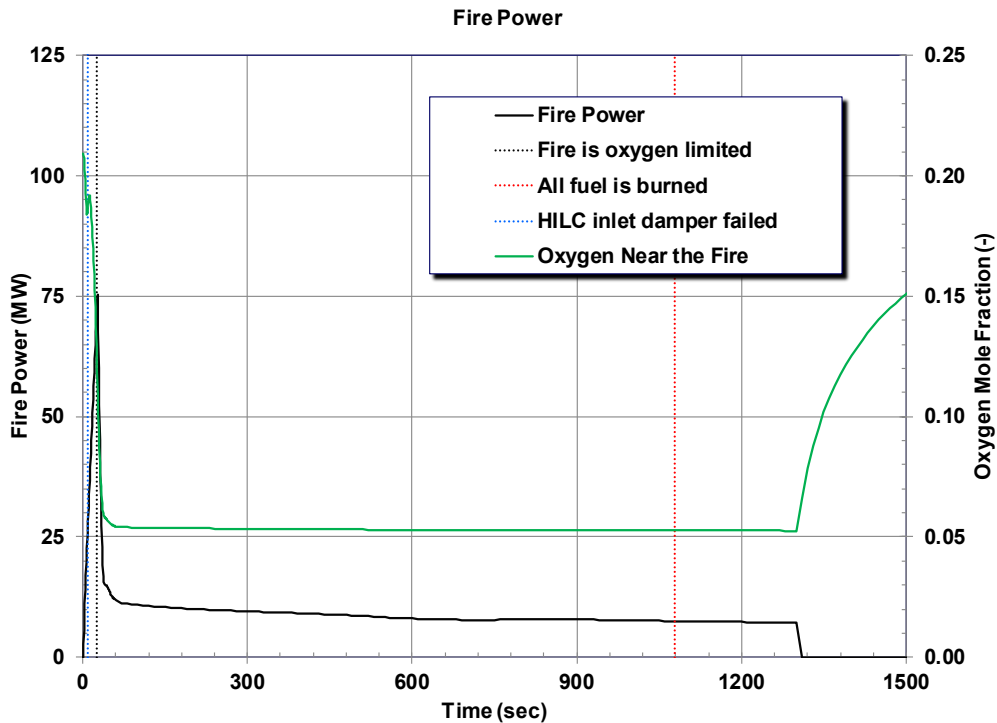


Figure 5-10 Fire Power and Oxygen Concentration near the Fire

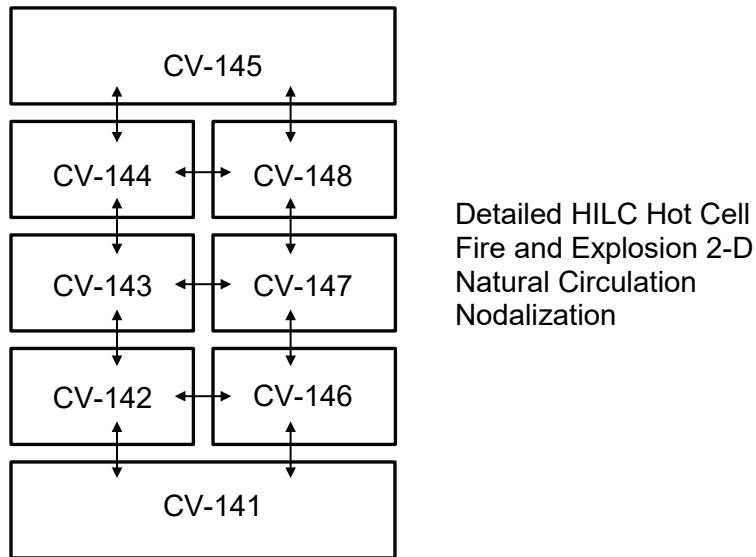
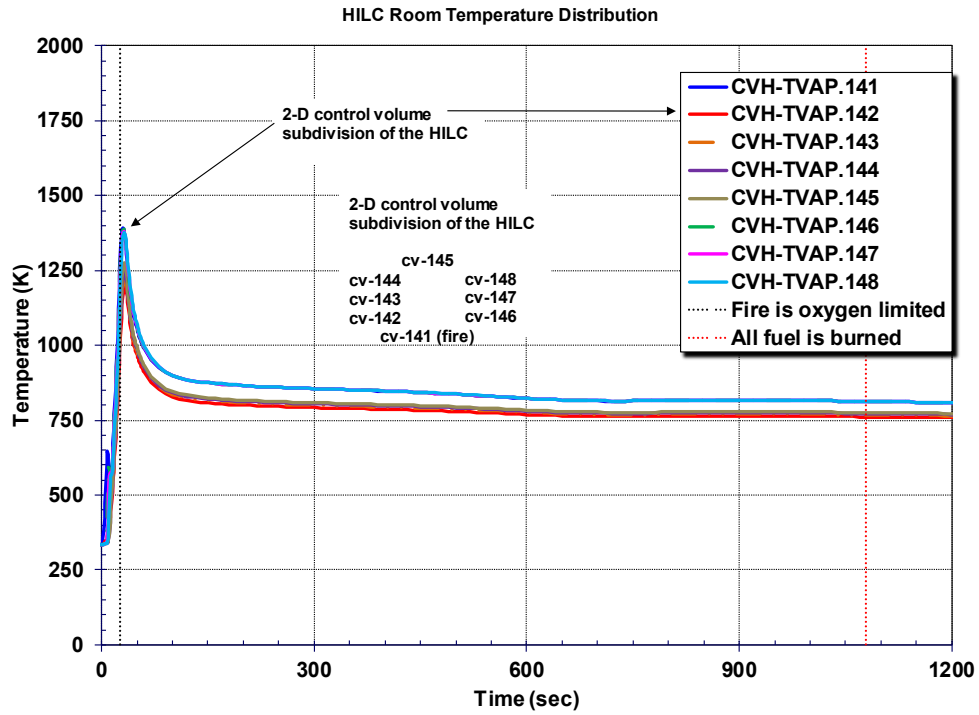


Figure 5-11 Temperature Distribution in the HILC during Solvent Fire Scenario 4, with a Representation of the Modeled Sub-divisions within the PPC Control Volume

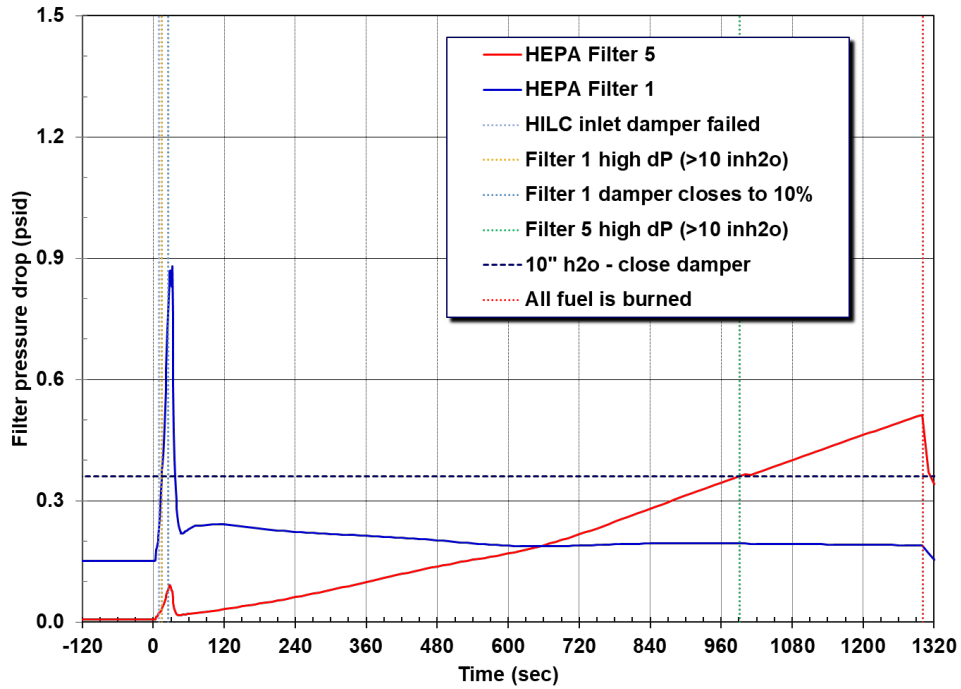


Figure 5-12 Filter Pressure Drops during Solvent Fire Scenario 4

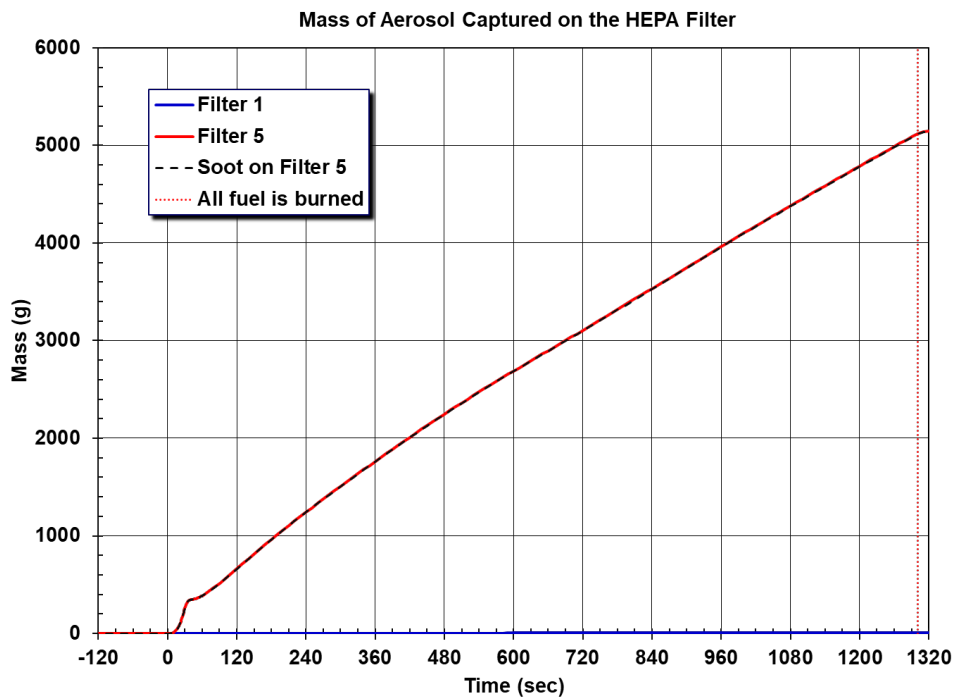


Figure 5-13 Filter 1 and 5 Mass Loadings during Solvent Fire Scenario 4

The radionuclide behavior for DBA Scenario 4 is shown in Figure 5-14 through Figure 5-17. The 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 HTG and the PEG as well as through the normal exhaust to Filter 5. Figure 5-14 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 (see Figure 5-15). 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. Figure 5-15 shows Filter 7 also captured some of the released activity but a negligible amount was captured by Filter 2 (see $<10^7$ Bq). Any activity that passes Filter 5 to Filter 1 is only small aerosols (see Section 4.4.4 for a discussion of the filter performance assumptions). The primary pathway to the environment was through the stack (see Figure 5-16). Most of the aerosols going to the stack through Filter 1 and 2 were pre-filtered by the other filters. Consequently, Filters 1 and 2 were ineffective at capturing any more activity (i.e., the activity captured by Filter 1 and 2 in Figure 5-15 is much lower than the amount of activity reaching the environment in Figure 5-14).

DBA Scenario 4 included fission products, so the fire released many types of radionuclides (see Figure 5-17). The highest releases were from the radionuclide class containing cesium, followed by ruthenium and cerium (i.e., the cerium group includes Pu, see MELCOR chemical groups in Table 3-1). The ruthenium class includes volatile gaseous ruthenium, which is not captured on the filter. The total source term to the environment for DBA Scenario 4 was 1.88×10^{11} Bq, or 5.09 curies; the filtration system captured 1.27×10^{12} Bq, or 34.4 curies; and 1.94×10^{12} Bq, or 52.4 curies were spread throughout the building.

The environmental release in Scenario 4 (1.94×10^{12} Bq, 52.4 curies) was about 65% larger than Scenario 2 (1.17×10^{12} Bq, 31.6 curies). Scenario 4 occurred in the codecontamination cycle with 0.039 MTU of the fuel inventory with the leaked solvent versus 0.085 MTU in Scenario 2. The Scenario 4 radionuclide inventory included volatile fission products such as ruthenium and iodine whereas Scenario 2 only had plutonium. Plutonium has an extremely low vapor pressure and transports as a particulate from the fire. In contrast, gaseous ruthenium and iodine are released in the Scenario 4 fire that pass 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 5-17). 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.

Figure 5-18 compares the total activity release to the environment for Scenarios 4, 7, and 8. The total source term to the environment for Scenario 7 was 1.79×10^{11} Bq, or 4.9 curies. Scenario 8 had 1.79×10^{10} Bq, or 0.84 curies, while for scenario 4, as mentioned above, the total source term was 1.94×10^{12} Bq, or 52.4 curies. 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 (see Figure 5-9).

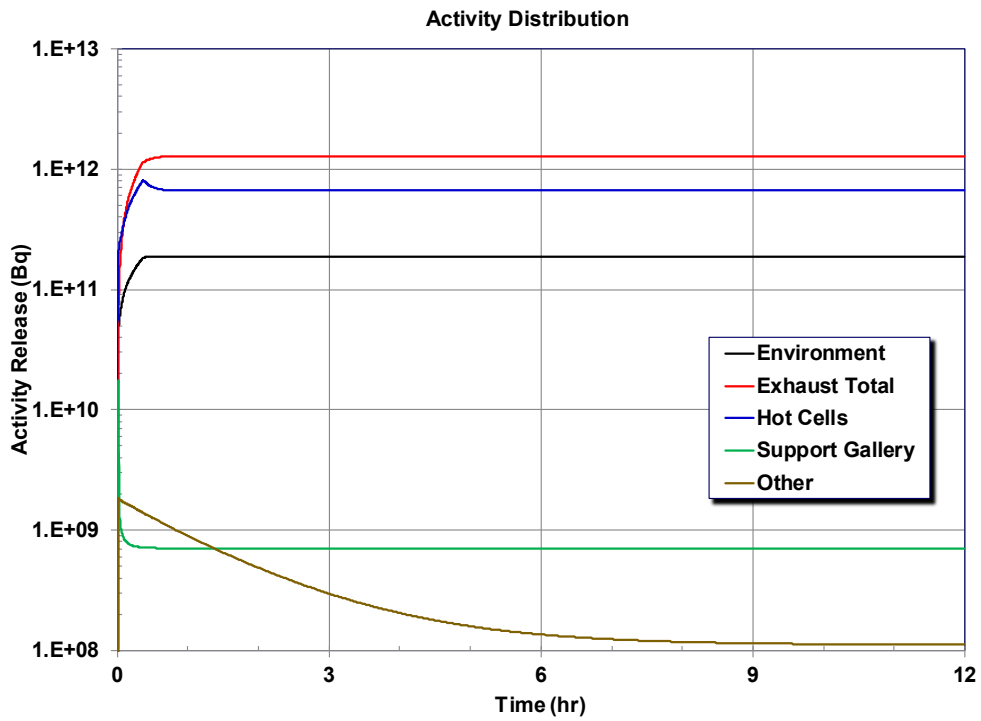


Figure 5-14 Activity Distribution within the BNFP during Solvent Fire Scenario 4

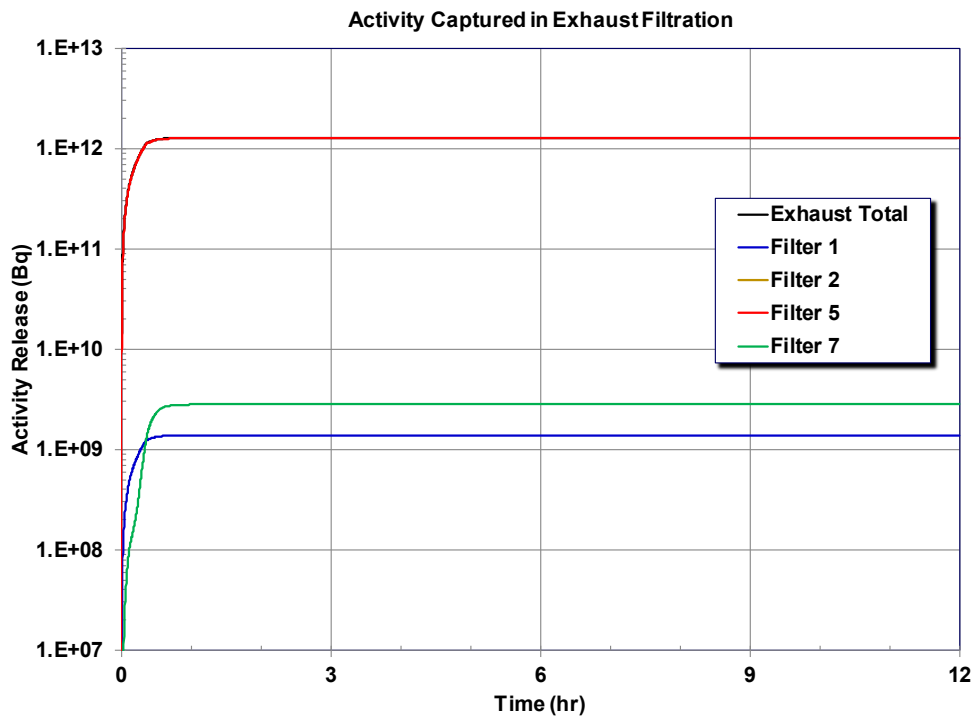


Figure 5-15 Activity Captured in the BNFP Filtration System during Solvent Fire Scenario 4

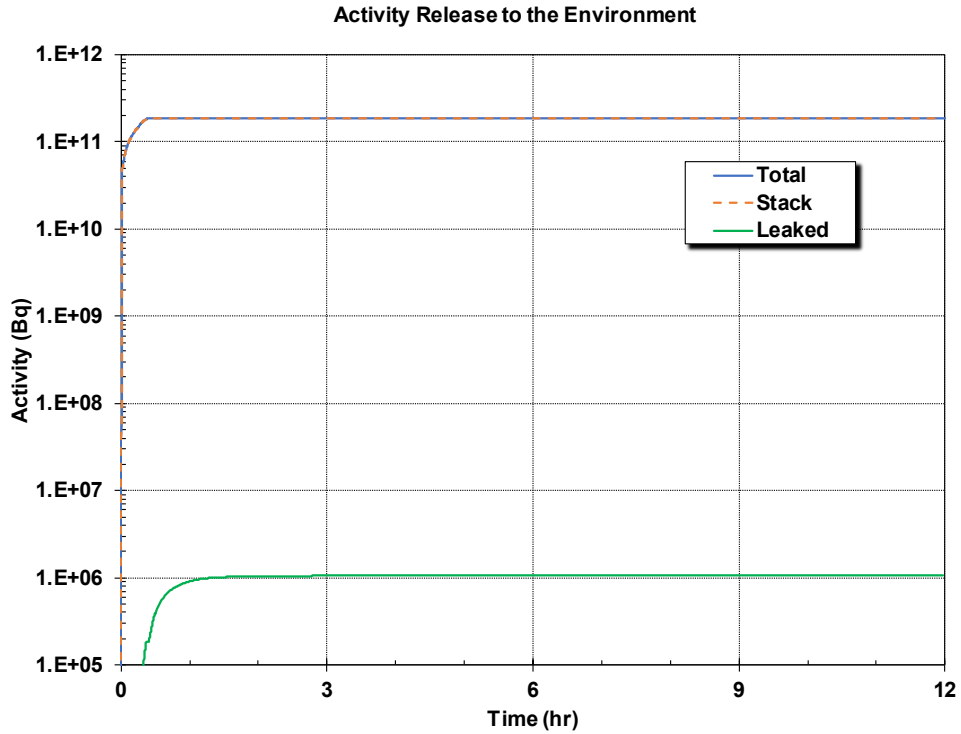


Figure 5-16 Comparison of Activity Vented through the Stack versus Unfiltered Building Leakage Paths during Solvent Fire Scenario 4

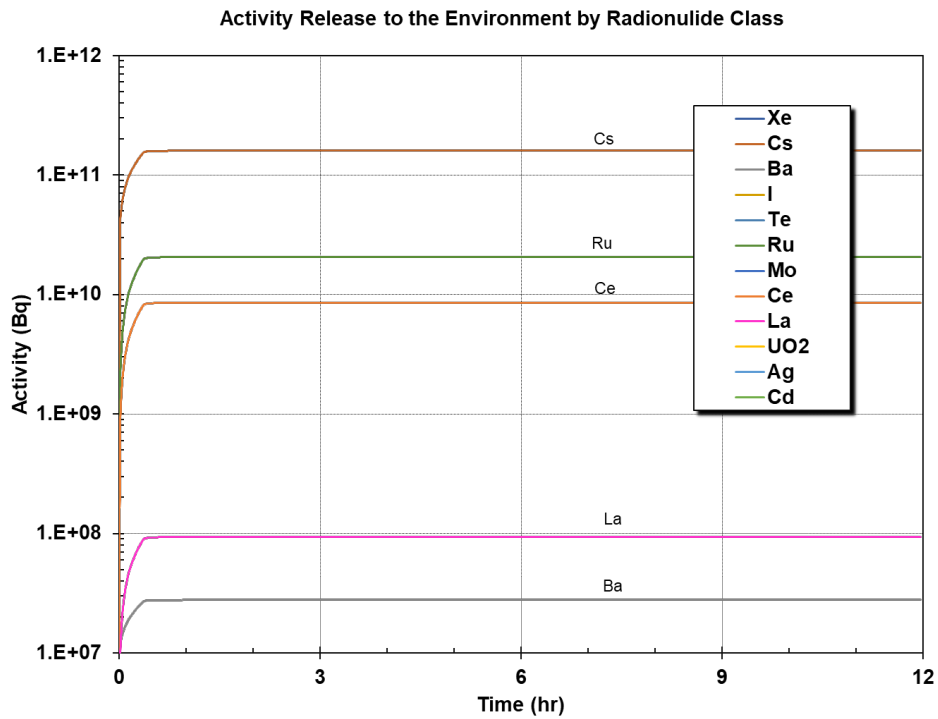


Figure 5-17 Radionuclide Composition of the Activity Released to the Environment during Solvent Fire Scenario 4

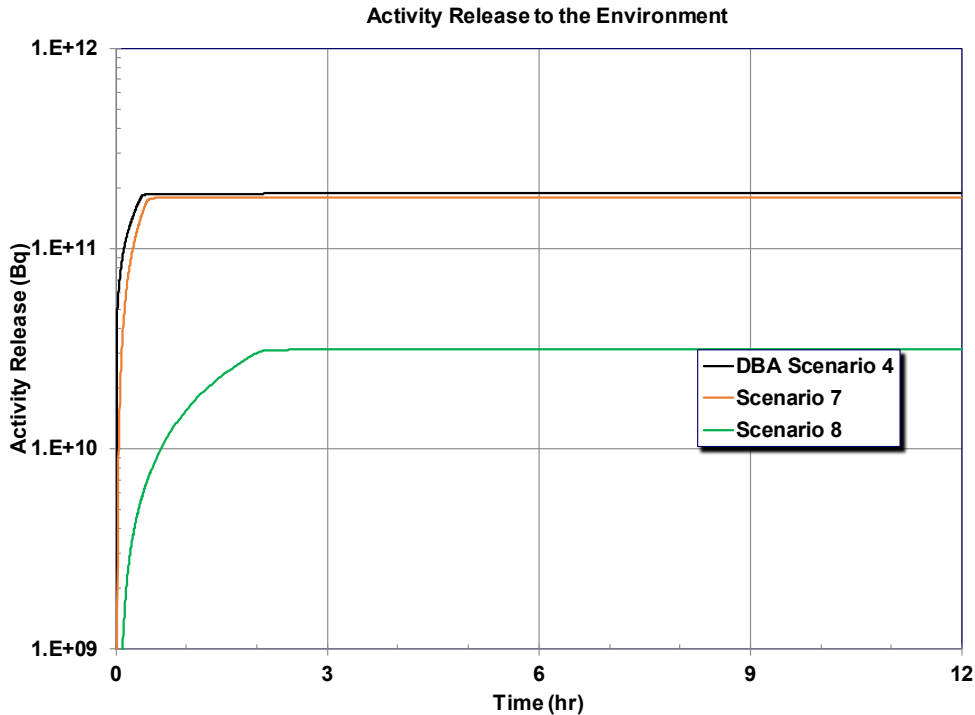


Figure 5-18 Activity Released to the Environment for Scenarios 4, 7, and 8

5.2 Explosion Scenarios

The “red oil” explosion accident scenarios in the high-activity waste (HAW), plutonium, and low-activity waste concentrators are presented in Sections 5.2.1, 5.2.2, and 5.2.3, respectively.

5.2.1 HAW Concentrator Explosion

DBA Scenario 1 from the BNFP FSAR is a “red oil” explosion in the High-Activity Waste (HAW) concentrator in the Remote Processing Cell (RPC) [1]. The scenario specifies 10% of the TBP in the concentrator is involved in the explosion. The resulting explosion has a TNT equivalent weight of 200 lb, which is the largest explosion in this report. The explosion has an energy of 4.27×10^8 J, which is released over 10 milliseconds. Two variations of the calculation were performed. The base calculation assumed power is available for the exhaust and supply fans and a second sensitivity calculation assumed the building power failed during the explosion.

The timings of key events are in Table 5-4 for the two sequences. The lack of power for the ventilation fans did not have a significant impact of the various failure timings during the explosion. The explosion caused a large pressure rise (see Figure 5-19) that failed all dampers connected to the room (i.e., the dampers from the RPC to the PPC, HILC, and ILC). The dedicated roughing and HEPA filters in the Filter 4 compartment failed during the explosion. The penetrations between the RPC and the adjacent filter niche region also failed.

Figure 5-19 and Figure 5-20 show the pressure and temperature response in the room. It is assumed that the shock wave is largely dissipated into the thick RPC cell walls. However, the consequences of the resulting static pressurization and gas heating are tracked throughout the facility. The RPC room pressure immediately drops below 10 psig following the expansion of the explosion energy addition throughout the RPC. The high RPC pressure fails all the connecting

ventilation dampers and the filter media in the Filter 4 compartment. The penetrations to the filter niche fail open at the time of the peak room pressure. The high temperature gases from the explosion expand throughout the room and escape through the failure locations. The long (5 minute) time scale in Figure 5-20 shows the RPC room temperature subsequently returns to ambient conditions once the pressure has dissipated and cool air from the surrounding rooms flows into the RPC.

The final filter compartments prior to the stack (i.e., Filters 1 and 2, see Figure 3-5) were monitored for failure. In the base scenario with the fans operating, the pressure drop across the HEPA filter exceeded 10 inH₂O at 2.0 s and 1.5 psid by 2.6 s as the high pressure in the RPC dissipated throughout the ventilation system and the building. Consequently, the Filter 1 HEPA was predicted to fail although the less efficient pre-filter remained intact. In contrast, the BNFP FSAR implicitly assumed the final filter remained intact. Filters 1 and 2 provide the final filtering before venting to the stack.

Figure 5-21 shows the pressure drops across HEPAs in Filter Compartments 1 and 4. The immediate pressurization from the explosion destroyed all filter components in the Filter Compartment 4, which filters gases leaving the RPC. On a slightly longer time scale, the RPC depressurizes into the ventilation system and surrounding rooms. The pressure near the HEPA element in Filter 1 increased above the setpoint for isolation by 2.0 s (10 inH₂O) and above the failure pressure at 2.5 s. All other HEPA filters remained intact, including Filter 2, which is the final filter for regions outside the hot cells. In the calculation without power, there was no additional pressure drop caused by the fan flow. Consequently, the pressurization of the Filter 1 HEPA was slightly slower than the base case with fans (i.e., at 3.0 s, see Figure 5-22).

Also included in Figure 5-21 and Figure 5-22 is the gage pressure in the AFS and VFS. When power is available, the building automatic safety controls trip the process building ventilation supply blower (75-G-725) if the gauge pressure increases above +0 psig (see Section 4.4.7). The pressure is monitored at the fan inlet location, which is usually significantly below +0 psig (i.e., approximately -1.2 psig during the steady state). As the pressure from the explosion is dissipated through the building, the VFS increases above +0 psig for a few seconds in the base calculation with power. However, the VFS returns to subatmospheric conditions before the 10 second delay to trip the supply fan (see Figure 5-21). In the calculation without power, both the VFS and AFS exceeded +0 psig. However, all fans had lost power due to the assumed damage of the electrical system during the explosion. Consequently, the high VFS and AFS pressure signals were not relevant.

Table 5-4 Summary of Key Event Timings for the Explosion in the HAW Concentrator

Event Timing [s]	No Power Failure	Power Failure ^A
Start of bldg. pressure/flow steady state balance	-10,000	-10,000
Explosion	0.0	0.0
RPC outlet damper to Filter 4 fails (>1.5 psid)	<0.01	<0.01
RPC inlet damper from the CMEG fails (>1.5 psid)	<0.01	<0.01
RPC inlet damper from the GVOS fails (>1.5 psid)	<0.01	<0.01
Pre-filter 4 fails (>1.5 psid)	<0.01	<0.01
RPC penetrations to Filter Niche Room fail	<0.01	<0.01
HEPA filter 4 fails	<0.01	<0.01
Failure of supply and exhaust fans	n/c	<0.01
Explosion ends	0.01	0.01
High pressure at the VFS (> +0 psig)	1.0 ^B	1.0
High pressure at the AFS (> +0 psig)	n/c	1.2
High HEPA filter 1 ΔP (>10" inH ₂ O)	2.0	2.0
High exhaust fan inlet temperature (>250°F)	2.6	2.5
HEPA filter 1 fails (>1.5 psid)	2.6	3.0
Filter 1 damper closes to 10%	n/c	n/a
Supply fan (75-G-725) tripped	n/c	n/a

n/c = not calculated

n/a = not applicable because no power was available

Notes:

A All onsite power is lost during the explosion and all ventilation fans fail.

B The high AFS or VFS plenum pressure exceeded +0 psig but did not last longer than 10 s, so the process building ventilation supply blower (75-G-725) did not trip.

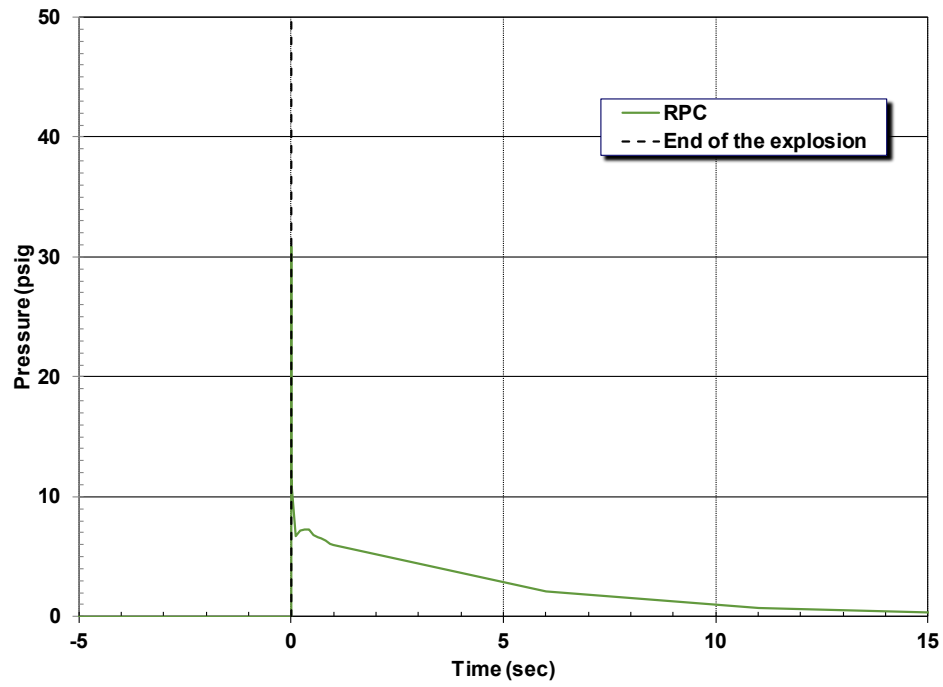
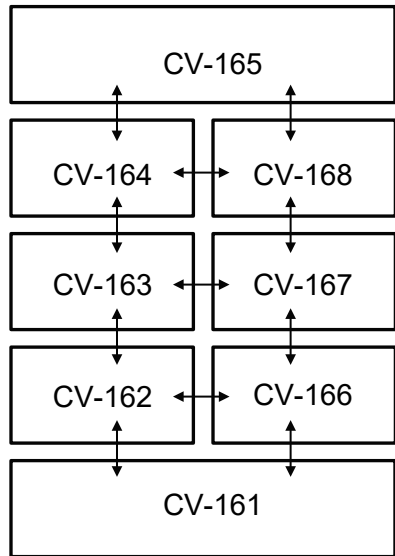
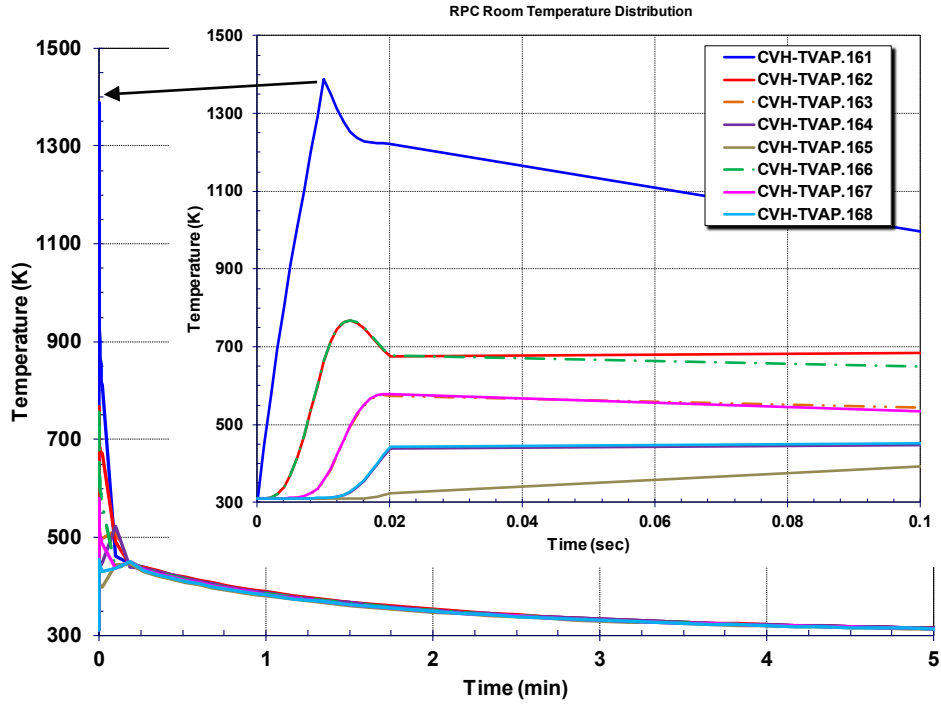


Figure 5-19 RPC Pressure Response for DBA Scenario 1



Detailed RPC Hot Cell
 Fire and Explosion 2-D
 Natural Circulation
 Nodalization

Figure 5-20 RPC Short-term and Long-term Temperature Response for DBA Scenario 1, with a Representation of the Modeled Sub-divisions within the PPC Control Volume

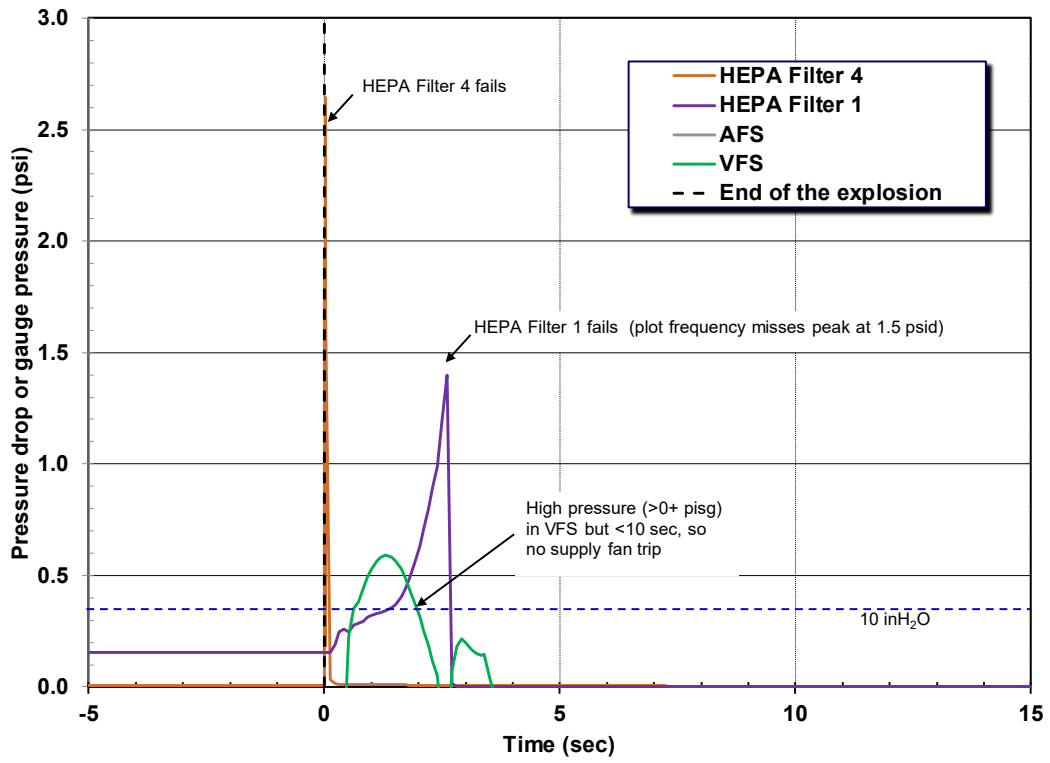


Figure 5-21 Filter 4 and 1 Pressure Drop with AFS and VFS Pressures for DBA Scenario 1

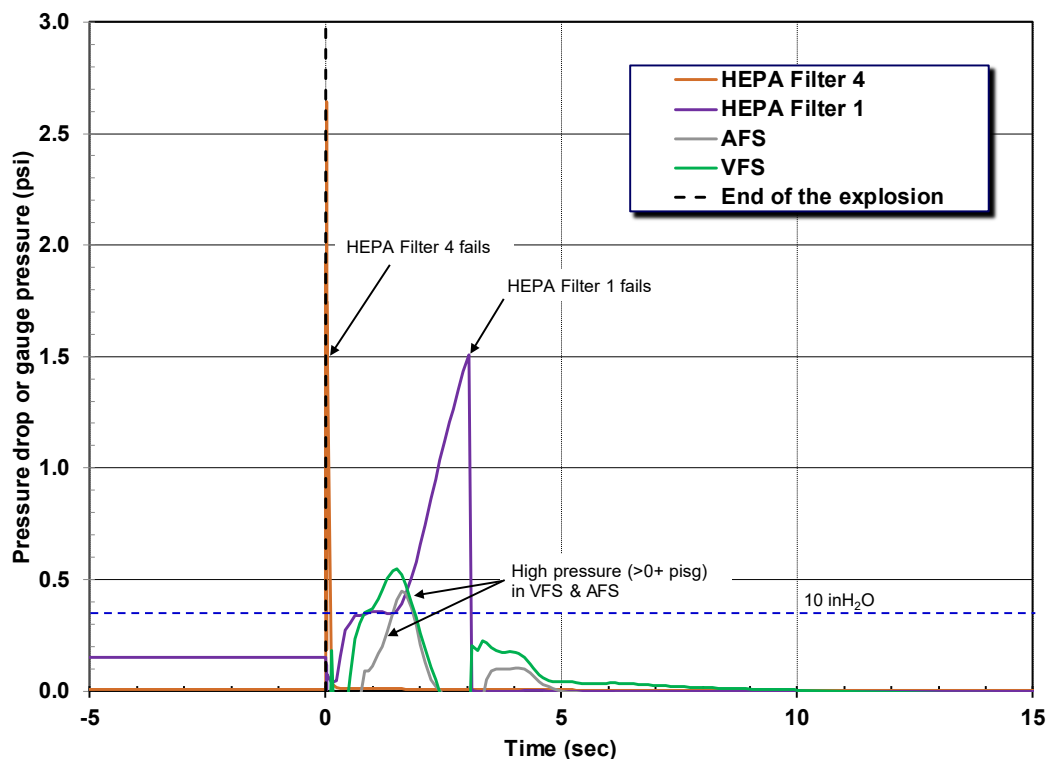


Figure 5-22 Filter 4 and 1 Pressure Drop with AFS and VFS Pressures for DBA Scenario 1 without Power

The radionuclide behavior for DBA Scenario 1 with fans is shown in Figure 5-23 through Figure 5-26 and without fans in Figure 5-27 through Figure 5-29. The activity released during the explosion is spread throughout the BNFP due to the cell pressurization, connecting ventilation failures, and penetration failure to the filter niche. The radionuclides are discharged to the CEMG, the GVOS, the Filter Niche, and through the normal exhaust pathway toward Filter 4, which was destroyed by the blast. Figure 5-23 shows the distribution of the activity through various regions in the facility as it leaves the RPC (i.e., included in the Hot Cell group). About the same amount of released activity is captured in the exhaust filtration system, which includes Filters 1 through 8, as was released to the environment. The HEPA filters on the primary pathway from the RPC to the environment fail, which leads to the large source term to the environment.

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% (see Section 4.4.4). Most of the activity was captured by the pre-filter in the Filter 1 compartment as shown in Figure 5-24. 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 (see Section 4.4.4). The explosion also caused the penetrations to the Filter Niche room to open. Filter 5, which normally filters the exhaust from the Filter Niche, also captured a significant amount of the released radionuclides. The other filters captured smaller amounts.

The case with the fan failure had a significantly smaller source term to the environment than the base case with the fans. Without forced circulation from the fans, the slower natural circulation flows allowed for more settling and retention within the building. After 12 hours, the environmental release without fans was over an order of magnitude lower than the base case with fans.

Figure 5-25 shows that although the explosion caused a large pressurization in the RPC, the fans quickly restored a negative pressure to the facility, which minimized the leakage from the building. Consequently, the release to the environment was dominated by release through the filters to the stack rather than the other building leakage pathways. In contrast, the amount of leakage when the fans are not available approaches the amount that flows out the stack due to natural circulation (see Figure 5-28).

DBA Scenario 1 occurred in the high-activity waste concentrator cycle, which includes a full-spectrum of radionuclides. Figure 5-26 shows the activity released to the environment as a function of MELCOR class (see Table 3-1). The cesium class release was the largest, followed by the lanthanum, ruthenium, and barium classes. The magnitudes of the radionuclide releases were correspondingly lower than the case with fans.

The total source term to the environment for DBA Scenario 1 with fans was 1.04×10^{15} Bq, or 28,151 curies. The filtration system captured 8.65×10^{14} Bq, or 23,376 curies. 2.96×10^{13} Bq, or 799 curies were spread throughout the building. The total source term to the environment for DBA Scenario 1 without fans was 9.30×10^{13} Bq, or 2513 curies; and 6.06×10^{14} Bq, or 16,390 curies were captured by the filtration system. The two separate results illustrate the potential negative impact of the fans if the filtration system is damaged.

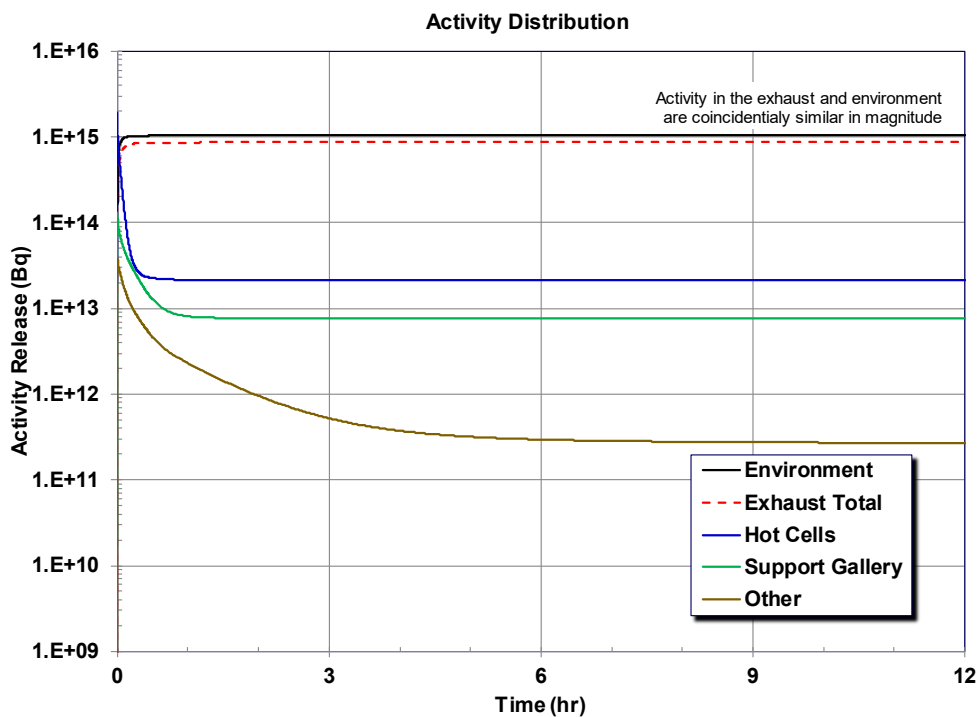


Figure 5-23 Activity Distribution within the BNFP during Explosion Scenario 1

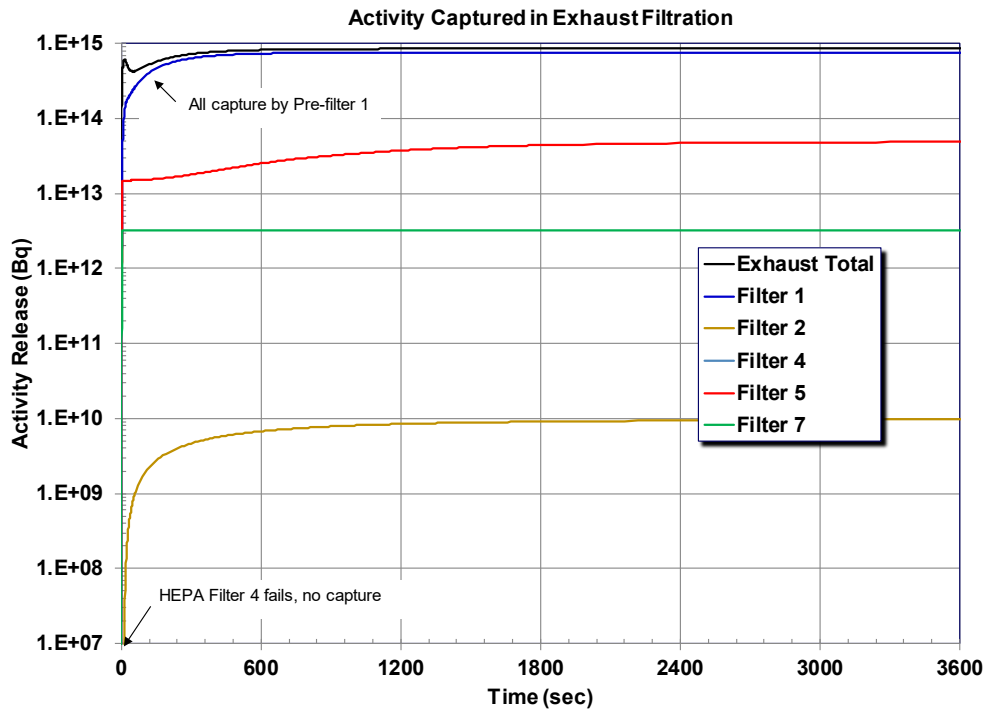


Figure 5-24 Activity Captured in the BNFP Filtration System during Explosion Scenario 1

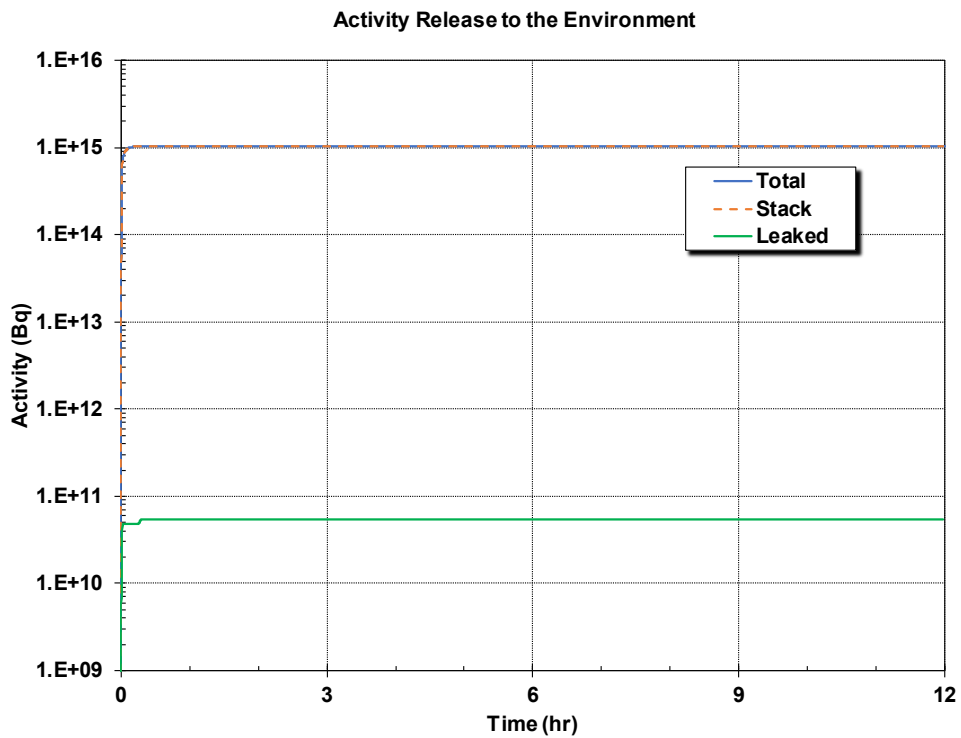


Figure 5-25 Comparison of Activity Vented through the Stack versus Unfiltered Building Leakage Paths during Explosion Scenario 1

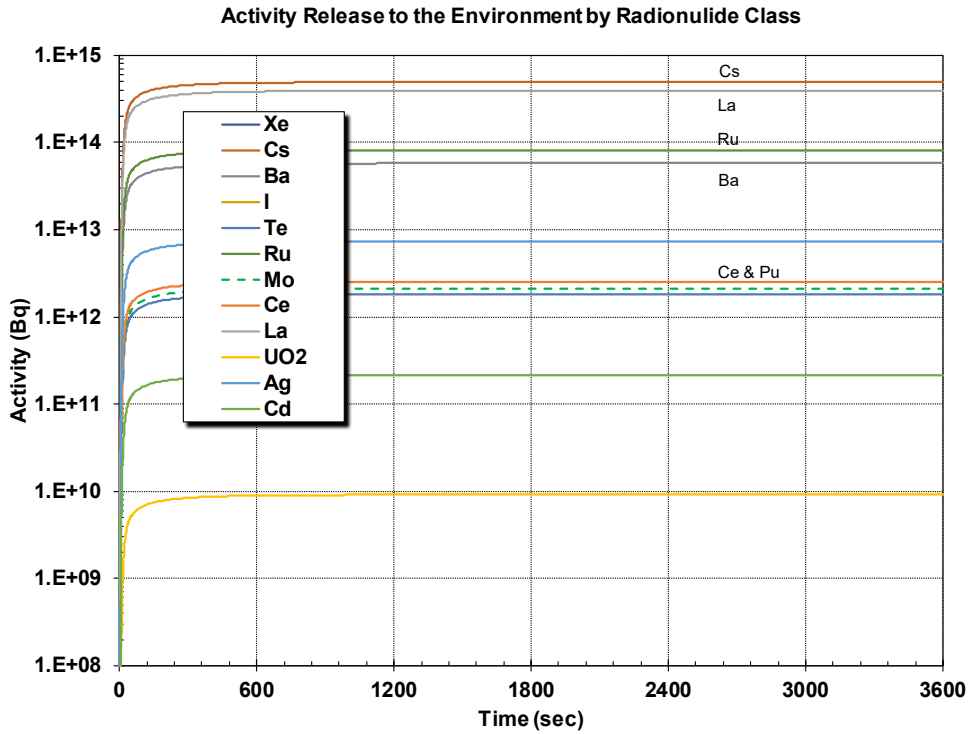


Figure 5-26 Radionuclide Composition of the Activity Released to the Environment during Explosion Scenario 1

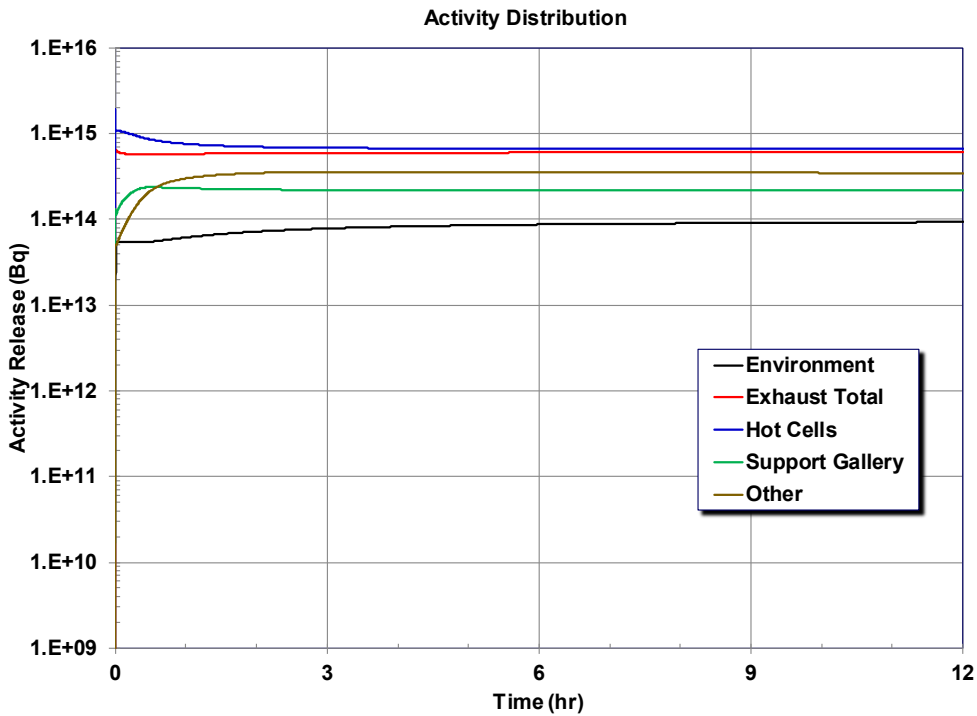


Figure 5-27 Activity Distribution within the BNFP during Explosion Scenario 1 without Fans

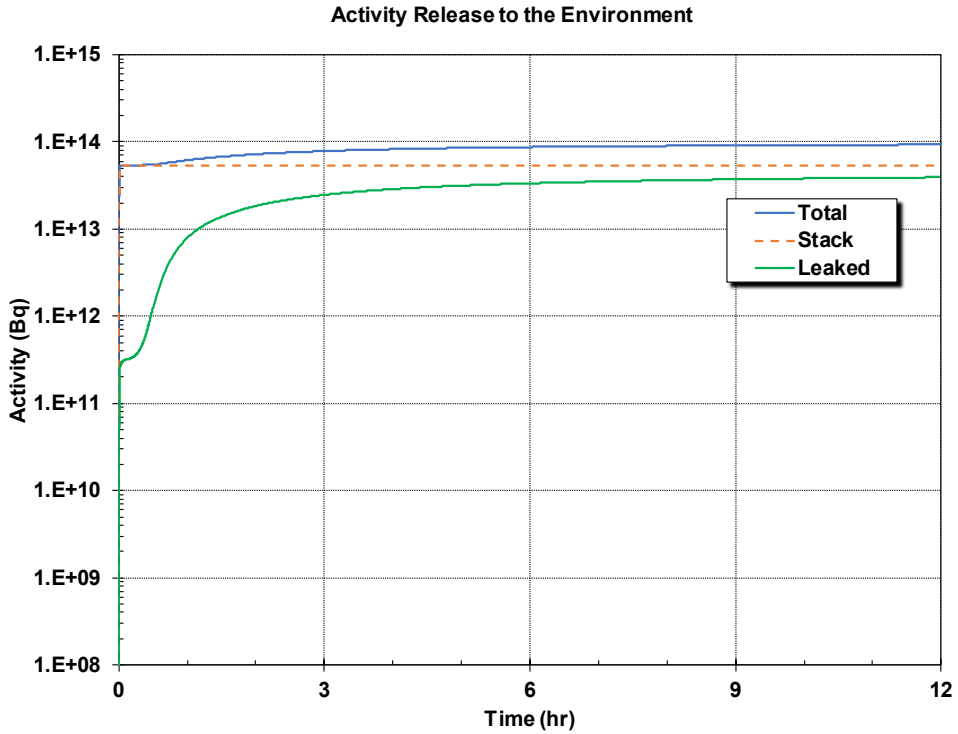


Figure 5-28 Comparison of Activity Vented through the Stack versus Unfiltered Building Leakage Paths during Explosion Scenario 1 without Fans

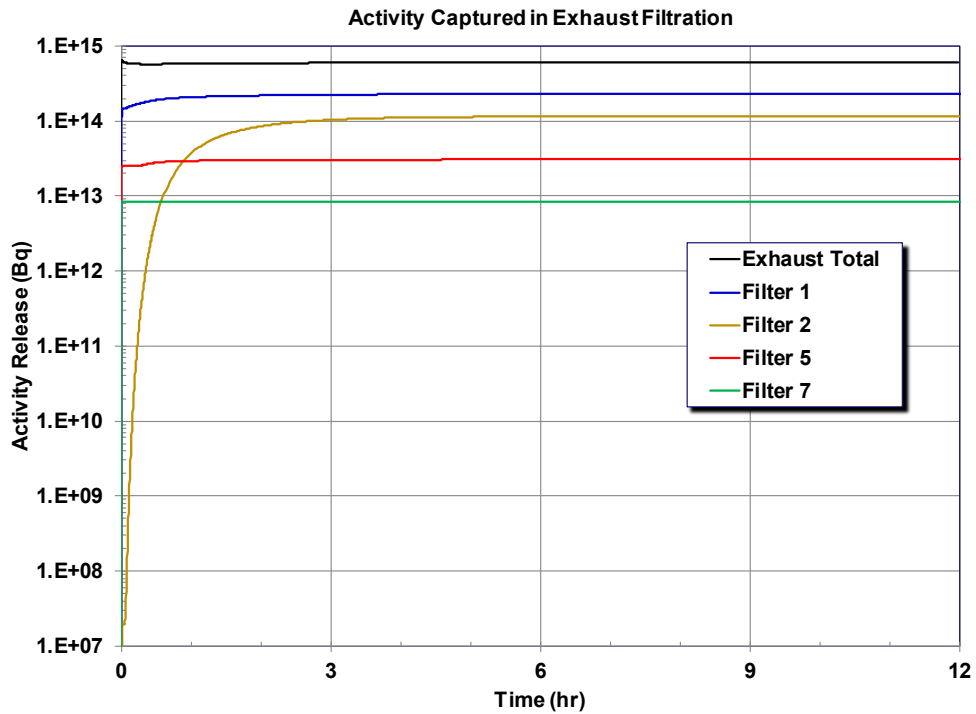


Figure 5-29 Aerosol Capture on the Filters during Explosion Scenario 1 without Fans

5.2.2 Plutonium Concentrator Explosion

DBA Scenario 3 from the BNFP is a “red oil” explosion in the 3P plutonium concentrator in the Plutonium Processing Cell (PPC) [1]. 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 TNT equivalent weight of 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.¹⁸ Onsite power is available for the exhaust fans and automatic safety controls.

The timing of key events is in Table 5-5. 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 (see Figure 5-30 and Figure 5-22). 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 5-32 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 toward Filter 1 is assisted by the exhaust fans, which are discharging to the plant stack. No other structural failures were predicted.

¹⁸ The DBA Scenario 3 explosion in the PPC is 1.28×10^8 J versus 4.37×10^8 J for DBA Scenario 1 in the RPC. However, the PPC is approximately 4X larger, so the magnitude of the damage and resulting static pressurization was expected to be smaller. Nevertheless, both led to a failure of the Filter 1 HEPA.

Table 5-5 Summary of Key Event Timings for the Explosion in the Plutonium Concentrator

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 ₂ O)	3.3
Low fan ΔP (<44" inH ₂ O, 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 (see Section 4.4.7).

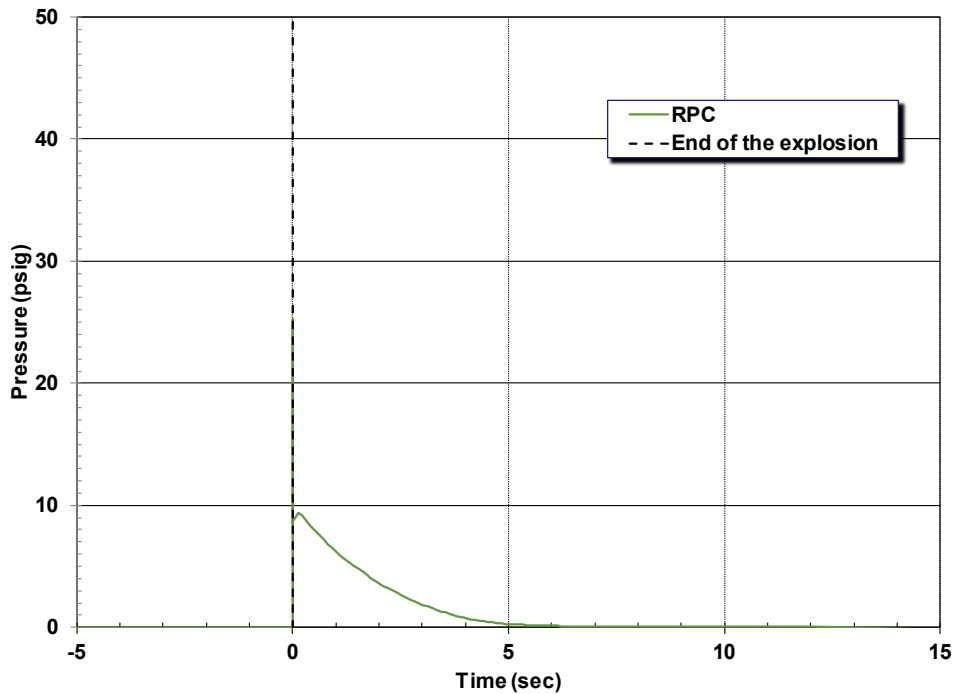


Figure 5-30 PPC Room Pressurization for DBA Scenario 3

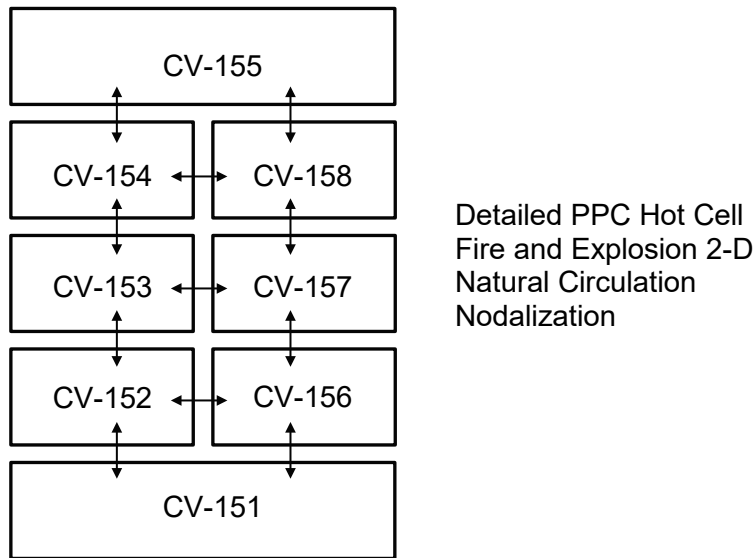
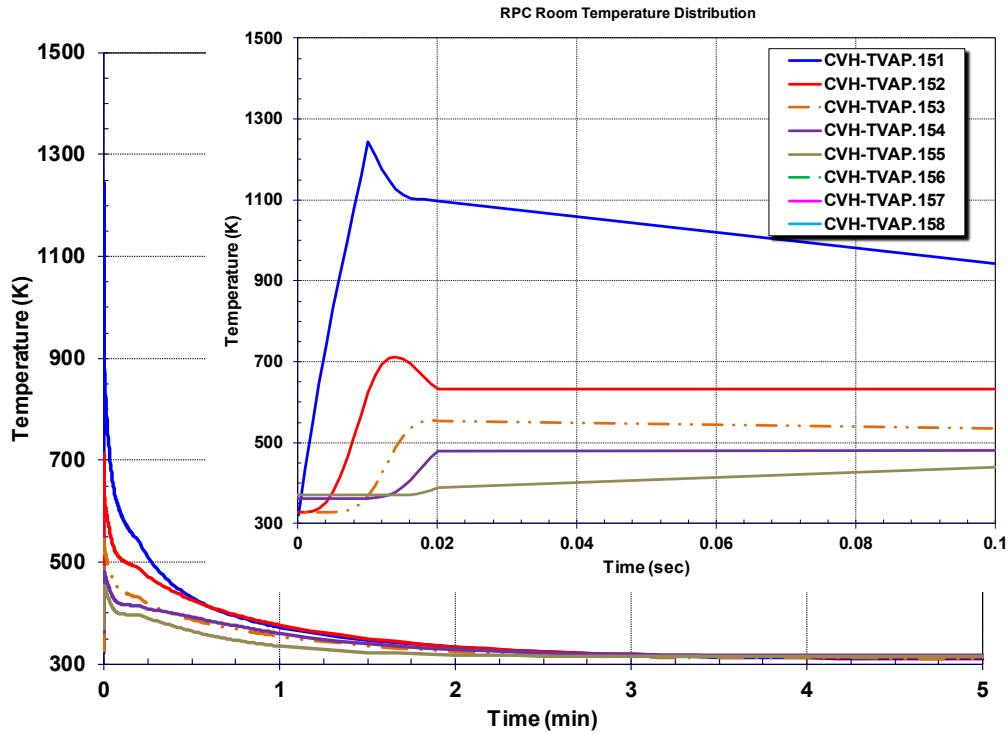


Figure 5-31 PPC Room Temperature Response for DBA Scenario 3, with a Representation of the Modeled Sub-divisions within the PPC Control Volume

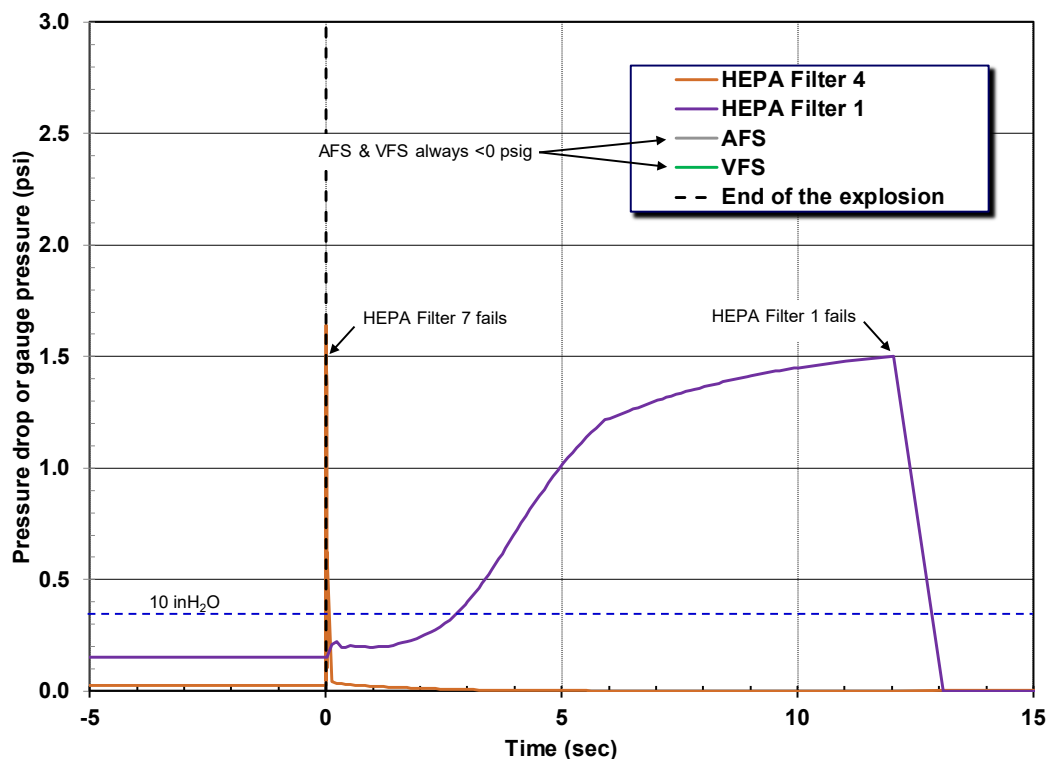


Figure 5-32 Filter 1 and 4 Pressure Drop with AFS and VFS Pressures for DBA Scenario 3

The radionuclide behavior for DBA Scenario 3 is shown in Figure 5-33 through Figure 5-35. The activity released during the explosion is spread into the FPIG, LPIG, and HTG & PEG regions of the BNFP due to the cell pressurization and connecting ventilation failures. Figure 5-33 shows the distribution of the activity through various regions in the facility as it leaves the PPC (i.e., included in the Hot Cell group in Figure 5-33). Most of the released activity is either captured in the filtered exhaust system (which is labeled as Exhaust Total in Figure 5-33) or released to the environment. The airborne activity in the support gallery and other locations (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.

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% (see Section 4.4.4). Most of the activity released in the accident was captured by the pre-filter in the Filter 1 compartment as shown in Figure 5-34. 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 (see Section 4.4.4). The other filters captured smaller amounts of radionuclides.

DBA Scenario 3 occurred in the plutonium concentrator cycle, which only includes plutonium, which is illustrated in Figure 5-35 (i.e., plutonium is part of MELCOR’s cerium group, see Table 3-1). Consequently, only plutonium was released.

The total source term to the environment for DBA Scenario 3 was 1.71×10^{15} Bq, or 46,316 curies. 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 (i.e., 1.71×10^{15} Bq) with only 2300 Bq exiting through building leak pathways. The filtration system captured 1.04×10^{15} Bq, or 28,027 curies¹⁹; and 3.77×10^{13} Bq, or 1018 curies were spread throughout the building. The failure of both HEPA filters between the PPC to the stack was critical for the very high activity release to the environment.

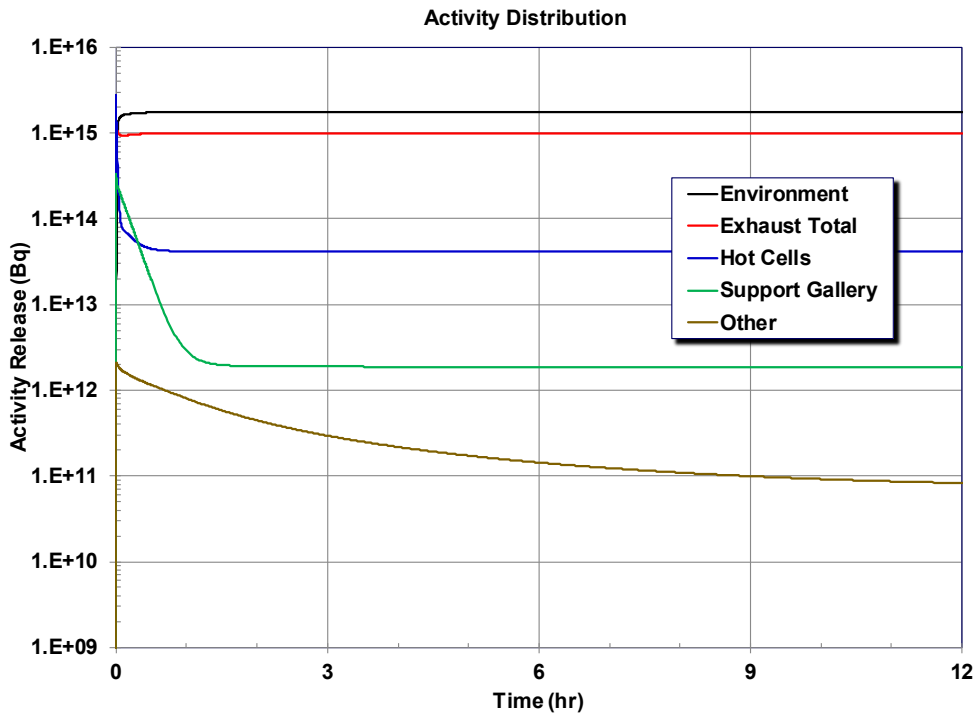


Figure 5-33 Activity Distribution within the BNFP during Explosion Scenario 3

¹⁹ The filters capture a very large amount of Pu in this scenario. However, over 25% is Pu²⁴⁰ and non-fissile. Furthermore, the large surfaces of the HEPAs are not expected to form a critical geometry. Although there was no assessment of recriticality, it is not expected for this scenario.

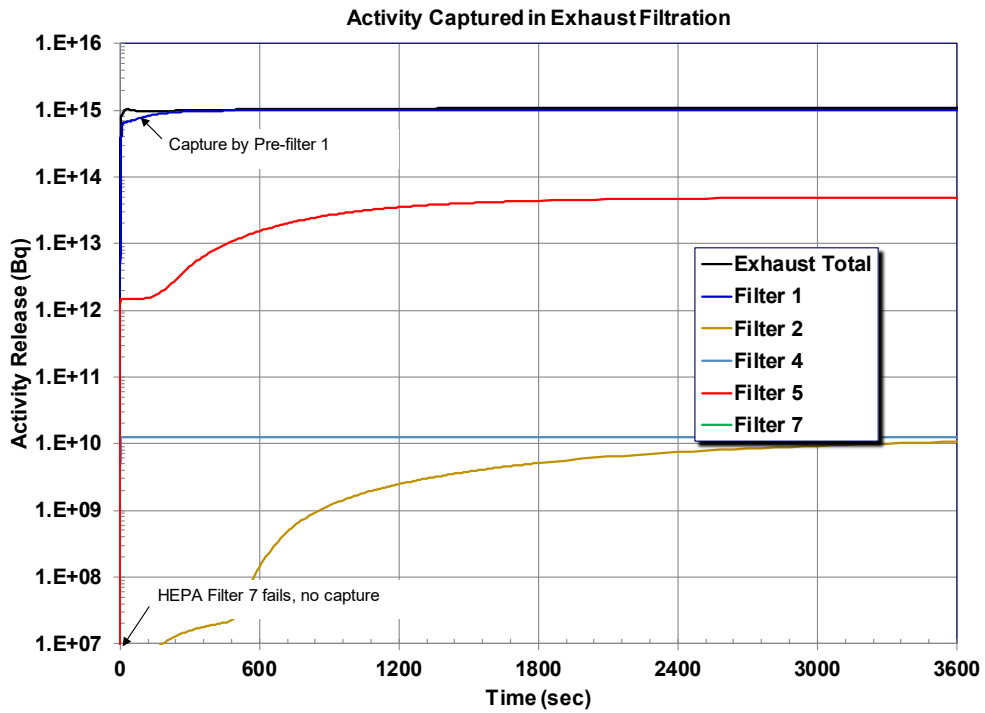


Figure 5-34 Activity Captured in the BNFP Filtration System during Explosion Scenario 3

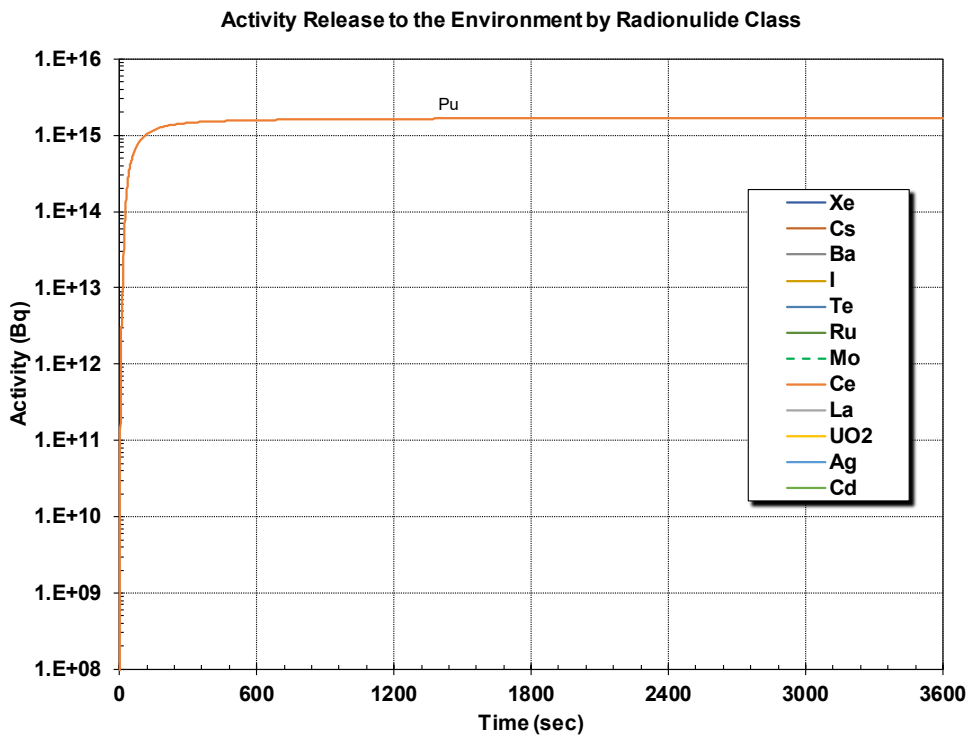


Figure 5-35 Radionuclide Composition of the Activity Released to the Environment during Explosion Scenario 3

5.2.3 LAW Concentrator Explosion

DBA Scenario 5 from the BNFP FSAR is a “red oil” explosion in the Low-Activity Waste (LAW) concentrator in the Intermediate Level Cell (ILC) [1]. The concentrator is assumed to rupture due to the explosion and expels its entire contents into the cell. The scenario specifies 1% of the TBP in the concentrator is involved in the explosion. The explosion has an energy of 1.1×10^8 J, which is released over 10 milliseconds. This is the smallest explosion of the three DBA scenarios with an explosion. Onsite power is available for the exhaust fans and the automatic safety controls.

The timing of key events is in Table 5-6. The explosion caused a large pressure rise in the ILC that failed the dampers connected to the room. However, the pre- and HEPA filters in the Filter 5 compartment were not significantly challenged and did not fail (see Figure 5-36). The ventilation manifold exiting the ILC is very large since it serves four of the hot cells and the Filter Niche region. The nominal flowrate through the ILC is also higher than the other connecting cells, which contributed to dissipating the pressure surge from the explosion inside the ILC with a lower impact.²⁰

At approximately the same time as the inlet ventilation damper between the ILC and the HTG & PEG regions failed (see cross-section A-A in Figure 3-3), the outlet damper from the HILC to Filter 5 failed.²¹ Both the ILC and the HILC are connected to the HTG & PEG region and the Filter 5 plenum. During the sharp pressurization of the ILC, the HILC outlet damper to Filter 5 also failed. The pressurization of the HILC from ILC leakage to the HTG & PEG limited the backflow from the Filter 5 inlet plenum as it also pressurized. Consequently, the outlet damper from the HILC failed due to system connectivity around the ILC. No other direct failures were predicted.

The pressure in the VFS rose above 0 psig but subsequently dropped before any signal to trip the supply blower (75-G-725). The HEPA in the Filter 1 compartment was not challenged and remained operational. However, the high temperature gases exiting the ILC exceeded 250°F at the exhaust fan inlet by 4.1 s.

²⁰ The ILC has approximately 12 air changes per hour (ACH) versus 6 and 10 for the RPC and PPC, respectively. The high ACH, the smaller explosion, and large common exit plenum serving four processing cells and the filter niche helped mitigate the impact from the explosion.

²¹ The ventilation ducting is not shown in the facility diagrams (i.e., Figure 3-1 through Figure 3-3). However, Figure 3-4 and Figure 3-5 provides a schematic of the supply and exhaust ventilation system, respectively.

Table 5-6 Summary of Key Event Timings for the Explosion in the LAW Concentrator

Event Timing [s]	Time
Start of building pressure/flow steady state balance	-10,000
Explosion	0.0
ILC outlet damper to Filter 5 fails (>1.5 psid)	<0.01
Explosion ends	0.01
HILC outlet damper to Filter 5 fails (>1.5 psid)	0.02
ILC inlet damper from HTG&PEG fails (>1.5 psid)	0.02
High VFS pressure (>0 psig) ^B	0.77
High exhaust fan inlet temperature (>250°F)	4.1

n/c = not calculated

Notes:

A The high VFS plenum pressure exceeded +0 psig but did not last longer than 10 s, so the process building ventilation supply blower (75-G-725) did not trip.

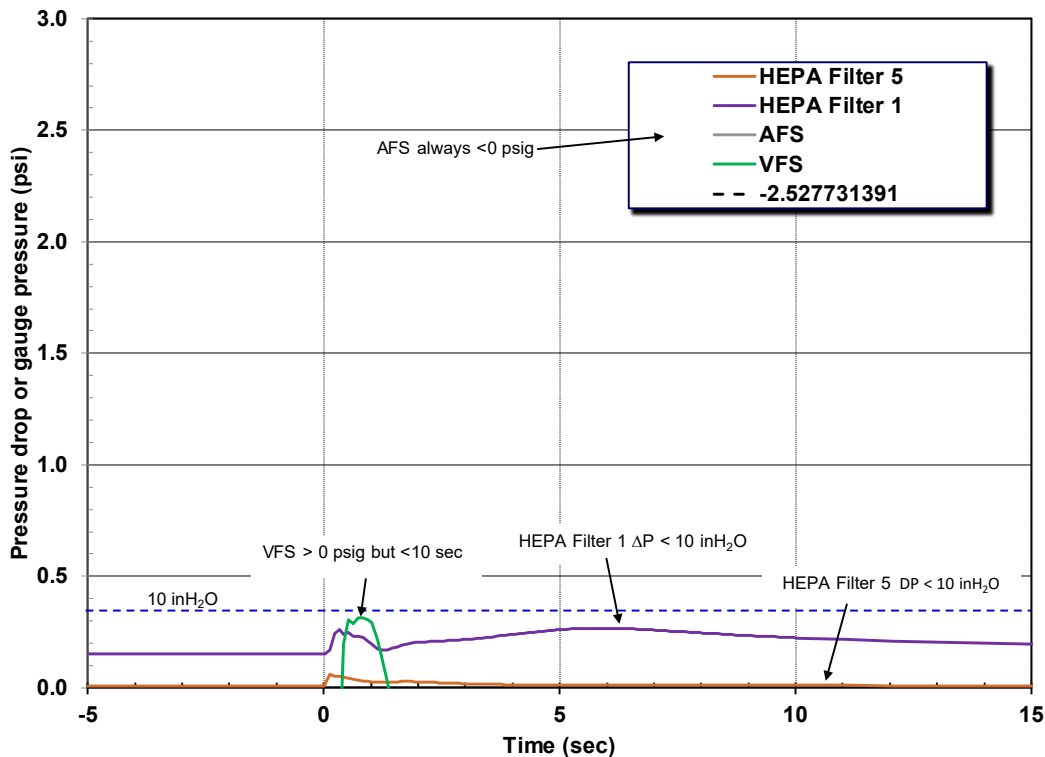


Figure 5-36 Filter 5 and 1 Pressure Drop with AFS and VFS Pressures for DBA Scenario 5

The radionuclide behavior for DBA Scenario 5 is shown in Figure 5-37 through Figure 5-40. The activity released during the explosion is spread into the HTG & PEG regions of the BNFP due to the cell pressurization and connecting ventilation failure. Figure 5-37 shows the distribution of the activity through various regions in the facility as it leaves the ILC (i.e., included in the Hot Cell group). Since both Filters 5 and 1 remained intact, the source term to the environment was expected to be small. However, the overall capture by the filtration system was relatively small.

Figure 5-38 shows the activity captured by the key filters around the ILC. Filter 5, which is adjacent to the ILC had the most capture with Filter 1 being an order of magnitude lower. The other filters had negligible capture.

It was expected that Filter 1 would capture limited activity because it is downstream of Filter 5. The capture would primarily be limited to activity collected from other locations that is not pre-filtered (e.g., the gallery regions). However, the limited capture on Filter 5 was unexpected. The scenario specifications include a conservative assumption that all activity released during the explosion is initially gaseous (see Section 4.3.5). The low capture is due to gases and very small aerosols below the size efficiency of the HEPA filter. Consequently, considerable activity passed through the filter without being captured.²²

To illustrate the impact of the filter efficiency for capturing small aerosols, Figure 5-39 shows the results of two sensitivity calculations. Both calculations assumed that the HEPA Filter 1 captured all sizes of aerosols at the rated efficiency (i.e., not limited to >0.3 micron, see Section 4.4.4). The “Gas + Filter 1 all aerosol sizes” sensitivity case did not change the explosion modeling (i.e., all activity was released as a gas). In the second sensitivity study, “Aerosol + Filter 1 all sizes”, the explosion generated aerosols in the smallest size section²³ rather than as a gas. The results for Filter 5 were identical for all cases, including the base case. Whether the explosion generated gases or very small aerosols, the Filter 5 response was the same. As the gases and very small aerosols continued to progress towards Filter 1, there is continued aerosol formation from the gases and aerosol growth due to condensation and agglomeration. However, as illustrated in the base case, these aerosol growth mechanisms were not impactful in this scenario and the aerosol capture at Filter 1 was small relative to the amount released to the environment. In contrast, when Filter 1 captures very small aerosols at the same efficiency as larger aerosols, most of the activity is captured (i.e., the two sensitivity cases show high capture at Filter 1). Consequently, the assumption on whether the activity was released as a gas or a very small aerosol had almost no impact on the results. However, if a filter could capture the smallest aerosols, then there would be a large impact on the results. The capture on the Filter 1 HEPA in the base case was 3.86×10^9 Bq versus 2.29×10^{12} Bq in the sensitivity cases. The release to the environment dropped from 2.29×10^{12} Bq in the base case to 3.21×10^9 Bq in the sensitivity cases when the HEPA filters were able to capture very small aerosols.

Finally, Figure 5-40 shows the activity release by RN Class for the base case (see Table 3-1). The largest releases in order of magnitude were the ruthenium, cesium, lanthanum, and cerium (i.e., includes Pu) classes. All other radionuclide releases were less than 10^{11} Bq. The total source term to the environment for DBA Scenario 5 was 2.29×10^{12} Bq, or 61.8 curies. The filtration system only captured 4.99×10^{10} Bq, or 1.35 curies, while 1.00×10^{10} Bq, or 0.27 curies were spread throughout the building. The poor ability of the HEPA filters to capture very small aerosols was critical for the relatively high activity release to the environment.

²² MELCOR will immediately start to condense explosion gases as determined by rate equations based on the surface areas, mass transfer coefficients, gas concentration, and the saturation concentrations corresponding to the temperatures of the surfaces of the aerosols and structure [5]. Each RN class has a unique vapor pressure characteristic of the representative transport species (see Table 3-1).

²³ Aerosols are modeled in the MELCOR BNFP model using 10 discrete sections from 0.1 μm to 50 μm . The diameter of the smallest aerosol section ranged from 0.1 μm to 0.19 μm . These are very small aerosols that have extremely slow gravitational settling velocities.

The poor performance of the HEPA in DBA Scenario 5 relative to DBA Scenarios 1 and 3 is due to the significantly smaller radioactivity release from the explosion (i.e., 80 grams versus 102 kg and 12.5 kg in DBA Scenarios 1 and 3, respectively). The small mass of aerosols meant the potential for aerosol agglomeration and growth was very limited. A secondary factor was the high air change rate for the ILC, which transported aerosols out of the ILC faster than the other explosion cases (see Footnote 20). The net effect was very low capture of aerosols despite two intact HEPA filters between the explosion and the environment.

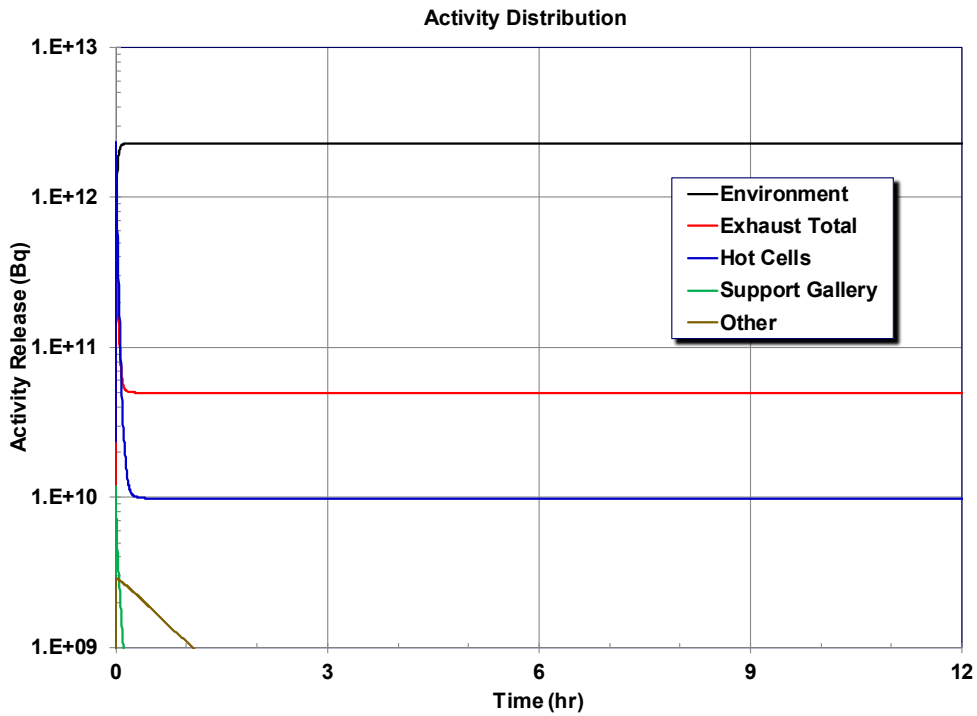


Figure 5-37 Activity Distribution within the BNFP during Explosion Scenario 5

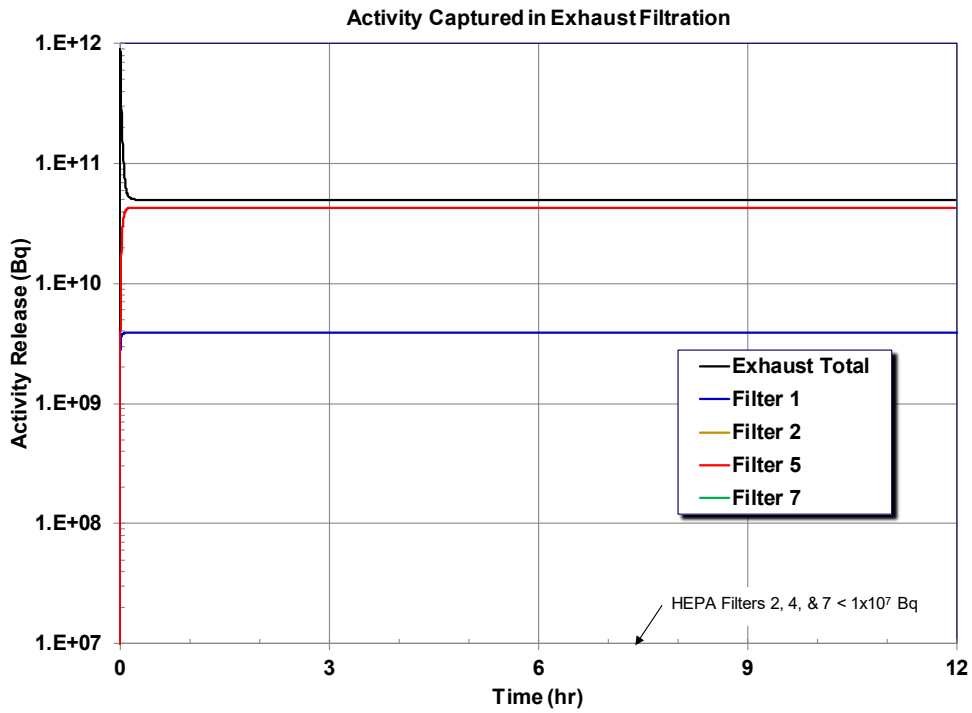


Figure 5-38 Activity Captured in the BNFP Filtration System during Explosion Scenario 5

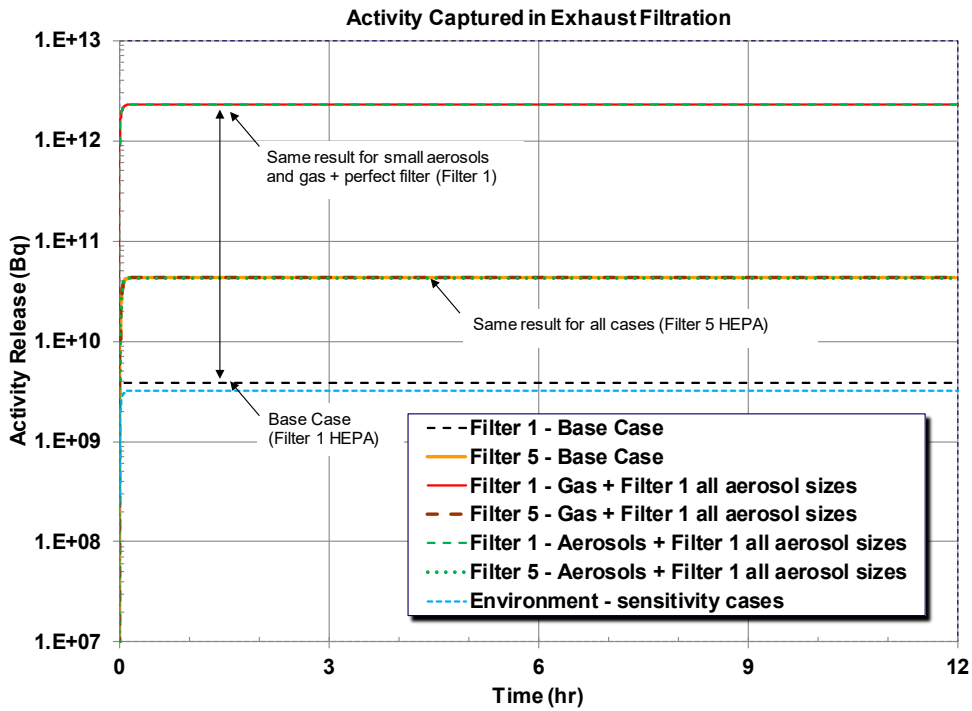


Figure 5-39 Activity Captured on Filters 1 and 5 - DBA Explosion Scenario 5 (Sensitivity Study)

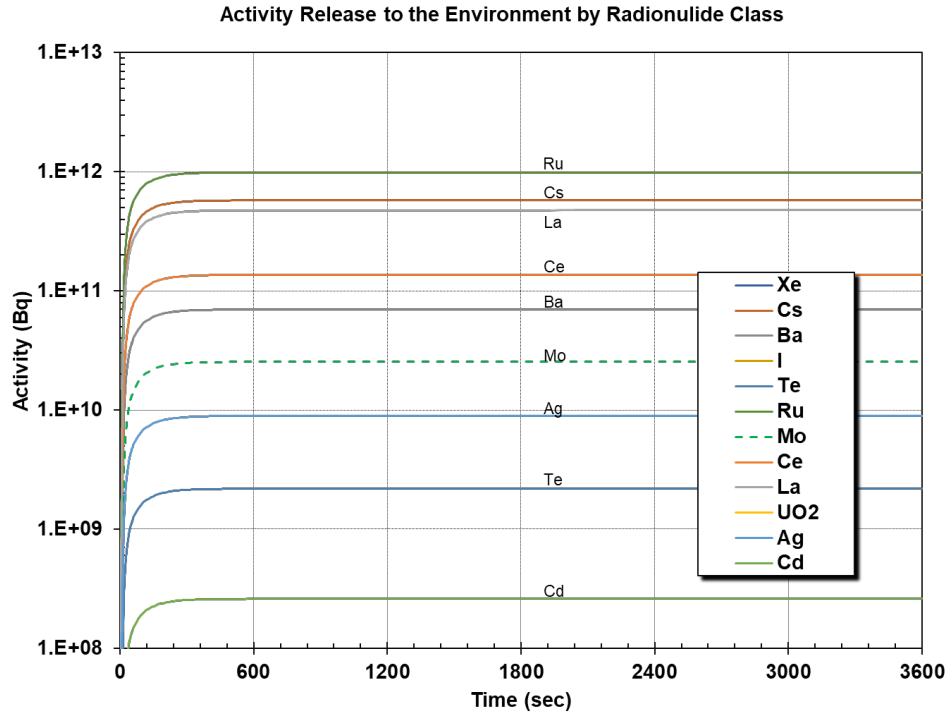


Figure 5-40 Radionuclide Composition of the Activity Released to the Environment during Explosion Scenario 5

5.3 Combined Explosion and Fire Scenarios

There were two scenarios with an explosion that induced a fire. The combined scenarios were developed from the previous DBA explosions scenarios. During the explosion, it is assumed that the remaining solvent ignites and burns. Section 5.3.1 described an explosion and fire during the HAW concentrator cycle based on DBA Scenario 1 (Section 5.2.1). Similar to the DBA explosion analysis, scenarios with and without power for the fans were considered. The second combined scenario occurs during the plutonium concentrator cycle based on DBA Scenario 3 (Section 5.2.2).

5.3.1 HAW Concentrator Explosion and Fire

Scenario 9 is a sensitivity study based on DBA Scenario 1 but with an induced fire of the solvent after the explosion (see Section 5.2.1). The scenario begins with a “red oil” explosion in the HAW concentrator in the RPC [1]. The combined explosion and fire scenario specify that 10% of the TBP in the concentrator is involved in the explosion. The resulting explosion has a TNT equivalent weight of 90.7 kg (200 lb), which is the largest explosion in this report (i.e., same as DBA Scenario 1). The explosion has an energy of 4.27×10^8 J, which is released over 10 milliseconds. The explosion induces a fire of the remaining 420 liters of solvent, which releases 1.36×10^{10} J.

Two variations of the calculation were performed. The base calculation assumed power is available for the supply and exhaust fans and a second sensitivity calculation assumed the building power failed during the explosion. The timings of key events are in Table 5-7 for the two sequences. The timings of the events during and immediately after the explosion were the same as DBA Scenario 1 (see Section 5.2.1). Similar to DBA Scenario 1, the availability of power for

the ventilation fans did not have a significant impact of the various failure timings during the explosion. The explosion caused a large pressure rise that failed all dampers connected to the room. The dedicated roughing and HEPA filters in the Filter 4 compartment failed during the explosion. The penetrations between the RPC and the adjacent Filter Niche region also failed.

The final filter compartments prior to the stack (i.e., Filters 1 and 2, see Figure 3-5) were monitored for failure. In the base scenario with the fans operating, the pressure drop across the HEPA filter exceeded 10 inH₂O at 2.0 s and 1.5 psid by 2.6 s as the high pressure in the RPC dissipated throughout the ventilation system and the building. Consequently, the Filter 1 HEPA was predicted to fail although the less efficient pre-filter remained intact. Filters 1 and 2 provide the final filtering before venting to the stack. Similar to DBA Scenario 1, the Filter 1 HEPA filter also failed in the sensitivity case without fans but slightly later at 3.0 s.

The explosion induced a fire that burned 420 liters of the solvent. When the fans were available, the fire reduced the oxygen concentration near the fire to less than 11%. The fire became oxygen-limited but burned near the maximum power of 16.8 MW until all the solvent was consumed at 873 s (see Figure 5-41). When the fans were not available, the fire was oxygen-limited to the natural flow of oxygen from adjacent rooms, which limited the power to less than 5 MW (see Figure 5-42).

The hot gas temperature in the room varied with the fire power. The peak temperature in the PPC remained near 865 K (1097°F) when the fans were available but was less than 570 K (566°F) without fans (see Figure 5-43). The PPC returned to ambient conditions after the fire ended. The room cooled down within 2 minutes if the fans were running but took approximately 30 minutes without the fans.

Table 5-7 Summary of Key Event Timings for the Explosion in the HAW Concentrator

Event Timing [s]	No Power Failure	Power Failure ^A
Start of building pressure/flow steady state balance	-10,000	-10,000
Explosion	0.0	0.0
RPC outlet damper to Filter 4 fails (>1.5 psid)	<0.01	<0.01
RPC inlet damper from the CMEG fails (>1.5 psid)	<0.01	<0.01
RPC inlet damper from the GVOS fails (>1.5 psid)	<0.01	<0.01
Pre-filter 4 fails (>1.5 psid)	<0.01	<0.01
RPC penetrations to Filter Niche Room fail	<0.01	<0.01
HEPA filter 4 fails	<0.01	<0.01
Failure of supply and exhaust fans	n/c	<0.01
Explosion ends & fire starts (420 liters)	0.01	0.01
High pressure at the VFS (> +0 psig)	1.0 ^B	1.0
High pressure at the AFS (> +0 psig)	n/c	1.2
High HEPA filter 1 ΔP (>10" inH ₂ O)	2.0	2.0
High exhaust fan inlet temperature (>250°F)	2.5	2.5
HEPA filter 1 fails (>1.5 psid)	2.6	3.0
Filter 1 damper closes to 10%	n/c	n/a
Supply fan (75-G-725) tripped	n/c	n/a
All fuel is burned	873	5305

n/c = not calculated

n/a = not applicable because no power was available

Notes:

A All onsite power is lost during the explosion and all ventilation fans fail.

B The high AFS or VFS plenum pressure exceeded +0 psig but did not last longer than 10 sec, so the process building ventilation supply blower (75-G-725) did not trip.

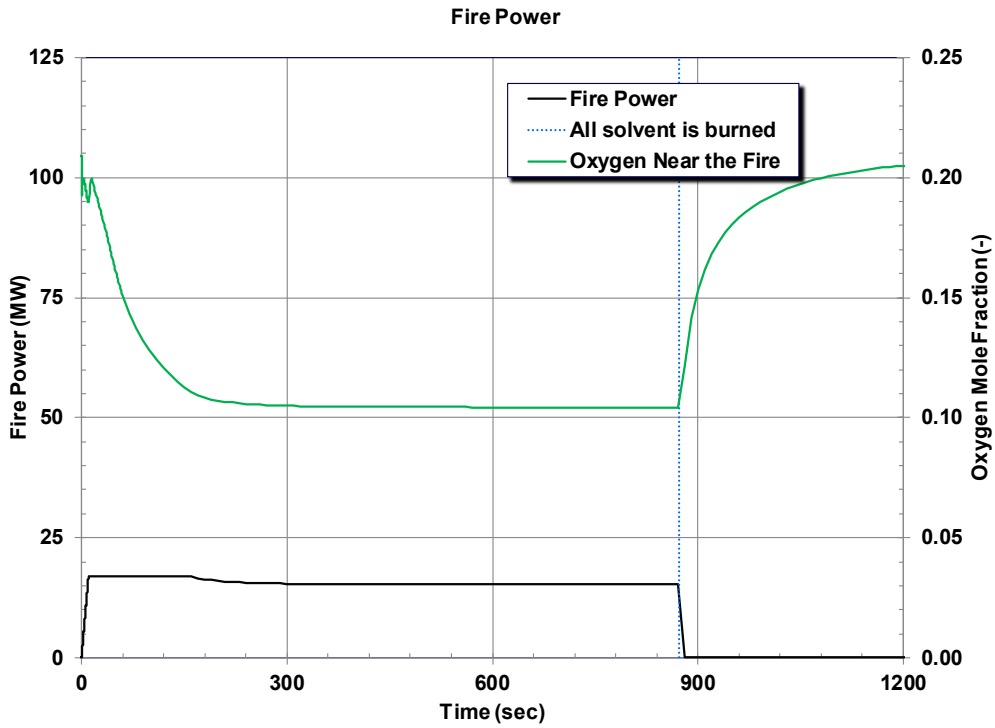


Figure 5-41 Fire Power and Oxygen Concentration in Scenario 9 near the Fire with Fans

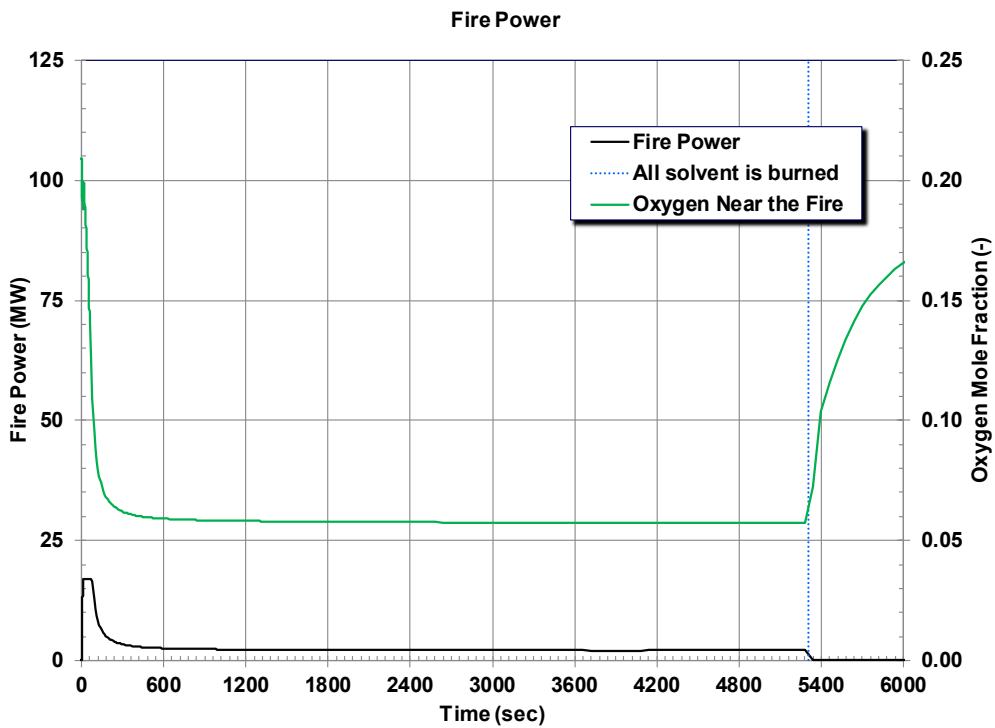


Figure 5-42 Fire Power and Oxygen Concentration in Scenario 9 near the Fire without Fans

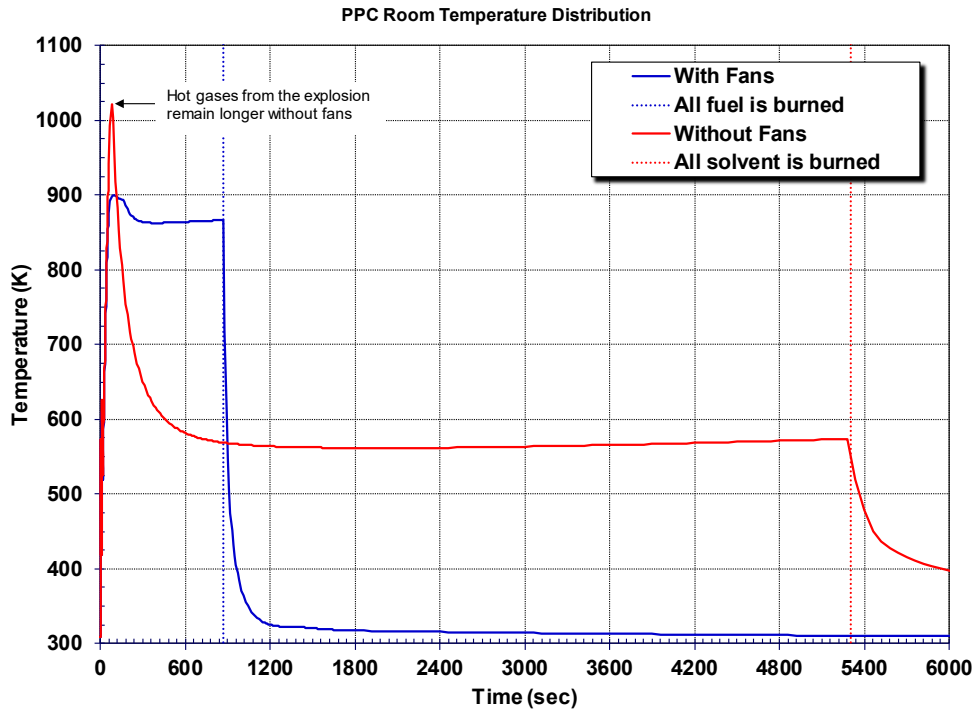


Figure 5-43 PPC Hot Gas Temperature in Scenario 9 with and without Fans

The radionuclide behavior for Scenario 9 is shown in Figure 5-44 and Figure 5-45. The radionuclides are discharged to the CEMG, the GVOS, the filter niche as well as through the normal exhaust pathway towards Filter 4, which was destroyed by the blast. Figure 5-44 and Figure 5-45 show the distribution of the activity through various regions in the facility as it leaves the PPC with fans and without fans, respectively. Most of the released activity is released to the environment when the fans continue to run whereas more activity is retained in the building when the fans fail. Due to the low natural circulation flowrate and natural aerosol deposition mechanisms, much of the activity released in the no fan case remained in the hot cell region. Similar to DBA Scenario 1, the Compartment 1 pre-filter remained intact following the explosion. BNFP reports the pre-filter has an aerosol capture efficiency between 80–85% for aerosols greater than 1 micron (see Section 4.4.4). Consequently, both cases showed some retention at Filter 1.

The total source terms to the environment for Scenario 9 with and without fans were 5.65×10^{15} Bq (152,837 curies) and 7.63×10^{14} Bq (20,609 curies), respectively. The failure of both HEPA filters between the PPC and the stack and the combined radiation releases from an explosion and the subsequent fire generated very high activity releases to the environment. The releases in Scenario 9 were higher than the comparable DBA Scenario 1 results due to the additional inventory from fire, which released more than twice as much radioactive material as the explosion (i.e., 2.88×10^{15} Bq released during the explosion versus 6.37×10^{15} Bq released from the fire). Consequently, the Scenario 9 environmental source terms were much larger than DBA Scenario 1 (see Figure 5-46). The four results illustrate the potential negative impact of the fans if the filtration system is damaged and there is a fire.

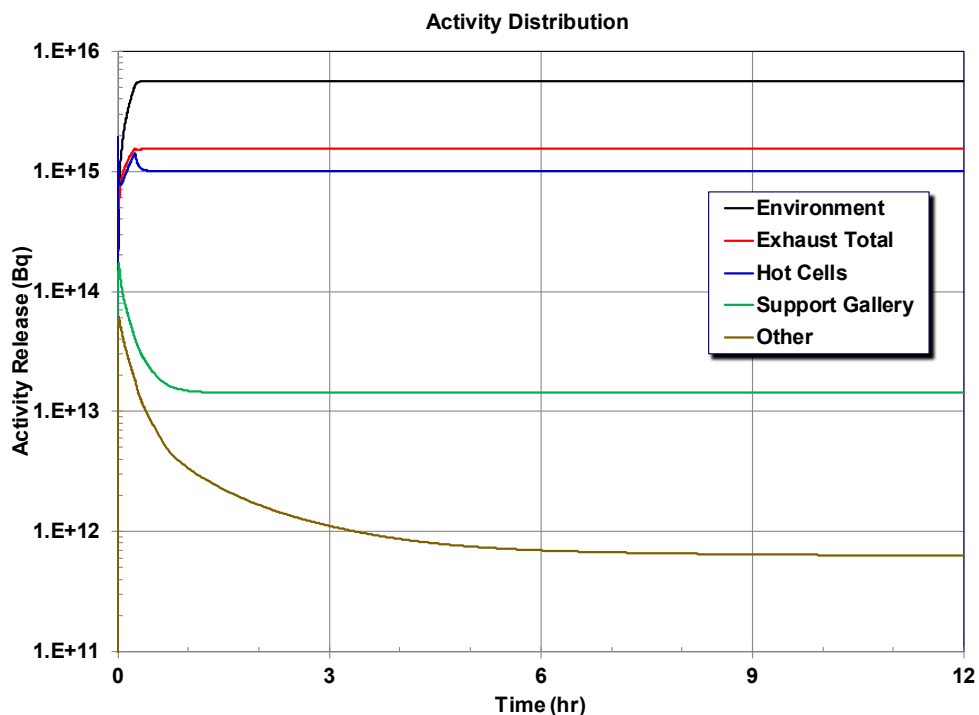


Figure 5-44 Activity Distribution within the BNFP during Scenario 9 with Fans

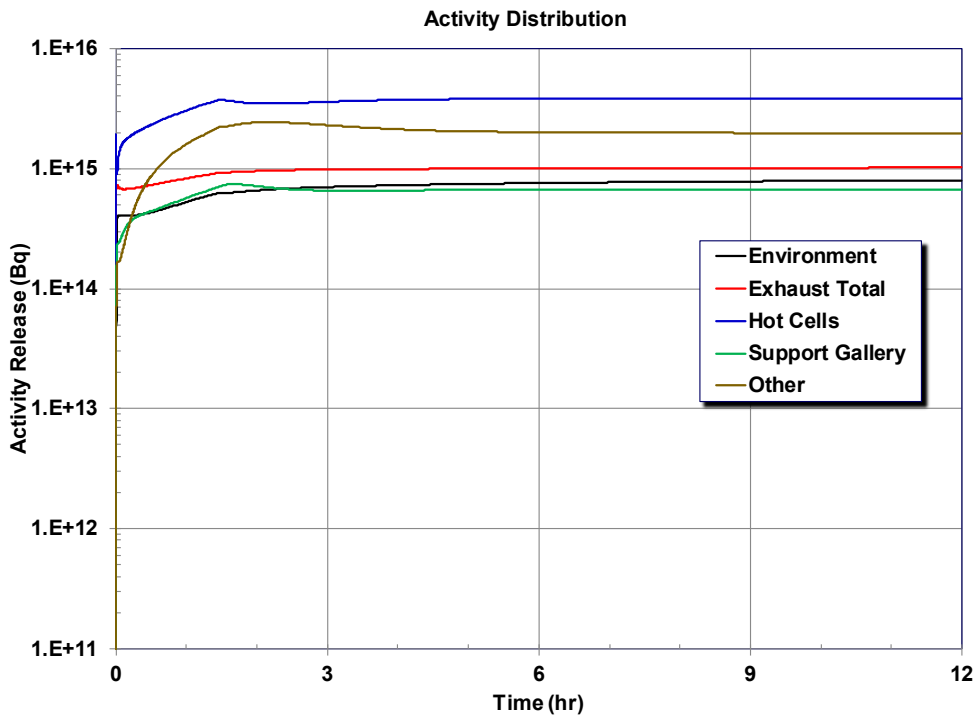


Figure 5-45 Activity Distribution within the BNFP during Scenario 9 without Fans

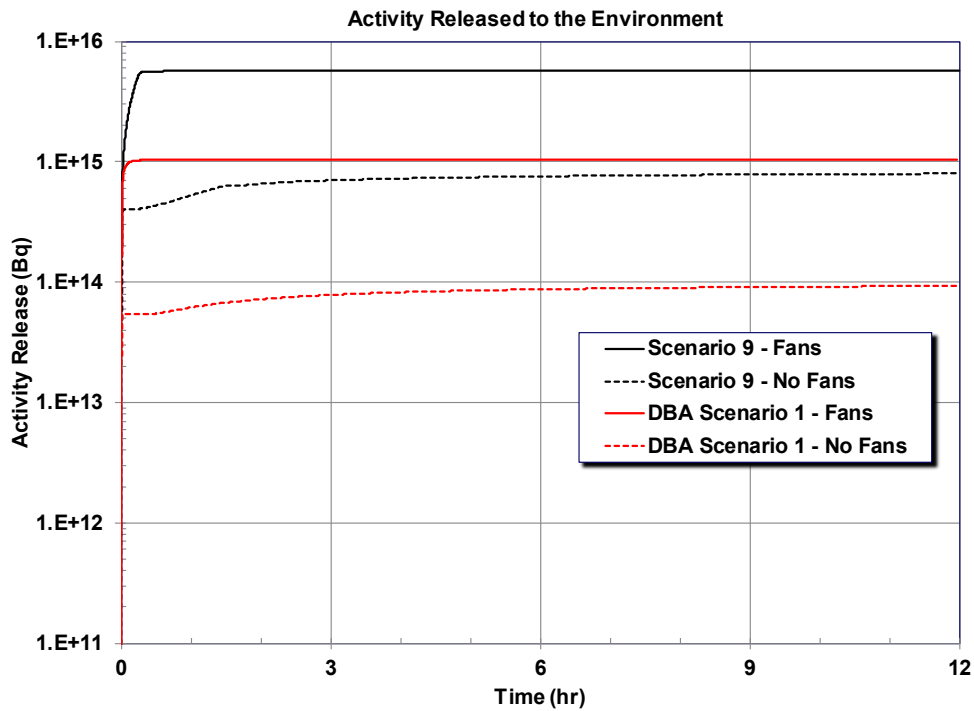


Figure 5-46 Comparison of the Activity Release to the Environment between DBA Scenario 1 and Scenario 9 with and without Fans

5.3.2 Plutonium Concentrator Explosion and Fire

Scenario 10 is a sensitivity study based on DBA Scenario 3 but with an induced solvent fire after the explosion (see Section 5.2.1). The scenario begins with a “red oil” explosion in the Plutonium Concentrator in the PPC [1]. The combined explosion and fire scenario specify 25% of the TBP in the concentrator is involved in the explosion. The resulting explosion has a TNT equivalent weight of 27.3 kg (60 lb) (i.e., same as DBA Scenario 3). The explosion has an energy of 1.28×10^8 J, which is released over 10 milliseconds. The explosion induces a fire of the remaining 51 liters of solvent, which releases 1.63×10^9 J.

The timing of key events is in Table 5-8. The dedicated roughing and HEPA filters in the Filter 7 compartment failed during the explosion. The dissipation of the high pressure from the explosion caused additional failures of the ventilation dampers from the PPC to the FPIG, LPIG, and HTG & PEG regions. The timing of the events during and immediately after the explosion was the same as DBA Scenario 3 (see Section 5.2.2).

The final filter compartments prior to the stack (i.e., Filters 1 and 2, see Figure 3-5) were monitored for failure. The pressure drop across the Filter 1 HEPA exceeded 10 inH₂O at 3.3 s and 1.5 psid by 5.5 s as the high pressure in the RPC dissipated throughout the ventilation system and the building. Consequently, the Filter 1 HEPA was predicted to fail although the less efficient pre-filter remained intact (e.g., see explosion response in Section 5.2.2).

The explosion induced a 1 m² fire with the solvent remaining after the explosion. The fire increased to its maximum burn rate of 1.68 MW over 10 s (see Figure 5-47). The fire burned at the maximum power until 993 s when all the fuel was burned. Relative to the other fires in this report, a 1 m² fire is small. Consequently, the forced circulation from the fan system maintained ample oxygen for combustion (see oxygen concentration near the fire in Figure 5-47). The room temperature stabilized below 455 K (359°F) until the fire burned out (see Figure 5-48). In comparison, DBA Scenario 3 cooled down to 310 K (98°F) almost immediately after the explosion. The forced circulation from the fans provided fresh air for the fire and removed the airborne radionuclides.

Table 5-8 Summary of Key Event Timings for the Combined Explosion and Fire in the Plutonium Concentrator

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 & fire starts	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 ₂ O)	3.3
Low fan ΔP (<44" inH ₂ O, monitored only) ^A	5.5
HEPA filter 1 fails	11.5
All fuel is burned	973

n/c = not calculated

Notes:

- A The differential pressure generated by the fan is not a control signal identified in the BNFPSAR but often monitored in other DOE facilities. The low differential pressure condition indicates excessive exhaust flow (see Section 4.4.7).

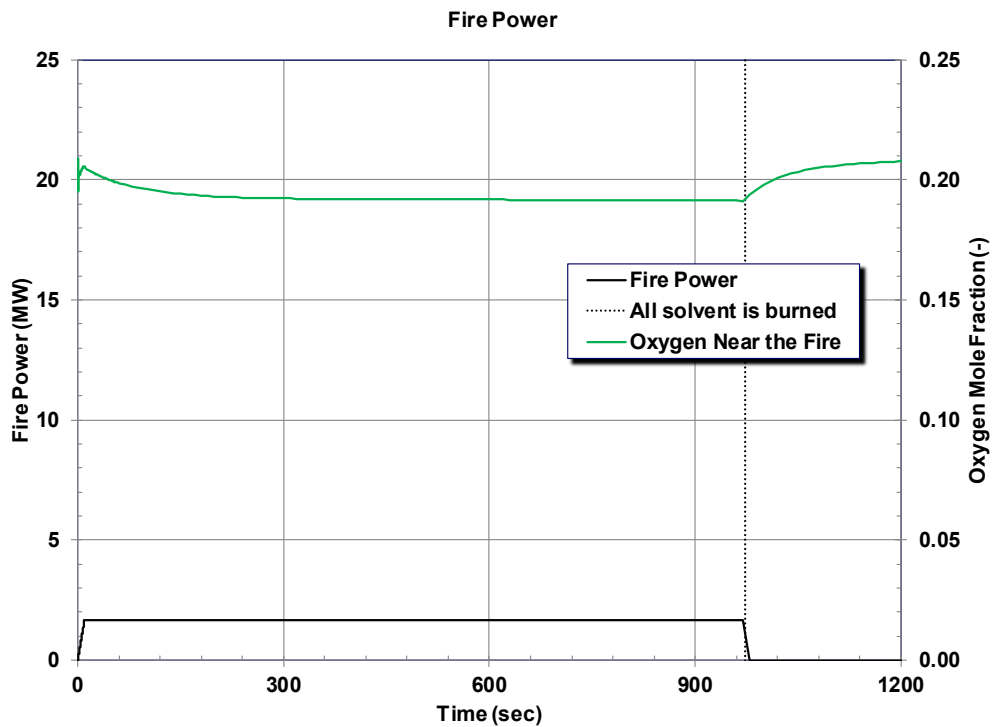


Figure 5-47 Fire Power and Oxygen Concentration near the Fire in Scenario 10

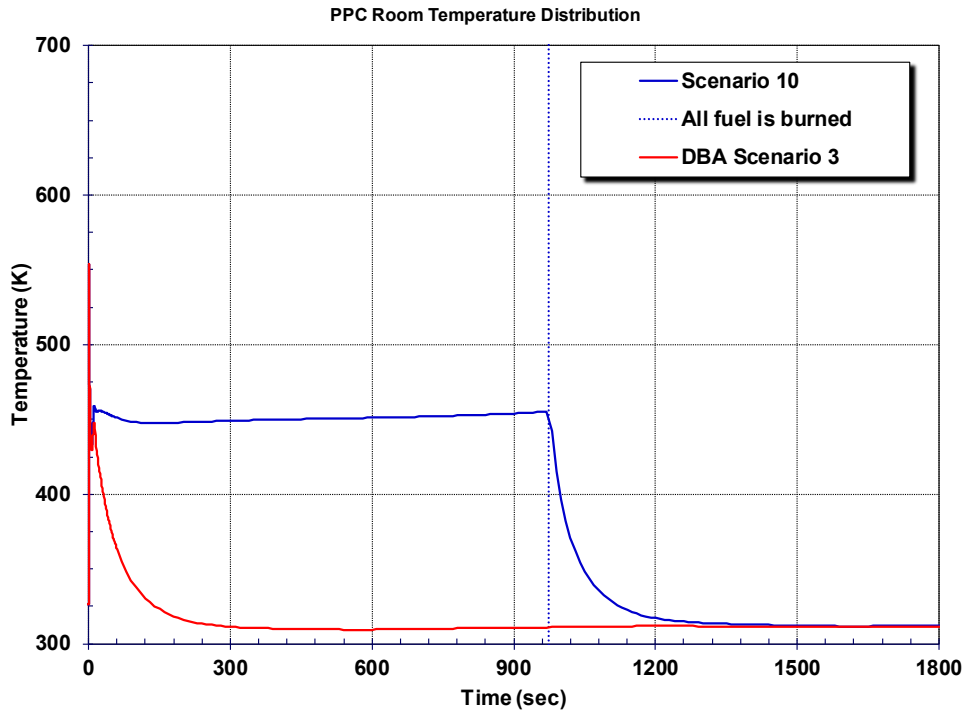


Figure 5-48 Comparison of Hot Gas Temperature in the PPC during Scenarios 1 and 10

The radionuclide behavior for Scenario 10 is shown in Figure 5-49 and Figure 5-50. The activity released during the explosion is spread into the FPIG, LPIG, and HTG & PEG regions of the BNFP due to the cell pressurization and connecting ventilation failures. Figure 5-49 shows the distribution of the activity through various regions in the facility as it leaves the PPC (i.e., included in the Hot Cell group). Most of the released activity is either captured in the filtered exhaust system or released to the environment. The airborne activity in the support gallery and other areas (e.g., the loading area) steadily decreases as the regions are filtered. The HEPA filters on the primary pathway from the PPC to the environment fail, which leads to the large source term to the environment.

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% (see Section 4.4.4). Most of the activity released in the accident was captured by the pre-filter in the Filter 1 compartment as shown in Figure 5-34. The pre-filter has limited effectiveness because the plutonium was released as a vapor, which quickly condenses into very small aerosols. The pre-filter only captures aerosols larger than 1 micron (see Section 4.4.4). The other filters captured smaller amounts than Filter 1.

In comparison to DBA Scenario 3, Scenario 10 had a slightly larger release to the environment, 1.75×10^{15} Bq (47,511 curies) versus 1.71×10^{15} Bq (46,316 curies) (see Figure 5-50). In contrast to the comparison of the combined fire and explosion in Scenario 9 and DBA Scenario 1, the additional source term from the fire in scenario 10 was relatively small. Only 50 liters of solvent burned in Scenario 10, which released 1.10×10^{14} Bq (2,962 curies). This is over an order of magnitude lower than the activity released from the explosion (i.e., 2.79×10^{15} Bq, 75,362 curies). In contrast, Scenario 9 burned 420 liters of solvent, which released 6.37×10^{15} Bq (173,065 curies) and was twice as large as the explosion release. Finally, since the fans remained operating in Scenario 10, the small source term and heat from the fire did not significantly impact the overall release to the environment. The agglomeration of the plutonium with the soot from the fire also increased the effectiveness of the pre-filter in Compartment 1.

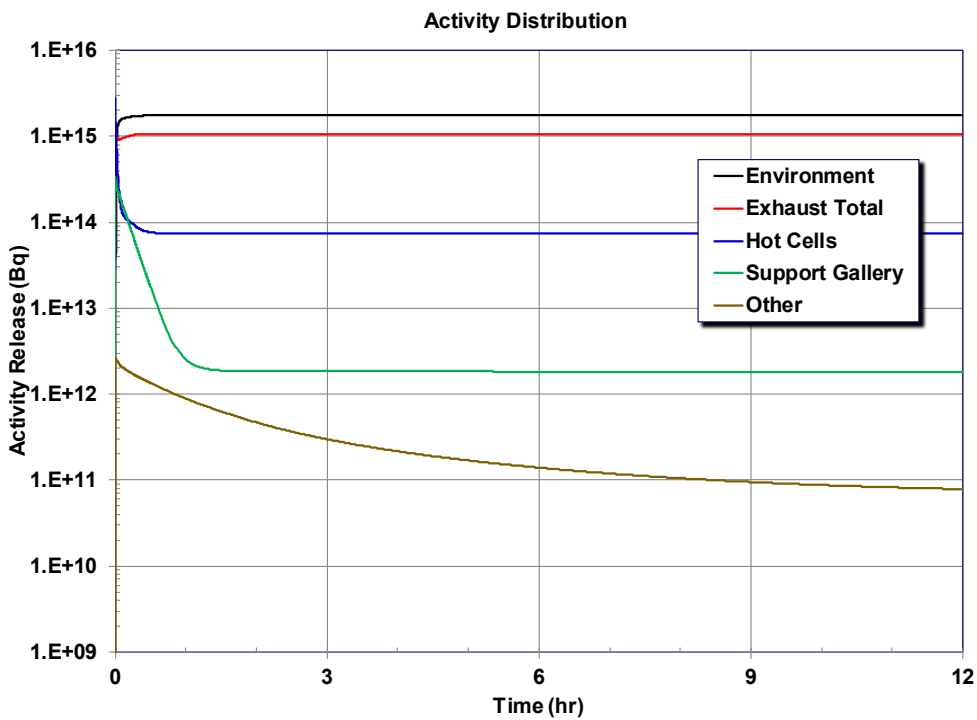


Figure 5-49 Activity Distribution within the BNFP during Scenario 10

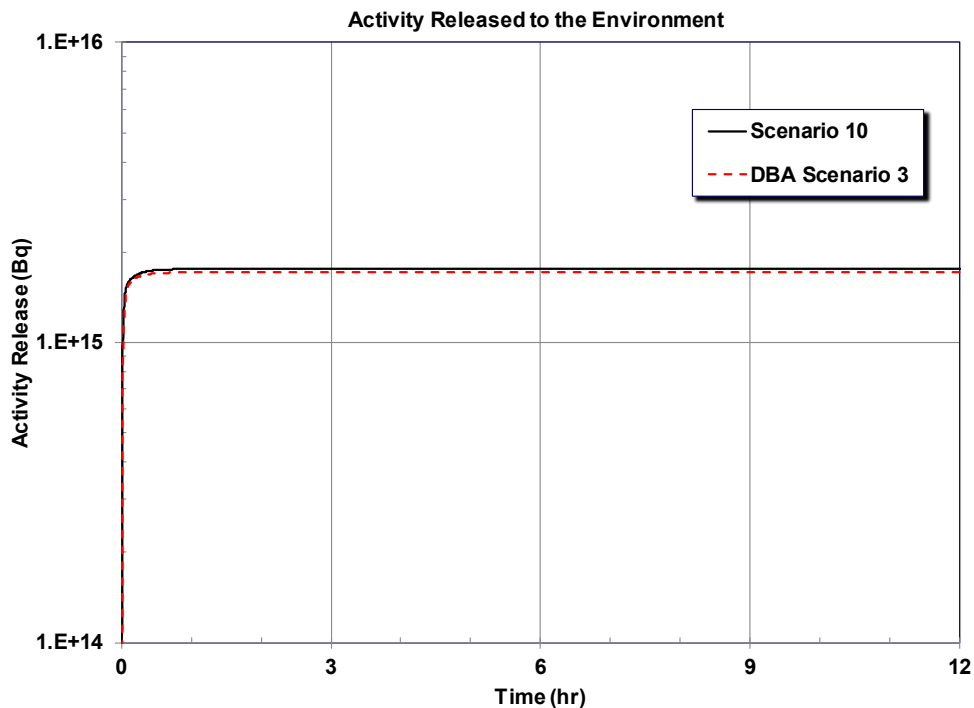


Figure 5-50 Comparison of the Activity Release to the Environment between DBA Scenario 3 and Scenario 10

5.4 Summary of Results

The results from the 10 scenarios are summarized in Table 5-9 through Table 5-11. All 10 scenarios originated in a hot cell. The total activity retained in any of the hot cells is in the Hot Cells column. The activity retained in the exhaust filtration ducting, all exhaust filters, and plant stack are in the Exhaust Column. The remaining galleries surrounding the hot cells are lumped into the column labeled Galleries. The total source term to the environment is in the column labeled Environment. The last two columns subdivide the source term to the environment into the activity vented out the plant stack versus all other sources of building leakage. Since the ventilation system normally keeps the building at a subatmospheric condition, building leakage occurs when the building is pressurized (e.g., following an explosion or large fire) and activity has leaked into the galleries near postulated leakage locations. If the exhaust fans are not working, then the leakage from the building becomes comparable to the leakage through the stack. Table 5-9 shows the activity distribution in becquerels; Table 5-10 shows the activity in curies; and Table 5-11 shows the activity distribution in percentages of the total activity released from the initiating event (i.e., fire, explosion, or both).

Scenarios 1+Fans, 3, 9+Fans, and 10 had the largest releases of radioactive material from the initiating events and source terms $>1 \times 10^{15}$ Bq. All four scenarios are very large red oil explosions that failed the exhaust filters between the pathway from the initiating event to the environment. The fans continued to run and pumped the activity to the environment. When the fans failed with the initial explosion, the source term to the environment was at least an order of magnitude smaller.

The HEPA filters were assumed to have zero efficiency at capturing very small aerosols (i.e., $<0.3 \mu\text{m}$). If the final exhaust filters capture the smallest aerosols with the same efficiency as the larger aerosols, the activity release to the environment in red oil explosion Scenario 5 dropped by nearly three orders of magnitude.

As shown in Table 5-11, the building leakage was relatively small in all scenarios. The highest building leakage to the environment occurred when the fans failed, although most of the inventory remained in the building for the failed fan sensitivity cases.

Table 5-9 Summary of Activity Distribution in Becquerels for the 10 Scenarios

Scenario	Hot Cells	Galleries	Exhaust	Source Term to the Environment		
				Environment	Stack to Env	Leak to Env
1 + Fans	2.16E+13	7.73E+12	8.65E+14	1.04E+15	1.04E+15	5.37E+10
1 + No Fans	6.69E+14	2.20E+14	6.06E+14	9.30E+13	5.37E+13	3.92E+13
2	1.65E+12	7.34E+10	1.54E+13	1.17E+12	1.17E+12	9.17E+03
3	3.59E+13	1.68E+12	1.04E+15	1.71E+15	1.71E+15	2.33E+04
4	6.64E+11	6.98E+08	1.27E+12	1.88E+11	1.88E+11	1.06E+06
5	9.83E+09	1.38E+08	4.99E+10	2.29E+12	2.29E+12	6.31E+06
5 + All ^A	9.83E+09	1.38E+08	2.33E+12	3.21E+09	3.21E+09	6.32E+06
6	1.98E+12	4.25E+10	1.47E+13	7.33E+11	7.33E+11	2.29E+03
7	4.64E+11	9.24E+06	1.46E+12	1.80E+11	1.80E+11	4.69E-03
8	4.63E+11	2.27E+07	1.61E+12	3.12E+10	3.12E+10	0.00E+00
9 + Fans	1.00E+15	1.43E+13	1.55E+15	5.66E+15	5.66E+15	9.04E+11
9 + No Fans	3.79E+15	6.66E+14	1.02E+15	7.98E+14	3.99E+14	3.99E+14
10	7.30E+13	1.83E+12	1.07E+15	1.76E+15	1.76E+15	4.04E+04

Note:

- A. 5 + All is the sensitivity study where Filter 1 captures all aerosols, including $<0.3 \mu\text{m}$.

Table 5-10 Summary of Activity Distribution in curies for the 10 Scenarios

Scenario	Hot Cells	Galleries	Exhaust	Source Term to the Environment		
				Environment	Stack to Env	Leak to Env
1 + Fans	583.8	208.9	23,378.4	28,108.1	28,108.1	1.5E+00
1 + No Fans	18,081.1	5,945.9	16,378.4	2,513.5	1,451.4	1.1E+03
2	44.6	2.0	416.2	31.6	31.6	2.5E-07
3	970.3	45.4	28,108.1	46,216.2	46,216.2	6.3E-07
4	17.9	0.0	34.3	5.1	5.1	2.9E-05
5	0.3	0.0	1.3	61.9	61.9	1.7E-04
5 + All ^A	0.3	0.0	63.0	0.1	0.1	1.7E-04
6	53.5	1.1	397.3	19.8	19.8	6.2E-08
7	12.5	0.0	39.5	4.9	4.9	1.3E-13
8	12.5	0.0	43.5	0.8	0.8	0.0E+00
9 + Fans	27,027.0	386.5	41,891.9	152,973.0	152,973.0	2.4E+01
9 + No Fans	102,432.4	18,000.0	27,567.6	21,567.6	10,783.8	1.1E+04
10	1,973.0	49.5	28,918.9	47,567.6	47,567.6	1.1E-06

Note:

A. 5 + All is the sensitivity study where Filter 1 captures all aerosols, including <0.3 μm.

Table 5-11 Summary of Activity Distribution in Percentages for the 10 Scenarios

Scenario	Hot Cells	Galleries	Exhaust	Source Term to the Environment		
				Environment	Stack to Env	Leak to Env
1 + Fans	1.1%	0.4%	44.7%	53.8%	53.8%	~0%
1 + No Fans	42.1%	13.9%	38.2%	5.9%	3.4%	2.5%
2	9.0%	0.4%	84.2%	6.4%	6.4%	~0%
3	1.3%	0.1%	37.3%	61.3%	61.3%	~0%
4	31.3%	0.0%	59.8%	8.9%	8.9%	~0%
5	0.4%	0.0%	2.1%	97.5%	97.5%	~0%
5 + All ^A	0.4%	0.0%	99.4%	0.1%	0.1%	~0%
6	11.3%	0.2%	84.2%	4.2%	4.2%	~0%
7	22.1%	0.0%	69.4%	8.6%	8.6%	~0%
8	22.0%	0.0%	76.5%	1.5%	1.5%	~0%
9 + Fans	12.2%	0.2%	18.8%	68.8%	68.8%	0.0%
9 + No Fans	60.4%	10.6%	16.3%	12.7%	6.4%	6.4%
10	2.5%	0.1%	36.8%	60.6%	60.6%	~0%

Note:

A. 5 + All is the sensitivity study where Filter 1 captures all aerosols, including <0.3 μm.

5.5 Comparison to the BNFP FSAR

The BNFP FSAR characterized the release from the building using a multi-factor formula (i.e., similar to the 5-factor formula from DOE Handbook [8] as discussed in Section 2).

$$C_i/t \times SF_i \times RF_i \times EF = R_i \quad (21)$$

where

C_i/t	Activity in curies for isotope i per MTU [Ci/MTU]
SF_i	Fraction of isotope i normally present in this process
RF_i	Fraction released to the stack for isotope i
EF	Quantity of uranium in metric tons involved [MTU]

The release to the stack was only calculated for important isotopes. The amount of activity per MTU in the concentrate for each isotope i prior to release is given in the C_i/t parameter.

Since this is a chemical processing plant, the relative amounts of isotopes change as the various processes selectively remove specific elements or isotopes. The SF_i parameter in the BNFP FSAR quantifies this parameter for each isotope i , which is also used in the present analysis. For example, two of the DBA scenarios (i.e., DBA Scenarios 2 and 3) only had plutonium present. In contrast, most of the plutonium had been removed in previous processes for DBA Scenario 1 in the high-activity waste concentrator but fission products were present (e.g., ^{137}Cs).

The BNFP FSAR developed RF_i by considering (a) the nonvolatile fraction dispersed during the accident, (b) the filtration efficiency, and (c) the volatile fraction (i.e., if any) that would not be filtered. The three quantities were combined to determine the release fraction from the accident to the stack. Note that this simple characterization does not include (a) filter degradation and failures, (b) low filter efficiencies for small aerosols, (c) building leakage, (d) aerosol agglomeration and deposition physics, (e) the transport compound vapor pressure (i.e., the ability to form gases in high temperatures), (f) other structural failures, and (g) dispersion within the building. All the previous factors are considered in the MELCOR analysis.

Finally, the EF parameter specifies the amount of material at risk in terms of MTU. The multiplication of $SF_i \times EF$ gives the amount of isotope i at risk in this process.

The BNFP used the 4-factor formula in Equation (21) to calculate release to the stack. Two analyses were presented in the BNFP FSAR: (1) a conservative analysis and (2) a realistic analysis. The conservative analysis used pessimistic assumptions whereas the realistic analysis used more optimistic release fractions from the concentrate, alternate filter efficiencies, and lower volatile fractions. The isotopes of ruthenium and iodine were the only two elements that included the volatile quantifications. If these elements are in their more volatile vapor form, then they are not filtered. The RF_i parameter includes this effect.

The effective building decontamination factor (DF) is one method for comparing best-estimate results from the current MELCOR analyses with the historical BNFP FSAR safety analyses. The effective building DF quantifies the transmission of the released radionuclides from the initiating event to the environment. The effective building DF is defined as,

$$DF_i = 1/RF_i \quad (22)$$

where

DF_i	Building decontamination factor for isotope i
RF_i	Fraction released to the stack for isotope i

The effective building DF in the BNFP FSAR was an assessment of the filter performance. The BNFP FSAR RF_i factor varied by element and included the effects of filter aerosol performance, the gaseous volatility of iodine and ruthenium. In contrast, the MELCOR evaluation of the effective building DF included all methods of radionuclide deposition within the building, filter failures, building leakage, and filter performance.²⁴ Since the BNFP and MELCOR released inventories released varied, the effective building DF is a useful method to compare the non-dimensional, effective transmission from the initiating event to the environment.

The effective building DFs from the BNFP FSAR analyses are presented in Table 5-12 and Table 5-13 for the conservative and the realistic cases, respectively. The conservative decontamination factors ranged from no retention for iodine (i.e., DF=1) to a value of 714.3 for elements with no volatility (i.e., Zr-Nb, OFPT²⁵, and Pu). In a somewhat nonintuitive manner, some of the realistic DFs are lower than the conservative values (i.e., lower release to the stack and higher building retention). The reasons are attributed to differences in the isotope release from the concentrate, which is not included in the DF evaluation and a less precise definition of the filter efficiency versus the conservative analysis. However, those differences are not terribly significant (i.e., 714.3 versus 500.0).

Other parameters for comparison, such as isotope, element, or total activity release to the stack from the BNFP analysis were not selected due to the large differences in the analysis methodology. First, the BNFP analysis only analyzed 4 to 17 isotopes depending on the specific DBA scenario. As described in Section 3.3, 323 isotopes are included in the ORIGEN/ARP inventory analysis for the MELCOR calculations. Consequently, a more complete activity evaluation was performed in the new analysis. Second, the current analysis assumed 5-year old, high burn-up fuel (i.e., 60 GWd/MTU) whereas the BNFP analysis used 40 GWd/MTU fuel with 160 days aging. The MELCOR analysis bounds current higher fuel burn-up practices and earliest timing for transport of fuel to a reprocessing facility (i.e., 5 years versus 160 days). Finally, the MELCOR analysis used newer experimental or recommended values for the release from the concentrate (i.e., as evaluated in Reference [2]). In consideration of these differences, only a comparison of the building DFs is presented, which removes methodology differences in the available inventory and its release from the concentrate.

The building decontamination (DF) results from MELCOR simulations of the DBA scenarios are in Figure 5-51 through Figure 5-56. The results from the DBA Scenarios 1 and 3 illustrate the adverse impact of the explosion on the filtration system response, which was not considered in the FSAR analysis. The explosion failed the two HEPA filters between the hot cell with the explosion and environment. Consequently, the class-specific DFs range from 2 to 21 versus 416.7 to 714.3 in the FSAR. Obviously, the failed HEPA had a major impact on the releases. However, other factors such as no filtration below 1 micron for the pre-filter also had an important impact.

As discussed in Section 5.2.3, DBA Scenario 5 in the LAW concentrator cycle scenario was adversely impacted by no HEPA filtration below 0.3 micron. The DF was approximately 1 as all

²⁴ The RF_i factor in the MELCOR analysis is the fraction released to the environment (i.e., perhaps better described as RE_i , or release to the environment). It includes building leakage, filter bypass, and leakage through the filter to the stack.

²⁵ The BNFP FSAR used OFPT as an abbreviation for Other Fission Product and Transuranium Elements, which signified other key elements not already cited.

the small aerosols formed from the explosion slipped past both HEPA filters to the environment (see Figure 5-56). Figure 5-57 shows the results from the DBA Scenario 5 sensitivity study where the HEPA filters were assumed to capture aerosols less than 0.3 microns. If the final HEPA filter is effective at capturing aerosols below 0.3 micron, then the building DF is 727, or in good agreement with the FSAR in Table 5-12. Furthermore, DBA Scenario 5 had very little retention in the building due to the very low aerosol density for agglomeration and the low deposition characteristics of small aerosols from an explosion.

The DF results from the two fire scenarios are shown in Figure 5-53 and Figure 5-55. Both HEPAs between the fire and the environment remained intact in these scenarios. Similar to the explosion results, the performance of the filters was reduced due to the inability to capture aerosols less than 0.3 microns and high gas temperatures forming vapors for the more volatile compounds. The calculated fire building DFs ranged from 4 to 15 (i.e., with iodine not being filtered) as compared to 9.8 to 500 in the FSAR.

Table 5-12 Conservative Building Decontamination Factors from the BNFP FSAR

Scenario	Type	Ru	Zr-Nb	I	OFPT	Pu
DBA 1	Explosion	416.7	714.3	1.0	714.3	714.3
DBA 2	Fire	n/a	n/a	n/a	n/a	100.0 ^A
DBA 3	Explosion	n/a	n/a	n/a	n/a	500.0
DBA 4	Fire	9.1	100.0 ^A	1.0	100.0 ^A	100.0 ^A
DBA 5	Explosion	416.7	714.3	1.0	714.3	714.3

Notes:

n/a = not applicable (i.e., element was not present in this process)

OFPT = Other fission product and transuranium elements.

Note A = The filter efficiency for radionuclides with smoke in a fire is reported in the BNFP FSAR as 99% [12].

Table 5-13 Realistic Building Decontamination Factors from the BNFP FSAR

Scenario	Type	Ru	Zr-Nb	I	OFPT	Pu
DBA 1	Explosion	500.0	500.0	2.0	500.0	500.0
DBA 2	Fire	n/a	n/a	n/a	n/a	500.0
DBA 3	Explosion	n/a	n/a	n/a	n/a	500.0
DBA 4	Fire	9.8	500.0	2.0	500.0	500.0
DBA 5	Explosion	500.0	500.0	2.0	500.0	500.0

Notes:

n/a = not applicable (i.e., element was not present in this process)

OFPT = Other fission product and transuranium elements.

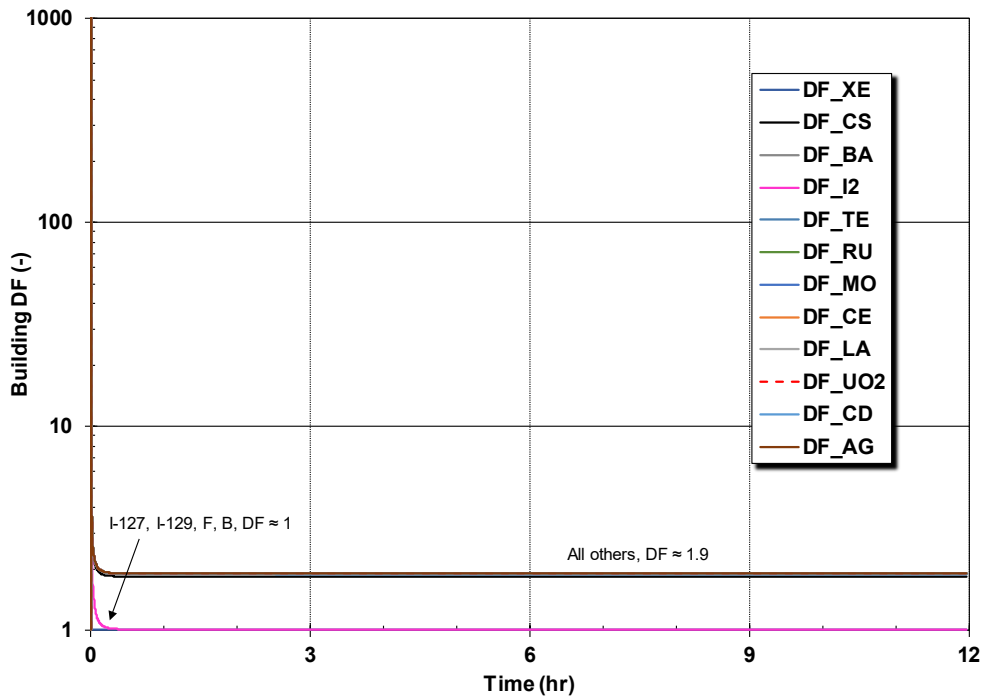


Figure 5-51 Building Decontamination Factors for DBA Scenario 1 with Fans

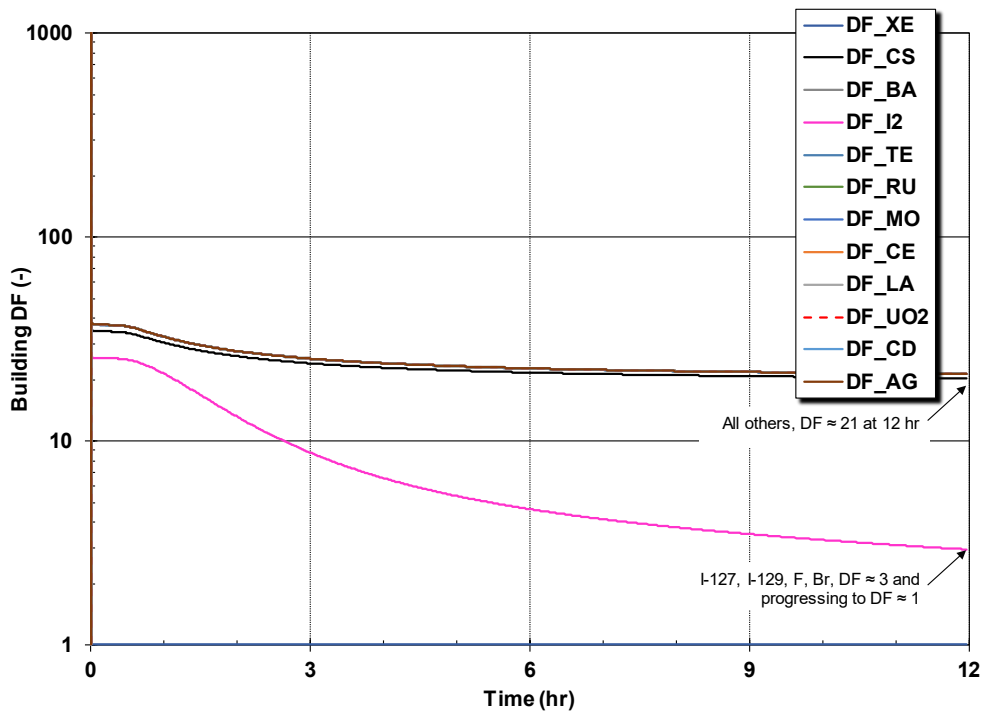


Figure 5-52 Building Decontamination Factors for DBA Scenario 1 without Fans

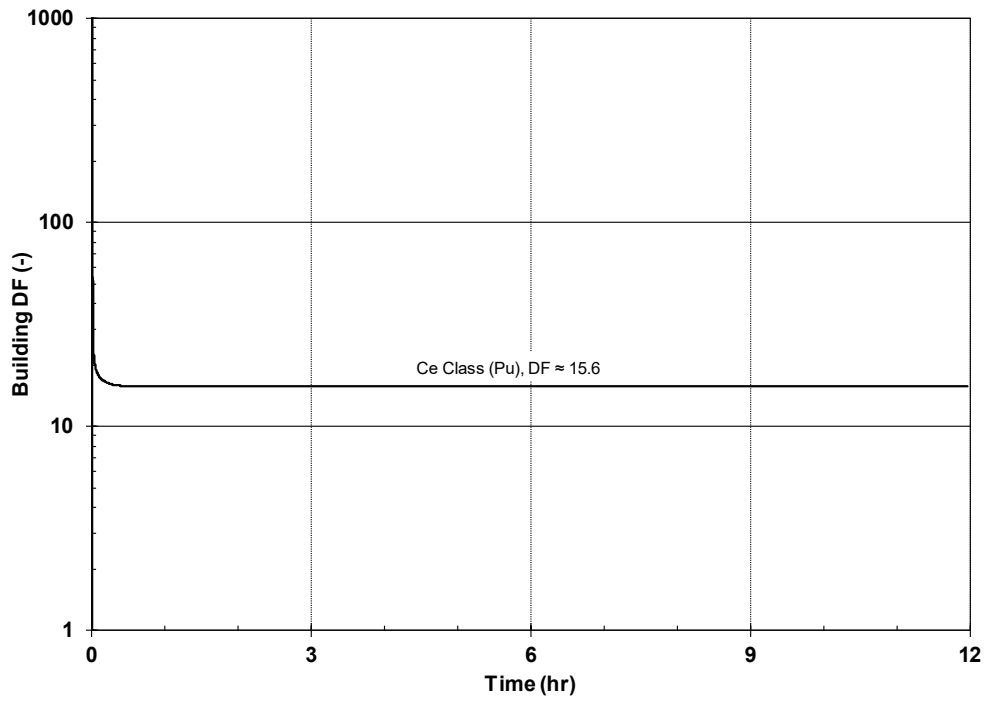


Figure 5-53 Building Decontamination Factors for DBA Scenario 2

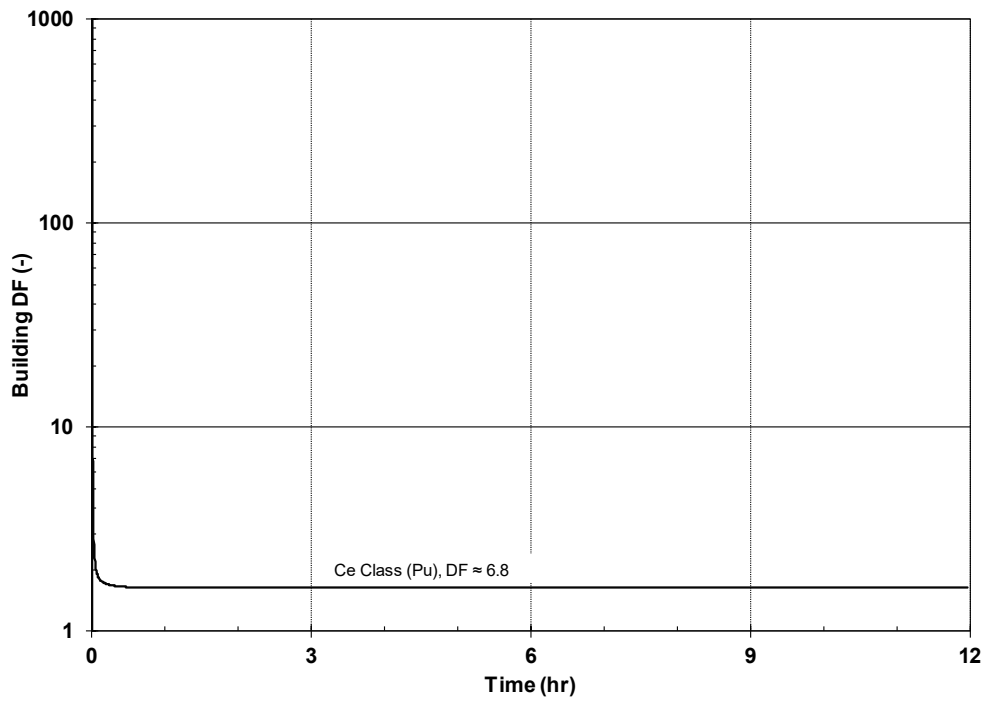


Figure 5-54 Building Decontamination Factors for DBA Scenario 3

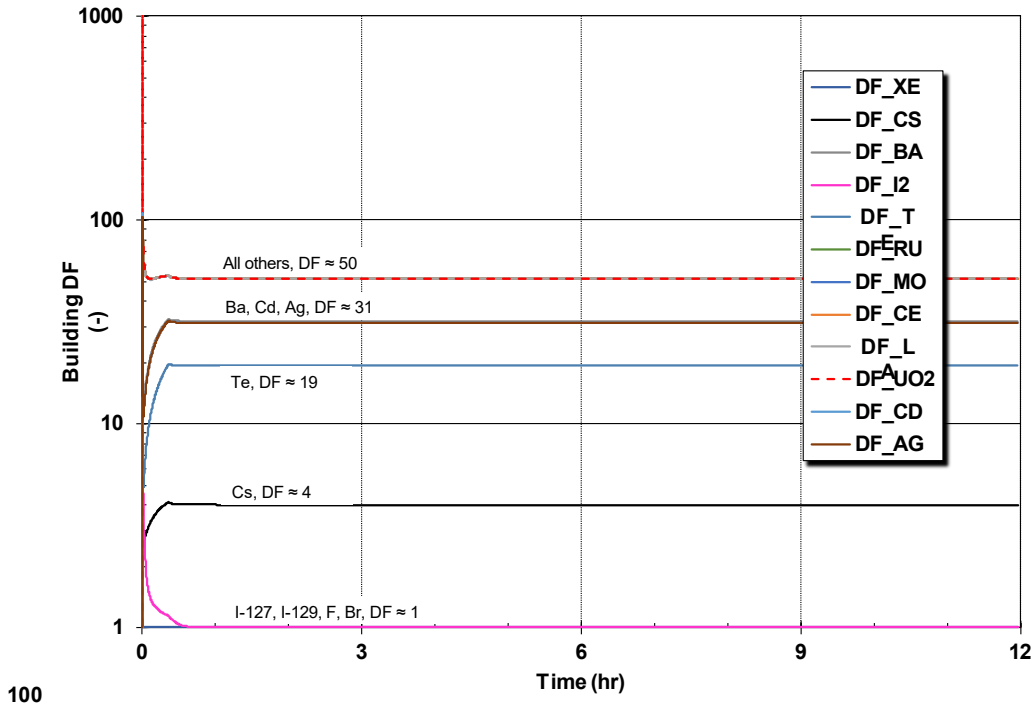


Figure 5-55 Building Decontamination Factors for DBA Scenario 4 ²⁶

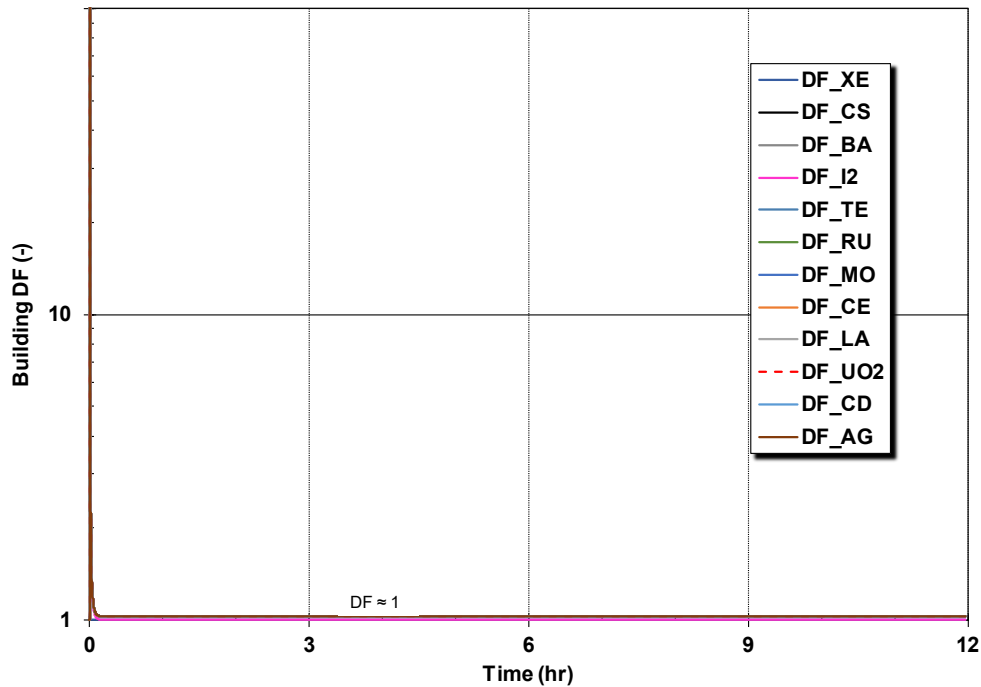


Figure 5-56 Building Decontamination Factors for DBA Scenario 5

²⁶ A MELCOR error was discovered where the separate DF for ruthenium was not applied. The filter DF for ruthenium was specified as 9.9 to account for the volatile fraction generated in a fire but a DF of 714.3 was applied. The calculated DF for Ru, which includes other retention and filter bypass mechanisms, was approximately 50. A full error report has been submitted to the code developer group, but a correction was not available for this report.

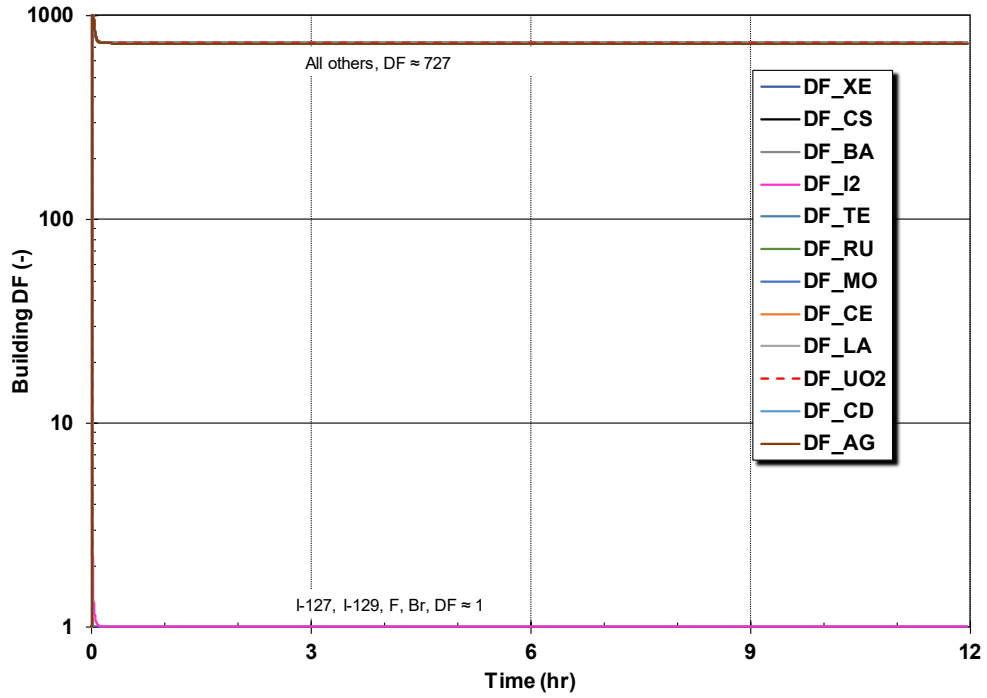


Figure 5-57 Building Decontamination Factors for DBA Scenario 5 with Filter Capture of Aerosols <0.3 microns

6 SUMMARY

Ten accident scenarios were modeled using NRC's best-estimate severe accident analysis code, MELCOR 2.2. The accident scenarios simulated a range of explosions and/or fires related to nuclear fuel reprocessing. Five of the accident scenarios were based on the Class 5 Design Basis Accidents from the BNFP FSAR [1]. Three of the remaining accident scenarios include sensitivity studies on smaller solvent fires. The final two accidents included an induced fire from an initial explosion. The explosion scenarios fell within estimated ranges of historical events (i.e., 50 to 700 MJ) that occurred at reprocessing facilities throughout the world. These hypothetical explosion scenarios caused damage to ventilation and filtration systems. There were two very large fire scenarios from the FSAR that also caused some ventilation system damage.

The previous MELCOR BNFP accident analyses used a trace release of activity to estimate the building LPF (i.e., the DOE approach described in Section 2). The model was enhanced for the current project to include representative accident radionuclide inventories based on ORIGEN calculations of commercial spent nuclear fuel. Consequently, the present calculations predict the full source term to the environment rather than an LPF. New radionuclide tracking features were added to predict the distribution of radionuclide activity within the facility and to the environment. The MELCOR model was also updated to include ventilation, filtration, and structural failures as well as filter degradation due to high temperatures and soot loading. The latest release of MELCOR Version 2.2 was used for these analyses.

The radionuclide inventory was developed from ORIGEN calculations of spent PWR fuel with an initial enrichment of 4.5% U-235 by weight. The fuel aged for five years after a final 500-day irradiation cycle. The burn-up was conservatively increased to 60 GWd/MTU to bound current US operations. In contrast, the BNFP FSAR assumed a lower burn up (40 GWd/MTU) typical of the mid-1970s but only 160 days cooling after last fission operation. Consequently, neither the burn-up nor the cooling time used in the FSAR is realistic for modern applications.

The results are characterized in terms of activity release to the environment and the building decontamination factor, which is related to the leak path factor used in Department of Energy safety analyses. The MELCOR 2.2 results monitor potential adverse consequences to the filters, the ventilation system, and the structures as a result of the explosions and fires, which were not considered in the original FSAR calculations. The calculations also include best-estimate models for aerosol transport, agglomeration, deposition, and radionuclide compound vapor pressure. The output from the simulations provide the radionuclide activity distributed throughout the facility and to the environment. The resultant source terms could be used to predict the maximum dose at the site boundary or the offsite dose to the public.

In contrast to 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 them in cooler regions), and
- chemical reactant and product generation associated with explosions and fires (e.g., oxygen consumption and soot production)

MELCOR does not model explosive shock waves. Instead, assumptions were made on immediate structural damages from the shock wave. MELCOR is used to evaluate the subsequent static pressurization from the energy addition. The static pressurization from the two largest explosions caused damage to the ventilation systems connected to the effected hot cell. As the high pressure from the explosion dissipated outside the hot cell, the HEPA filters between the cell and the environment were predicted to fail. The penetrations between the processing cell and an adjacent low radioactivity region also failed as a consequence of the largest explosion. The source terms from the explosion scenarios were very large (i.e., 1.04×10^{15} Bq, or 28,151 curies for the largest explosion and 1.71×10^{15} Bq, or 46,316 curies for the second largest explosion). Nonintuitively, the smallest explosion had the highest percentage of the released activity getting to the environment. Due to the relatively small amount of inventory released from the smallest explosion, there was significantly less agglomeration and deposition of the very small aerosols formed in the explosion. The small aerosols (i.e., many below the capture efficiency of the HEPA filters) passed through the filters to the environment. Consequently, the magnitude and constituents of the source term to the environment is highly dependent on (a) the amount of material involved in the accident, (b) the efficiency of the physical deposition and agglomeration processes, and (c) the filter efficiency.

Two of the FSAR DBA accident scenarios were very large fires (i.e., 84 MW and 169 MW maximum fire power). However, the MELCOR model considers oxygen availability, which limited the fires from reaching their maximum power. Consequently, the fires burn longer at an oxygen-limited rate until all the solvent was consumed. The rapid heatup of the air pressurized the hot cell room and failed ventilation dampers to the room. Similar to the explosion results, the fire scenarios had releases to the environment due to very small aerosols passing through the filters. Unlike the large explosions, there were two intact HEPA filters between the fire in the hot cell and the stack that captured most of the activity. However, the net retention was much lower than the filter efficiency due to the filtration bypass mechanisms.

The most meaningful comparison to the BNFP FSAR results was the effective building decontamination factor due to the significant differences in the inventory and methods. The FSAR results reflect the rated filter efficiency with allowances for volatile ruthenium and gaseous iodine passing through the filter. The conservative decontamination factors from the FSAR for the DBA scenarios range from 416.7 to 714.3. The MELCOR calculations include the benefits of aerosol retention in the building but also consider consequential failures of filter elements and ineffective filtering of small aerosols or gaseous forms of the radionuclides. The explosion DFs ranged from almost 1 (i.e., no retention) to 21, which was much smaller than FSAR values. The differences are caused by HEPA filter failures for the two large explosions and ineffective capture of small aerosols for the smallest explosion.

The two fires had slightly better building decontamination factor comparisons than the explosion comparisons. The conservative decontamination factors from the FSAR for the DBA scenarios range from 9.1 for ruthenium up to 100 for aerosols. The MELCOR results for aerosols ranged from 4 to 50. Due to a code error, the reduced capture efficiency for volatile ruthenium was not

calculated differently than the other aerosols.²⁷ However, DBA Scenario 2 showed reduced building retention for cesium, tellurium, barium, silver, and cadmium, which also became more volatile due to their increased vapor pressure in high temperature fire conditions. There were no HEPA failures in the fire scenarios, but the very small aerosols or gases were not captured. Consequently, the building decontamination factors for fires were lower than the design values. However, the MELCOR and the FSAR results for the fire scenarios are in closer agreement than explosions due to no HEPA filter failures and a reduced efficiency of the filter.

²⁷ The error has been reported to the code development group, but a code update was not available prior to the completion of this project.

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BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

NUREG/CR-7266

2. TITLE AND SUBTITLE

MELCOR Modeling of Accident Scenarios at a Facility for Aqueous
Reprocessing of Spent Nuclear Fuel

3. DATE REPORT PUBLISHED

MONTH	YEAR
January	2020

4. FIN OR GRANT NUMBER

5. AUTHOR(S)

Kenneth Wagner
David Louie

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Sandia National Laboratories
PO Box 5800 MS-0748
Albuquerque, NM 87185-0748

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)

Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

The work presented in this report enhances 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. The simulations were performed using a MELCOR 2.2 model of the Barnwell Nuclear Fuel Plant (BNFP), a facility that never operated. The approach centers on design basis accidents that were defined in the Final Safety Analysis Report (FSAR) which are intended to determine the effectiveness of various lines of defense within the facility. Ten accidents were modeled to assess potential impacts due to explosions and/or fires related directly to nuclear fuel reprocessing. Important processes included, physical failure of air filters, by-pass of filters by very small aerosols, vaporization of radionuclides, and agglomeration and deposition of radionuclides within the building. The ability of MELCOR to evaluate this type of facility was demonstrated and results were compared to those in the FSAR. Decontamination Factors calculated by MELCOR were much lower (higher releases) than those in the FSAR. The differences are caused by HEPA filter failures for the two large explosions and ineffective capture of small aerosols for the smallest explosion.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Re-processing, spent nuclear fuel, severe accident, decontamination factor, MELCOR

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

(This Page)

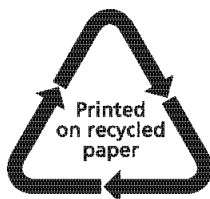
unclassified

(This Report)

unclassified

15. NUMBER OF PAGES

16. PRICE



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NUREG/CR-7266

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for Aqueous Reprocessing of Spent Nuclear Fuel**

January 2020