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FSAR Fire Accident Analysis for a Plutonium Facility

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Introduction

The Final Safety Analysis Report (FSAR) for a plutonium facility as required by DOE Orders 5480.23[1] and 5480.22[2] has recently been completed and approved. The facility processes and stores radionuclides such as Pu-238, Pu-239, enriched uranium, and to a lesser degree other actinides. DOE Order 5480.23 and DOE-STD-3009-94[3] require analysis of different types of accidents (operational accidents such as fires, explosions, spills, criticality events, and natural phenomena such as earthquakes). The accidents that were analyzed quantitatively, or the Evaluation Basis Accidents (EBAs), were selected based on a multi-step screening process that utilizes extensively the Hazards Analysis (HA) performed for the facility. In the HA, specific accident scenarios, with estimated frequency and consequences, were developed for each identified hazard associated with facility operations and activities. Analysis of the EBAs and comparison of their consequences to the evaluation guidelines established the safety envelope for the facility and identified the safety-class structures, systems, and components.

This paper discusses the analysis of the fire EBA. This fire accident was analyzed in relatively great detail in the FSAR because of its potential off-site consequences are more severe compared to other events. In the following, a description of the scenario is first given, followed by a brief summary of the methodology for calculating the source term. Finally, we discuss how we determined a key parameter affecting the source term, the leakpath factor, which is the focus of this paper.

Fire Scenario

The evaluation basis fire occurs in Room B adjacent to glovebox GB-X and the fire breaches the glovebox. GB-X is used for a slug and screen process during the early stages of heat source production in which fine particles are involved. The source term in GB-X is finely-powdered Pu-238 in oxide form. The basic elements of the localized fire scenario are that low-level-waste boxes filled with combustible room waste are stacked in front of the glovebox and ignited due to internal heat generation or a spill of flammable liquid. The laboratory room is unattended, and the initiating fire is allowed to ignite the bottom of a polymethyl methacrylate (PMMA) slab (the plastic material used primarily to shield workers against neutrons emitted from materials inside the glovebox). The fire suppression system is not available or does not put out the fire, and the PMMA burning surface grows exponentially upward and burns the gloves, breaching the glovebox. The ventilation system is also unavailable.

Aerosol and combustion product gases produced by the fire are convected throughout the fire room, into the ventilation ductwork, and into the neighboring rooms and corridor via door gaps. The resultant amount of radioactivity released into the environment depends on the transport of the aerosol within the facility building and the openings present (external door; building leakages; ventilation inlet, exhaust, and bleed-off paths).

An event tree is presented in Fig. 1 which shows all the possible event progression sequences for this accident. Five of the eleven sequences result in no release or filtered release with no significant off-site dose consequences. Among the other sequences, which lead to unfiltered or partially filtered release, sequence number 6 has the highest probability (10^{-5} per year) and was chosen as the evaluation basis fire scenario. (The other sequences, 7 through 11, were treated as beyond evaluation basis accidents. Although not discussed further in this paper, these BEBA scenarios were also analyzed using the modeling base developed for the EBA.)

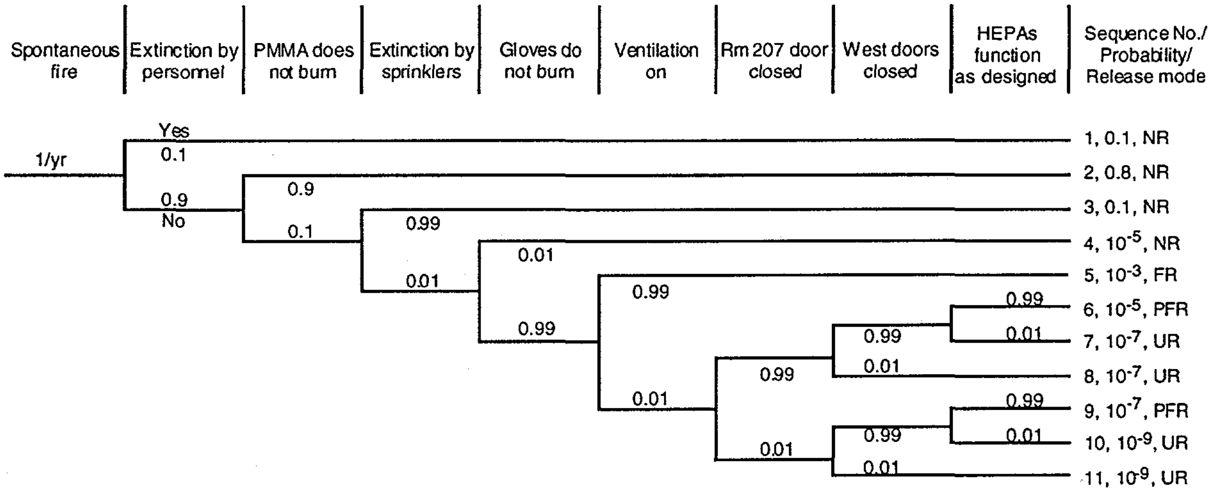

Fig. 1. Event tree for fire accident scenario. Sequence number 6 is the EBA selected for detailed, quantitative analysis. Release mode: NR = no release, FR = filtered release, PFR = partially filtered release, UR = unmitigated release.

Source Term Analysis

To determine the final source term released external to the facility due to this accident, the formula in DOE-HDBK-3010-94[4] was used:

Source Term = MAR x DR x ARF x RF x LPF, where

MAT = Material at Risk
DR = Damage Ratio (≤ 1.0)
ARF = Airborne Release Fraction (≤ 1.0)
RF = Respirable Fraction (≤ 1.0)
LPF = Leakpath Factor (≤ 1.0)

The total source term is a linear combination of the source terms from all mechanisms by which respirable Pu powder is driven airborne. Possible ways by which the Pu can be aerosolized include combustion of contaminated gloves, aerodynamic entrainment of exposed powder in trays in the glovebox, and aerodynamic resuspension of powder that has been deposited on internal glovebox structures and surfaces.

The product of the first four factors in the source term formula gives the respirable initial source term, which is dependent largely on the amount of radioactive material that can be affected by the fire and on the airborne mechanisms. Guidance on estimating the ARF and RF under specific sets of induced physical stresses (such as combustion, aerodynamic entrainment and resuspension in this accident) is provided in DOD-HDBK-3010-94. The initial source term multiplied by the LPF gives the final source term that is needed as input for the off-site dose calculations. We will not discuss the initial source term further here. Instead, the modeling effort required to determine the LPF will be described in the following section.

Determination of the Leakpath Factor

In the absence of active ventilation air flows, transport of the initial source term from the accident location to the facility boundaries is mainly driven by the energy of the fire. Figure 2 shows a simplified floor plan of the Laboratory Areas including the fire room and the corridor. Figure 3 shows schematically the major environmental release pathways for the source term after it has become airborne in the Laboratory Area volumes

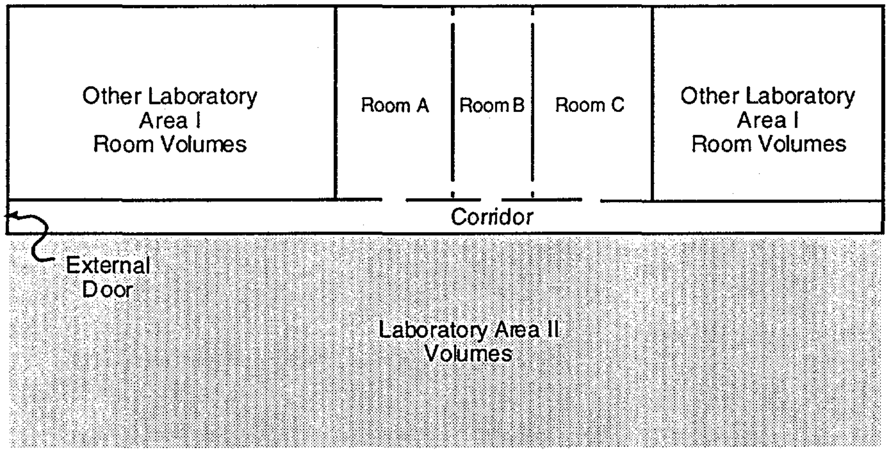

Fig. 2. Simplified floor plan of Laboratory Areas I and II, showing locations of the fire room, Room B, the corridor, and the external door.

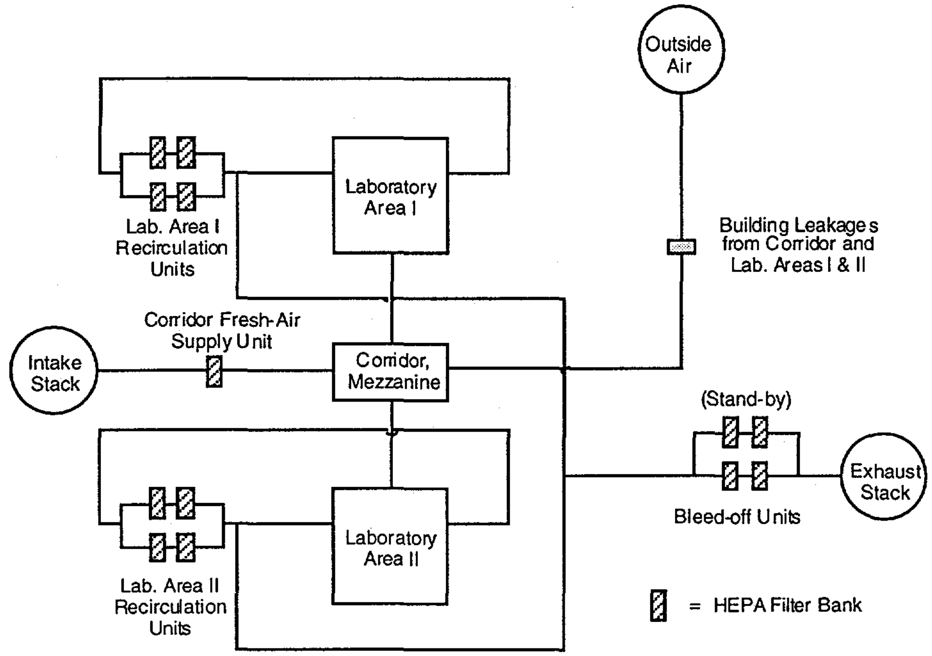

Fig. 3. Schematics of the Laboratory Area volumes modeled and major environmental release pathways for the fire accident scenario.

For the purpose of obtaining the final source term, this transport to the outside environment via all available pathways can be characterized by a single factor, the LPF. Clearly, the number of existing release paths and their characteristics—i.e., whether the path is via building leakages, an open doorway, or ventilation ductwork with high-efficiency particulate-air (HEPA) filtration, etc.—will dictate the LPF magnitude. In addition, the LPF depends on many complex physical effects such as heat loss to building structures (which reduces the transport driving potential); convective patterns set up by the fire; and aerosol behaviors such as agglomeration, deagglomeration, various deposition mechanisms, and resuspension. In the following subsections, assumptions and important physical model parameters used in the analysis calculations that determine the LPF are discussed, followed by the results obtained.

Major Assumptions

The initial source term is assumed to be instantaneously and uniformly mixed into the volume of the Laboratory Area volumes including the corridor and mezzanine. The aerosol is assumed to follow the gas motion exactly, and no credit is taken of any depletion due to agglomeration, gravitational settling, inertial impaction, and thermophoretic effects. The pressurized gases (caused by heating and combustion products due to the fire) are released to the outside environment through three paths as shown in Fig. 4. The release through the ventilation intake and bleed-off paths are filtered, while the release through the building leakage path is unmitigated.

The flow resistance for the leakpath is characterized by the measured in-leakage flow across a design pressure differential during normal operation with active ventilation. This leakpath flow resistance is expressed in the model in terms of a "flow conductance," β_ℓ, which has a value of 2.8×10^3 cfm/(in-wc)$^{0.91}$.

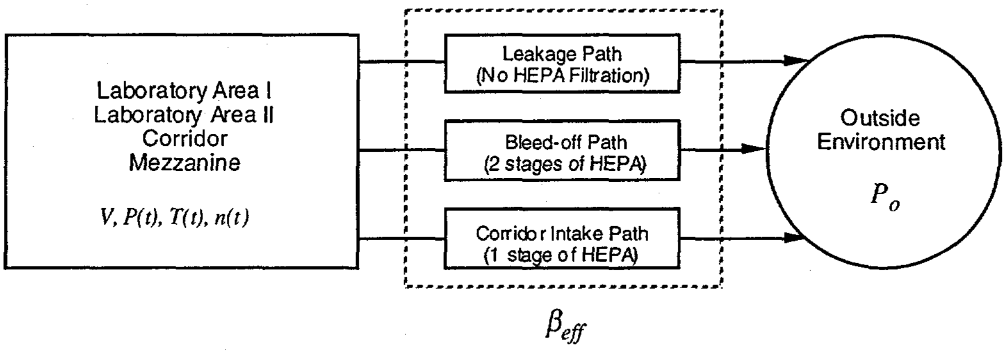

Fig. 4. Lumped-volume model for calculation of LPFs for the fire accident scenario.

Flow resistances for the intake and bleed-off paths are determined based on the flow vs. pressure drop relation for a single 2' by 2' HEPA filter. Each of the intake and bleed-off filter banks consists of 12 HEPA filters in parallel. The intake path has just one filter bank while the bleed-off path has four filter banks arranged two in parallel and two in series. These filter arrangements lead to flow conductances of $\beta_i = 1.2 \times 10^4$ cfm/(in-wc)$^{0.91}$ for the intake path and $\beta_b = 1.3 \times 10^4$ cfm/(in-wc)$^{0.91}$ for the bleed-off path.

The gas flow across all the three paths depicted in Fig. 4 is characterized by:

$$Q = \beta \cdot \Delta P^{0.91} \tag{1}$$

Because the pressure difference ΔP is the same across the three paths, Eq. (1) can be applied to each path or to all of the three paths combined with appropriate values for the flow conductance β. Therefore, a combined, effective flow conductance,

$$\beta_{eff} = \beta_\ell + \beta_i + \beta_b = 2.8 \times 10^4 \text{ cfm/(in-wc)}^{0.91} \tag{2}$$

can be used to give the total volumetric flow rate Q as a function of ΔP. Next we will outline how to obtain ΔP, hence Q, during the fire, and determine the LPF from the volumetric flow rate.

Model Equations and Parameters

As the fire progresses, pressure in the model volume (see Fig. 4) builds up due to the energy generated and combustion product gases produced (minus the amount of oxygen consumed). The rate of pressure build-up and its quasi-static value will be determined by the balance of the rate of energy and gas generation against the rate of gas outflow into the environment.

The net rate of energy produced by the fire that goes into heating up the gases, $\dot{E}_{net}$, can be obtained from results of detailed analysis which characterizes the fire and heat loss to solid structures. Such an analysis, which involves three-dimensional, mechanistic fire and fluid-dynamic modeling with the GASFLOW code[5], was performed and has been reported in Ref. 6. The GASFLOW analysis also provides estimates for other important quantities such as the net rate of moles of gas generated, $\dot{n}_{burn}$, and the duration of the fire (due to oxygen limitation), t_{burn}.

The net energy rate $\dot{E}_{net}$ determines the rate of temperature increase $\frac{dT}{dt}$ of the air in the model volume, V:

$$\frac{dT}{dt} = \frac{\dot{E}_{net}}{nC_v} \tag{3}$$

where n is the total number of gas moles in V and C_v is the molar heat capacity at constant volume. The rate of change of number of moles in V is given by the difference between the rate generated by the fire and the rate of outflow:

$$\frac{dn}{dt} = \dot{n}_{burn} - \frac{Q\rho}{M} \tag{4}$$

where ρ and M are the density and molecular weight of the air flowing out, respectively. The rate of temperature increase and the rate of change of gas moles combine to determine the change in pressure P. The rate of pressure change is given by:

$$\frac{dP}{dt} = \frac{P_o}{n_o T_o}\left[\frac{\dot{E}_{net}}{C_v} + T\left(\dot{n}_{burn} - \frac{\beta_{eff} \cdot \Delta P^{0.91}\rho}{M}\right)\right] \tag{5}$$

where P_o, n_o, and T_o, are respectively the pressure, number of moles, and temperature before the fire begins. Because of the absence of active ventilation, P_o is also the ambient outside pressure, hence the driving potential for the outflow is $\Delta P = P - P_o$. The ideal gas law and differentiation by the chain rule have been invoked in deriving Eq.(5). Noting that $\frac{dP}{dt} = \frac{d\Delta P}{dt}$ and approximating the quantities T and ρ on the right side of Eq.(5) by their initial values, one obtains

$$\frac{d\Delta P}{dt} = a - b \cdot \Delta P^{0.91}, \quad \text{where } a \equiv \frac{P_o}{n_o}\left[\frac{\dot{E}_{net}}{C_v T_o} + \dot{n}_{burn}\right], \; b \equiv \frac{P_o}{n_o}\left(\frac{\beta_{eff} \cdot \rho_o}{M}\right) \tag{6}$$

The quasi-static value of ΔP can be obtained from Eq.(6) by setting $\frac{d\Delta P}{dt} = 0$:

$$\Delta P_{ss} = \left(\frac{a}{b}\right)^{1/0.91} = \left[\frac{\left(\dot{E}_{net} + \dot{n}_{burn} C_v T_o\right)M}{\beta_{eff} \cdot \rho_o C_v T_o}\right]^{1/0.91} \tag{7}$$

According to Eq.(1), the quasi-static outflow of gases to the environment is then $Q_{ss} = \beta_{eff} \cdot \Delta P_{ss}^{0.91}$. The time to reach the steady ΔP is short compared to the duration of the fire, represented by t_{burn}.

Therefore, the total, fractional volumetric air outflow can be written as $F_{total} = \frac{Q_{ss} \cdot t_{burn}}{V}$. The fractional outflow through the three individual paths are

$$F_\ell = f_\ell \cdot F_{total} \,, \qquad F_i = f_i \cdot F_{total} \,, \qquad F_b = f_b \cdot F_{total} \tag{8a,b,c}$$

where
$$f_\ell \equiv \frac{\beta_\ell}{\beta_{eff}} \,, \qquad f_i \equiv \frac{\beta_i}{\beta_{eff}} \,, \qquad f_b \equiv \frac{\beta_b}{\beta_{eff}} \tag{9a,b,c}$$

Because the initial source term has been assumed to be well mixed with the gases in the model volume V, the fractional outflow (F_ℓ, F_i, or F_b) also represents the fraction of the source term that leaves V via a particular path. The leakpath factor, LPF, for the radioactive aerosol, is then obtained from the sum of the contributions from all three paths:

$$\mathrm{LPF} = \mathrm{LPF}_\ell + \mathrm{LPF}_i + \mathrm{LPF}_b \tag{10}$$

where
$$\mathrm{LPF}_\ell = F_\ell \qquad \text{[No HEPA filtration]} \tag{11a}$$
$$\mathrm{LPF}_i = (1 - 0.999) F_i = 1 \times 10^{-3} \times F_i \tag{11b}$$
$$\mathrm{LPF}_b = (1 - 0.999)(1 - 0.998) F_b = 2 \times 10^{-6} \times F_b \tag{11c}$$

In Eqs.(11b) and (11c), HEPA filter aerosol collection efficiencies of 0.999 for the first stage and 0.998 for the second stage are applied to obtain the final environmental release.

The following table gives a summary of most of the model parameters used.

Variable	**Value**	**Units**
V (Model volume)	6.40×10^5	ft^3
P_o (Initial pressure)	313.9	in-H_2O
n_o (Initial gas moles)	5.706×10^5	moles
T_o (Initial temperature)	77	°F
ρ_o (Initial gas density)	0.062	lb/ft^3
C_v (Specific heat of gas)	0.011	BTU(°F-mole)
M (Molecular weight of gas)	29	g/mole
β_{eff} (Effective, total flow conductance)	2.8×10^4	cfm/(in-wc)$^{0.91}$
β_ℓ (Leakage flow conductance)	2.8×10^3	cfm/(in-wc)$^{0.91}$
β_i (Intake flow conductance)	1.2×10^4	cfm/(in-wc)$^{0.91}$
β_b (Bleed-off flow conductance)	1.3×10^4	cfm/(in-wc)$^{0.91}$
f_ℓ (fraction of *gas* release via leakage)	0.10	--
f_i (fraction of *gas* release via intake)	0.44	--
f_b (fraction of *gas* release via bleed-off)	0.46	--

The three parameters characterizing the fire dynamics, which were obtained from the GASFLOW analysis, are: $t_{burn} = 2.1$ hr, $\dot{E}_{net} = 1.83 \times 10^5$ Btu/hr, $\dot{n}_{burn} = 17.6$ moles/min.

Results

Based on the above parameter values, the model shows that it takes about 20 sec to reach the quasi-static over-pressure, $\Delta P_{ss} = 0.013$ in-wc. The corresponding total volumetric flow rate of air leaving the model volume is $Q_{ss} = 544$ cfm. The total fractional volumetric outflow (or fraction of the gases in the model volume that has escaped) is $F_{total} = 0.108$. The breakdown of the total release in gases and in aerosol (source term) is as follows:

Pathway	**Fractional outflow**	**Fractional aerosol release**
Leakages	$F_\ell = 1.1\ \%$	$\text{LPF}_\ell = 1.1\ \%$
Intake	$F_i = 4.7\ \%$	$\text{LPF}_i = 4.7 \times 10^{-3}\ \%$
Bleed-off	$F_b = 5.0\ \%$	$\text{LPF}_b = 1.0 \times 10^{-5}\ \%$

It can be seen that $\text{LPF}_\ell = 1.1\%$ dominates the others hence the total leakpath factor is 1.1%.

References

1. U.S. Department of Energy, *Nuclear Safety Analysis Reports*, DOE Order 5480.23 (1992).

2. U.S. Department of Energy, *Technical Safety Requirements*, DOE Order 5480.22 (1992).

3. U.S. Department of Energy, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Report*, DOE-STD-3009-94 (1994).

4. U.S. Department of Energy, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, DOE-HDBK-3010-94 (1994).

5. J.R. Travis, K.L. Lam, and T.L. Wilson, *GASFLOW: A Three-Dimensional Finite-Volume Fluid-Dynamics Code for Calculating the Transport, Mixing, and Combustion of Flammable Gases in Geometrically Complex Domains*, Los Alamos National Laboratory report LA-UR-94-2270, July 11, 1994.

6 K.L. Lam, W.R. Bohl, and T.L. Wilson, "Accident Analysis of a Fire Scenario in a Plutonium Facility," in Proceedings of the Fifth Annual Safety Analysis Workshop, Augusta, Georgia, June 19-23, 1995.