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Source Term and Radiation Dose Estimates for Postulated Damage to the 102 Building at the General Electric Vallecitos Nuclear Center

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Prepared for
Division of Environmental Impact Studies
Argonne National Laboratory
under Contract EY-76-C-06-1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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SOURCE TERM AND RADIATION DOSE ESTIMATES FOR POSTULATED DAMAGE TO THE 102 BUILDING AT THE GENERAL ELECTRIC VALLECITOS NUCLEAR CENTER

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SUMMARY

Three scenarios representing significant levels of containment loss due to moderate, substantial, and major damage to the 102 Building at the Vallecitos Nuclear Center are postulated, and the potential radiation doses to the general population as a result of the airborne releases of radionuclides (hereafter called source terms) are estimated. The damage scenarios are not correlated to any specific level of seismic activity. The three scenarios are:

1. Moderate damage scenario - perforation of the enclosures in and the structure comprising the Plutonium Analytical Laboratory.
2. Substantial damage scenario - complete loss of containment of the Plutonium Analytical Laboratory and loss of the filters sealing the inlet to the Radioactive Materials Laboratory hot cells.
3. Major damage scenario - the damage outlined in (2) plus the perforation of enclosures holding significant inventories of dispersible plutonium in and the structure comprising the Advanced Fuels Laboratory.

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INTRODUCTION

Various procedures involving significant inventories of radionuclides are performed in the 102 Building (Radioactive Materials Building) at the General Electric Vallecitos Nuclear Center, Vallecitos, California. Recent geological findings suggest the Verona Fault may extend into the site, and seismic activity can lead to the loss of containment of some of the radionuclides in the 102 Building. The level of seismic activity required to lead to each degree of containment loss has not been determined. Loss of containment of these radionuclides may result in potential radiation exposures of the general population. The radionuclides in the 102 Building with the greatest radiological significance are the isotopes of plutonium, and thus, the principal mode of exposure is inhalation of radioactive particles.

A comprehensive analysis of the risks involved in the operation of such a facility required an in-depth study of many factors. These factors include the probability of various levels of seismic activity, the loss of containment associated with each level of seismic activity, and the potential airborne release of radionuclides associated with each level of containment loss. The components to perform such an analysis are not currently available. As an interim measure, the potential airborne releases of plutonium are estimated for three levels of damage without regard to the levels of seismic activity required to attain the damage levels. The potential environmental consequences in terms of radiation dose to people resulting from these postulated plutonium releases are estimated.

Argonne National Laboratory, at the request of the U.S. Nuclear Regulatory Commission (NRC), has asked Pacific Northwest Laboratory to estimate the potential source terms and resultant radiation doses to the general population that are a result of three levels of containment loss in the 102 Building.

CONCLUSION

The "best estimates" of the source terms generated by the three postulated levels of containment loss are shown in Table 1.

TABLE 1. Postulated Airborne Releases for Various Degrees of Containment Loss for Barriers in the 102 Building

Scenario 1

Perforation of the Enclosures in and the Pu Analytical Laboratory Structure

Instantaneous airborne release	---
Additional airborne release of Pu within next 2 hours	0.4 mg Pu
Additional airborne release of Pu within next 6 hours	4 mg Pu
Additional airborne release of Pu within next 16 hours	10 mg Pu
Additional airborne release of Pu within next 3 days	8 mg Pu

Scenario 2

Collapse of the Pu Analytical Laboratory and Loss of HEPA Filter-sealing Entry to the Radioactive Materials Laboratory Hot Cells

Instantaneous airborne release	20 mg Pu
Additional airborne release of Pu within next 2 hours	0.8 µg Pu + 4 µCi FP
Additional airborne release of Pu within next 6 hours	3 µg Pu + 10 µCi FP
Additional airborne release of Pu within next 16 hours	7 µg Pu + 30 µCi FP
Additional airborne release of Pu within next 3 days	10 µg Pu + 130 µCi FP

Scenario 3

Collapse of the Pu Analytical Laboratory and Loss of HEPA Filter-sealing Entry to the Radioactive Materials Laboratory and Perforation of the Enclosures in and the Structure Enclosure of the Advanced Fuels Laboratory

Instantaneous airborne release	20 mg Pu
Additional airborne release of Pu within next 2 hours	2 mg Pu + 4 µCi FP
Additional airborne release of Pu within next 6 hours	50 mg Pu + 10 µCi FP
Additional airborne release of Pu within next 16 hours	400 mg Pu + 30 µCi FP
Additional airborne release of Pu within next 3 days	3 g Pu + 13 µCi FP

A summary of the calculated most likely 50-yr committed dose equivalents for the three damage scenarios is presented in Table 2 for the maximum-exposed individual and the population within a 50-mile radius of the General Electric Vallecitos Nuclear Center. The most likely maximum plutonium deposition at the nearest pasture is also included.

TABLE 2. Most Likely 50-Yr Committed Dose Equivalents(a) and Pu Depositions

Scenario	Description	Organ of Reference		Surface Deposition
		Lungs	Bone	
1	Resident (rem)	0.005	0.008	
	Population (person-rem)(b)	40	60	
	Pasture ($\mu Ci/m^2$)			0.002
2	Resident (rem)	0.09	0.1	
	Population (person-rem)(b)	60	100	
	Pasture ($\mu Ci/m^2$)			0.05
3	Resident (rem)	0.7	1	
	Population (person-rem)(b)	7000	10,000	
	Pasture ($\mu Ci/m^2$)			0.2

(a) A translocation class Y has been assumed.
(b) Collective dose to the population residing within 50 miles of the Vallecitos Center.

The calculated 50-yr collective committed dose equivalents for the three scenarios are much lower than the collective dose equivalent from 50 years of exposure to natural background radiation and medical x-rays. The most likely maximum residual plutonium contaminants on the ground at the significant locations for the three scenarios are all within the Environmental Protection Agency proposed guideline of 0.2 $\mu Ci/m^2$.

PROCESS AND FACILITY DESCRIPTION

102 BUILDING

The 102 Building (Radioactive Materials Building), of one-story construction, is in the fenced portion of the 100 Area of the Vallecitos Nuclear Center (VNC) (see Figure 1). The basement and ground floor slabs are composed of reinforced concrete. The roof has structural steel framing and a metal deck supported by structural steel columns. In the ground floor area (of primary interest to this report) the walls are composed of 8-in. reinforced concrete block, 4-in. reinforced concrete block, precast reinforced concrete, and wood studs with gypsum board. Resistance to horizontally-acting loads on the ground

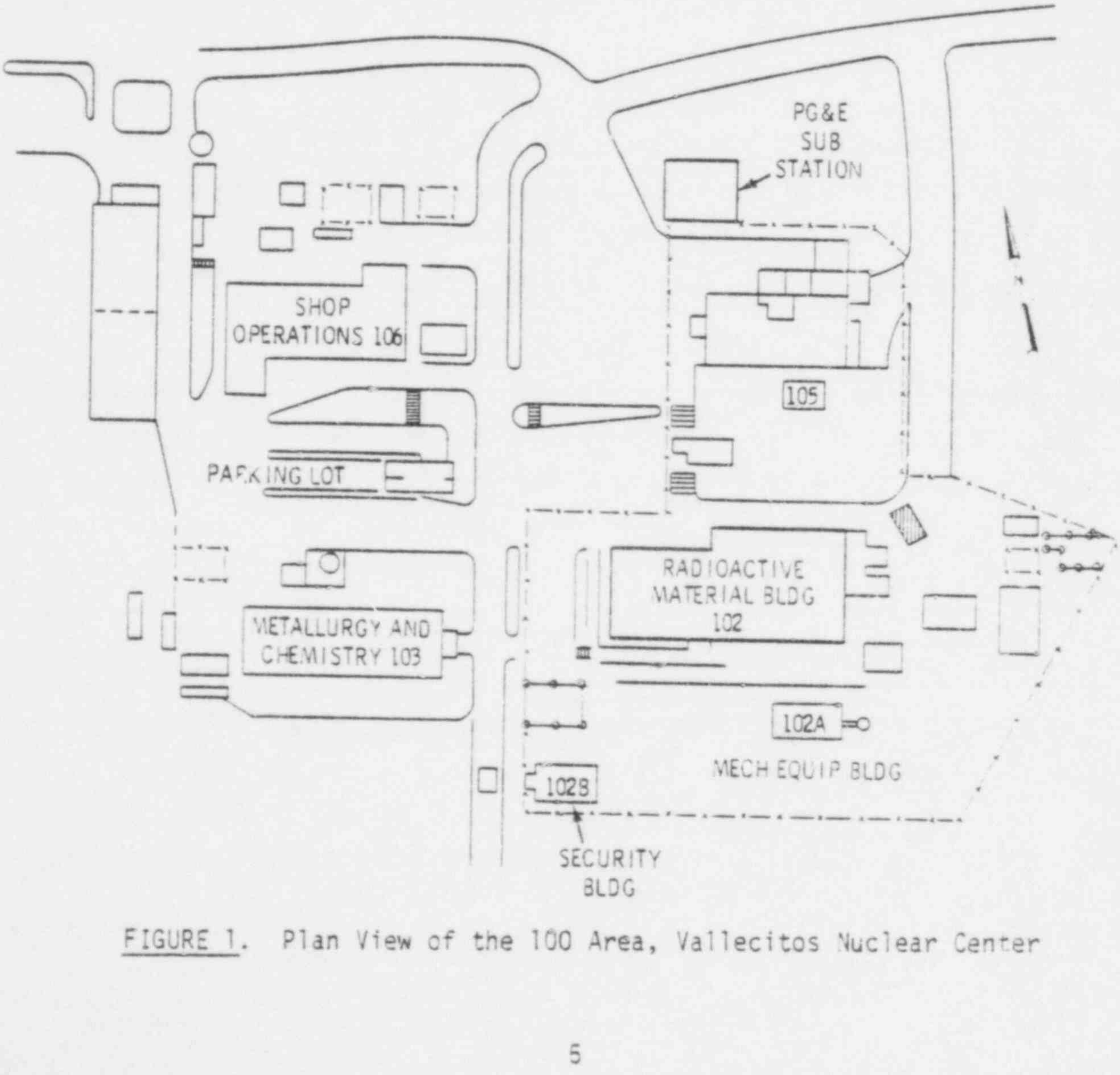

FIGURE 1. Plan View of the 100 Area, Vallecitos Nuclear Center

floor is provided primarily by interior 8-in. concrete block partition walls and exterior precast concrete walls that connect to the roof system, steel columns, intersecting walls, and floor slab. Although the structural steel framing was not designed for earthquake loads, it functions as bounding frames for the interior concrete block shear walls and thus acts as a part of the lateral load system.

The plutonium laboratory is housed in the basement. The floor slab over the basement area is composed of reinforced concrete, as are the basement walls, columns, floor slabs, and footings. The construction is monolithic in character with conventional construction joints and is heavily reinforced. The RML cells are of heavy, reinforced concrete constructions and are monolithic with basement walls and the first floor slab (Engineering Design Analysis Company 1977).

Plan views of the ground floor showing the location of the Plutonium Analysis Laboratory (PAL) and the Radioactive Materials Laboratory (RML) hot cells, and of the basement in which the Advanced Fuels Laboratory (AFL) is housed are shown in Figures 2 and 3, respectively.

Radioactive Materials Laboratory (RML) Hot Cells

The RML is located on the south end of the ground floor level of the 102 Building (see Figure 2). Most operations involving by-product materials (dissolution, separation, conversion to final product or waste form, etc.) are performed in the RML hot cells. The four principal hot cells are relatively compact, massive structures with two- to three-feet thick walls of high-density concrete. Cells handling mixed fission products and alpha-emitters are equipped with a 3/16-in. thick, free-standing stainless steel liner.

Plutonium Analytical Laboratory (PAL)

The PAL is located in the middle of the east side of the ground floor of the 102 Building (see Figure 2). The laboratory's primary function is the analysis of plutonium solutions and compounds. Although the quantity of plutonium in this area is limited, the plutonium is included due to its apparent vulnerability.

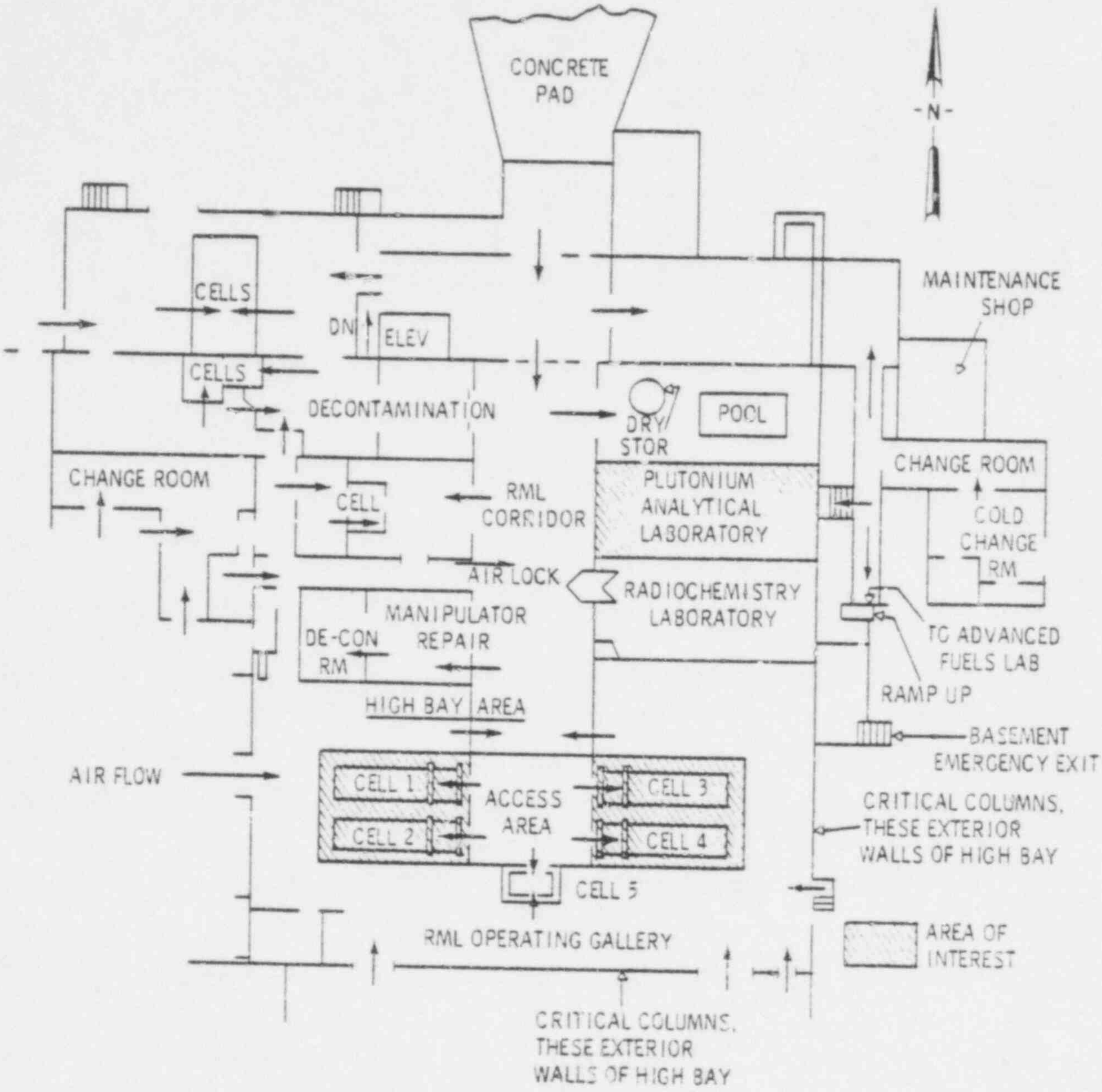

FIGURE 2. Building 102 Main Floor (Source: Engineering Design Analysis Company 1977)

Advanced Fuels Laboratory (AFL)

The AFL occupies almost all of the basement area of the 102 Building (see Figure 3) and is the primary area at the VNC for plutonium processing. The AFL is an experimental facility involved in the development of mixed oxide (MO) fuel production. Plutonium contents may range from 10% to 25% with an operational value of 20%.

Operations are nonroutine in the sense that this is not a production facility, although the procedures followed may be the same from run to run. The AFL has the capability of dry-blending oxides, although the primary emphasis is on co-precipitation of uranium and plutonium, which are handled as an entity after the initial mixing of solution. (Definition of the process and scrap recovery chemistry of the co-precipitation process is one of the tasks of the facility.) Thus, the plutonium and uranium compounds and physical forms may be more varied than encountered in a dry-blending production facility. Fuel elements may be produced by pellet loading or vibration compaction.

Room air is drawn into most of the enclosures via High Efficiency Particulate Air (HEPA) filters equipped with rain shields. The room is at a negative pressure with respect to the atmosphere, and the enclosures are at a negative pressure with respect to the room. Glovebox 40, the sintering furnace, is an exception and is held at a few inches W.G. positive with respect to the room pressure. All overhead exhaust ducts are currently being connected to stainless steel pipe. During the transition period, they are composed of a combination of stainless steel, painted mild steel, and plastic. Some enclosures have flexible (spring-reinforced plastic) connections attached to the exhaust system. Exhaust flows are controlled by valves designed to maintain a constant pressure differential between the enclosure and exhaust system. Loss of a single gloveport or similar item would not result, then, in an airborne release of a significant amount of the contained radionuclides.

Fire detection and protection is provided in the AFL. Both thermal and smoke detectors are used. An overhead sprinkler system is in the AFL, and dry extinguishers fitted with a special probe for piercing gloves are currently provided. The fire potential in the facility is limited. Most of the structural

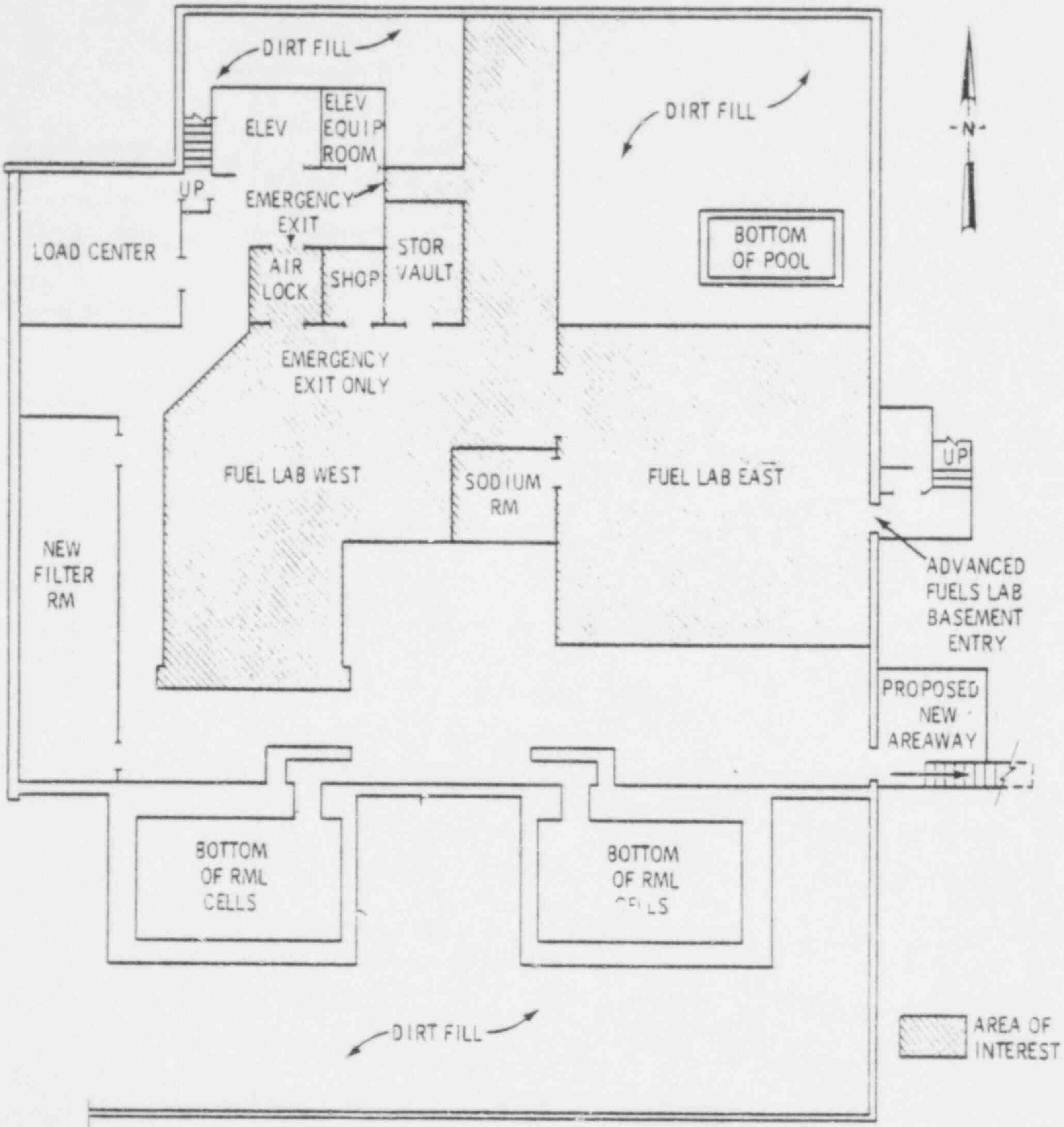

FIGURE 3. Building 102 Basement (Source: Engineering Design Analysis Company 1977)

material present (concrete, metal, etc.) will not burn under normal circumstances. A limited amount of combustible material (celluloic waste in 55-gal drums, rubber and plastic gloves, wood, etc.) and materials that can provide fuel when heated (plastics, such as the enclosure windows and exhaust ducts) are sometimes present. Two hydraulic fluid reservoirs are located in the Ceramics Processing area under gloveboxes 38 and 39. The hydraulic fluid currently in use is water soluble. A limited, undefined volume of isopropanol(a) is available in glovebox 39 where it is used as a die lubricant. The normal amount of isopropanol present is 50 mℓ; the maximum inventory is 200 mℓ.

(a) Flammable limits in air: 2% to 12%; flash point: 58°F; autoignition temperature: 750°F.

POSTULATED DAMAGE SCENARIOS AND SOURCE TERM ESTIMATES

DAMAGE SCENARIO

Three scenarios that result in the release of radioactive materials to the environment are considered. The scenarios arranged in order of increasing severity follow:

- Moderate Damage Scenario: the seismic event shakes the facility and gloveboxes in the Plutonium Analytical Laboratory (PAL) to the extent that containers inside are broken and their contents are spilled into the glovebox. More than one breach occurs in each glovebox, and the gloveboxes are parted from exhaust ducts. This damage is caused by falling debris, toppled equipment, or minor structural damage. The PAL exhaust ventilation is parted, and a path is provided that permits communication between the PAL interior and the environment ambient to the 102 Building. Otherwise, the PAL and the 102 Building structures remain intact.

  Radioactive material exists in other areas of the 102 Building, specifically in the cells of the Radioactive Materials Laboratory (RML), in the gloveboxes of the Advanced Fuels Laboratory (AFL) located in the basement of the 102 Building, and the gloveboxes of the Radiochemistry Laboratory (RL). The massive structures of the cells and the below-grade location of the AFL preclude damage that contributes to releases in terms of this scenario. Radiochemistry routinely handles up to 8 Ci of ^{99}Mo, 0.04 Ci of ^{32}P, and 100 mg of low burnup mixed oxide fuel in solutions. These quantities of radionuclides are considered insignificant when compared with the potential effects of plutonium release from the PAL.

- Substantial Damage Scenario: Sufficient vibratory forces are applied to the 102 Building to induce the walls on the ground floor to collapse, bringing the roof down upon the gloveboxes in the PAL and the RL. The contents of gloveboxes are spilled during the early vibratory motion, and gloveboxes themselves are then tipped over and/or crushed by falling walls and roof segments. The falling structure carries with it the inlet ventilation ducts to the RML cells, but the cells proper are not breached by vibratory motion or the falling structure. The ground-level floor of the 102 Building, which is the ceiling of the AFL, remains intact. Glass columns in the AFL are broken, and contents are drained onto the floor of the containing gloveboxes, but the gloveboxes themselves and their first-stage filters remain intact. The stresses imposed upon gloveboxes in the ceramic processing area are insufficient to effect either significant damage to gloveboxes or appreciable spillage of contained materials.

- Major Damage Scenario: Sufficient vibratory forces are applied such that a level of damage that exceeds that of Scenario 2 is sustained. The above-grade walls and roof of the 102 Building collapse and fall onto the floor. Gloveboxes in the PAL and RL are crushed and their contents spilled. The floor (ceiling of the AFL) suffers damage resulting in partial collapse, and large segments fall onto gloveboxes in the AFL. The vibratory motion and subsequent damage to the gloveboxes in the AFL result in the release of plutonium-bearing liquid and powder into the basement laboratory. As in Scenario 2, the inlet ventilation ducts to the hot cells are carried away by the collapse of above-grade structures, but the cells proper are not breached.

SOURCE TERM ESTIMATION

1. Moderate Damage Scenario

In the absence of a detailed study of the response of the equipment and structures to various levels of seismic activity, engineering judgment and experience were used to select responses that could lead to the airborne release of the contained radionuclides. The assumptions were:

- Loss of the exhaust flow from the facility by significant breaching of the main exhaust duct on the roof.
- A direct, unfiltered path from the Plutonium Analytical Laboratory (PAL) to the ambient atmosphere by breaching of the exhaust duct in the laboratory or breaching of the roof over the PAL.

- A higher than normal airborne concentration of plutonium within the enclosures generated by the violent breaking of equipment and bottles containing plutonium solutions.
- Release to the PAL of a portion of the airborne activity by multiple breaching of all enclosures.

Estimation of the potential source term is based upon the following sequence:

The breaking of the equipment generates an airborne concentration of 10 mg of solution per cubic meter[(a)] in the 17-m^3 volume of the six enclosures containing plutonium in the PAL. The concentration of the solution is 200 g Pu/ℓ (the maximum Pu concentration received) and has a specific gravity of 1.5. Thus, approximately 22 mg Pu are contained in the 17-m^3 volume (1.3 mg Pu/m^3).

Wind striking the sides of the building penetrates doorways, and air flows through the PAL at the rate of 10% of the room volume/hour. (The approximate volume of the PAL is 8000 ft^3, and the indicated flow rate is 13.3 ft^3/min or 0.38 m^3/min). The air velocity in PAL would be approximately 0.03 to 0.07 fpm.

The enclosures are breached, and air flows through the enclosure at a rate of 10% of enclosure volume per hour. (The approximate volume of the six enclosures is 17 m^3, indicating flow out of the enclosures of 0.03 m^3/min, or approximately 1 cfm.) The activity release to the room is C_{enc} X flow. The activity released is assumed to be instantaneously mixed, producing a uniform concentration throughout the room.

A resuspension rate of 10^{-9}/sec[(a)] is assumed for the liquid spilled in the enclosure. These postulated conditions are shown schematically in Figure 4.

Enclosures in the Radiochemistry Laboratory are breached, and the same response scenario postulated for the PAL is anticipated. The airborne release of radionuclides is insignificant compared to the release from the PAL.

(a) Appendix A presents the rationale for the choice of the value.

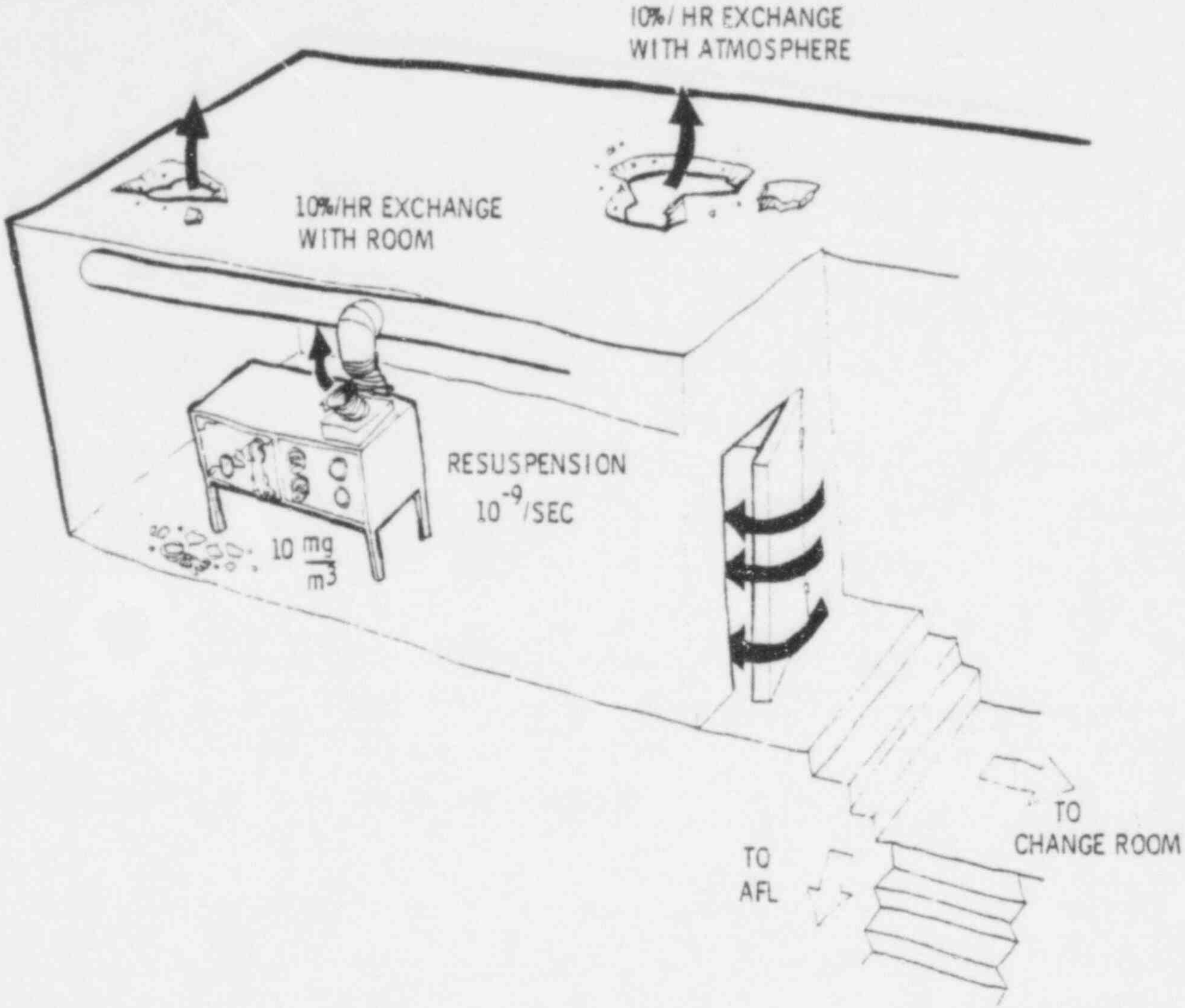

FIGURE 4. Scenario 1 - Schematic Diagram of Leak Path of Particulate Material from Perforated PAL

Mass balance equations expressing the relationship among the airborne concentrations in the various compartments were set up using parameters shown in Figure 5.

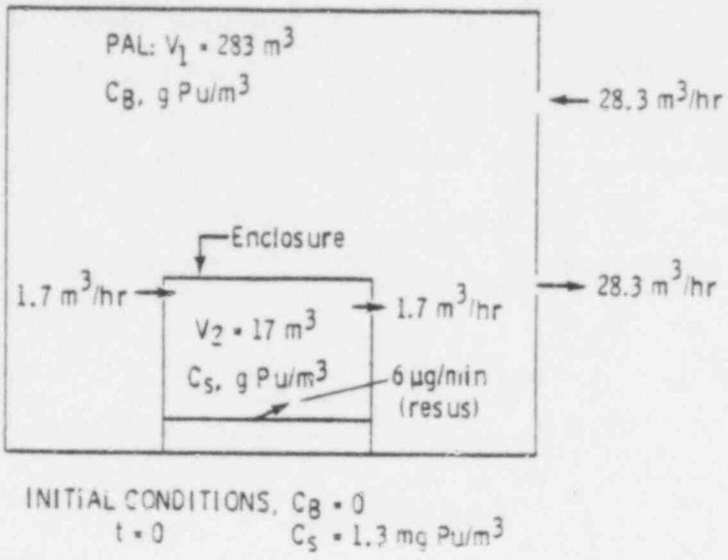

FIGURE 5. Volumetric Flows from Perforated Enclosures and PAL Structure

The relationships among concentrations as a function of time was expressed as follows:

$$C_s(t) = C_{s_1} e^{\lambda_1 t} + C_{s_2} e^{\lambda_2 t} + C_{s_3} \tag{1}$$

and

$$C_B(t) = C_{B_1} \epsilon^{\lambda_1 t} + C_{B_2} e^{\lambda_2 t} + C_{B_3} \tag{2}$$

in which

C_s · concentration of airborne Pu in enclosure
C_B · concentration of airborne Pu in PAL
t · time after event, min
λ_1, λ_2 · rate of change.

The Pu airborne mass concentrations in the enclosures as a function of time were calculated by solving the matrix for the coefficients C_{S_1}, C_{S_2}, C_{S_3}, C_{B_1}, C_{B_2} and C_{B_3}, and exponents λ_1 and λ_2, using a computer program. The derivation of the calculational formulae and computer program are presented in Appendix B.

The calculated Pu airborne concentration at various times following its suspension are shown graphically in Figures 6 and 7. The Pu mass airborne concentration in the glovebox decays exponentially (see Figure 6). The Pu mass concentration in the PAL increases rapidly during the first three to four hours, reaches a maximum value of approximately 1×10^{-4} g/m^3 during the ninth to twelfth hours, and slowly declines.

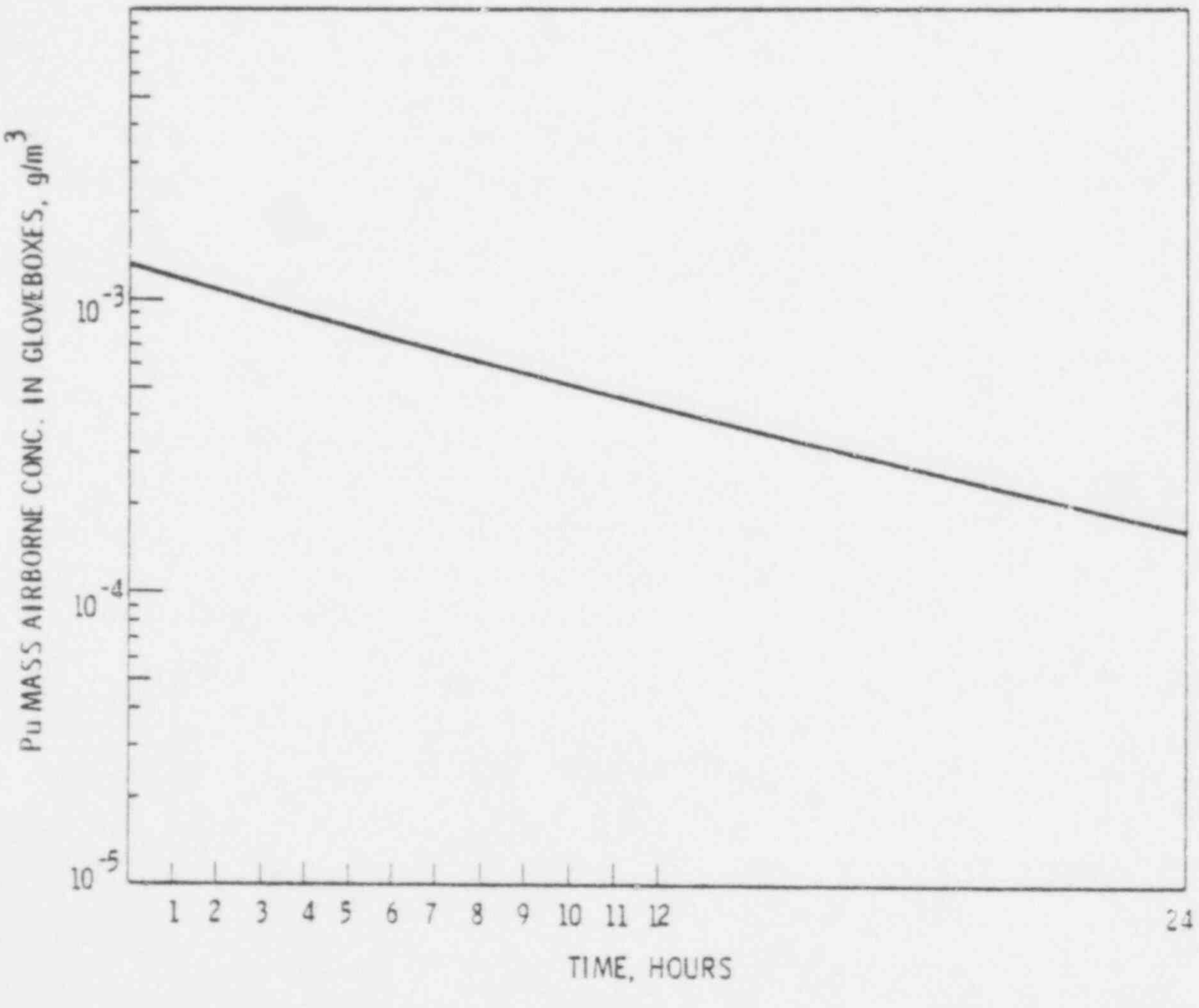

FIGURE 6. Scenario 1 - Pu Airborne Concentration in Perforated PAL Enclosures as a Function of Time

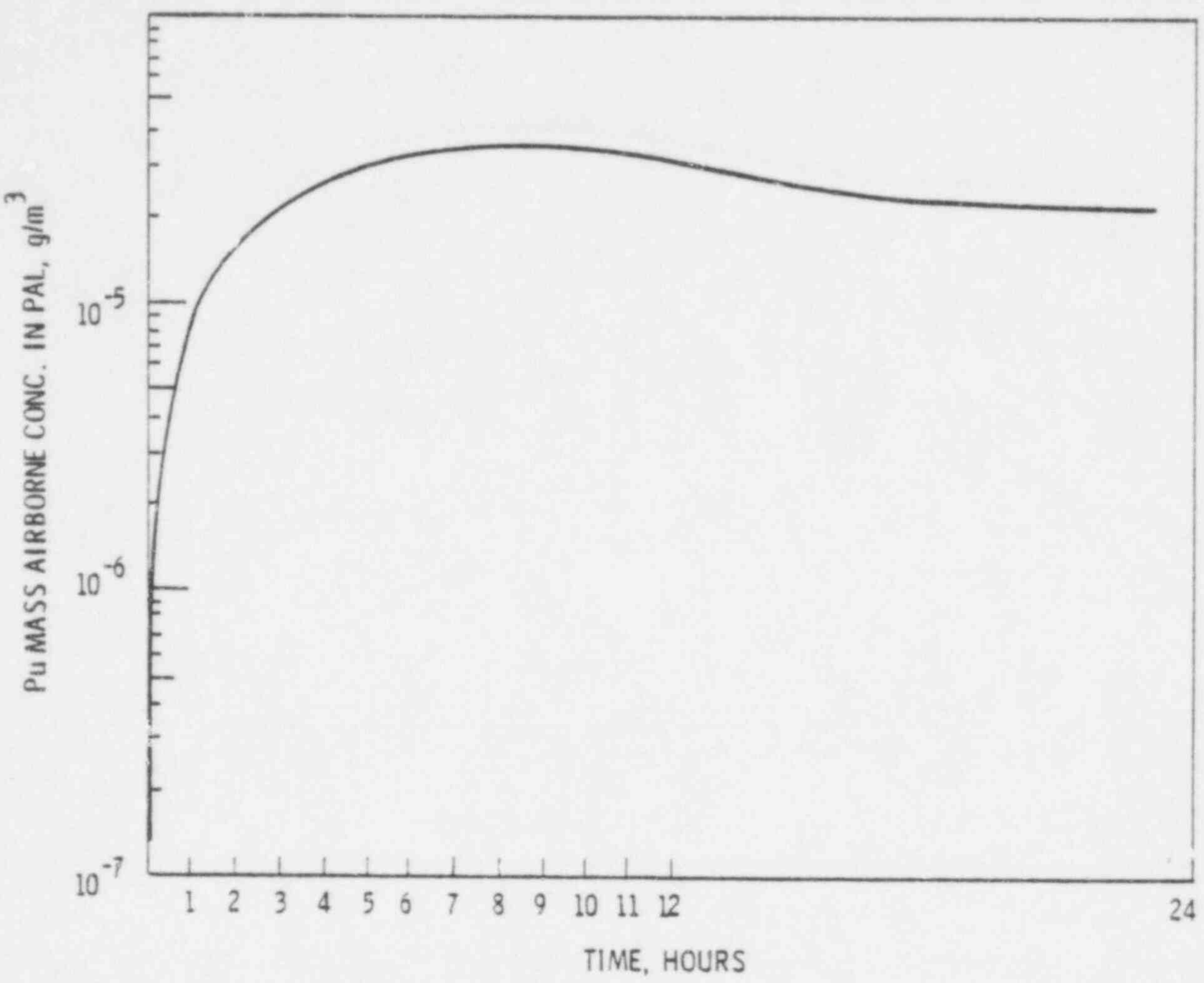

FIGURE 7. Scenario 1 - Pu Airborne Concentration within PAL as a Function of Time

The release rate at any time can be estimated by multiplying the Pu mass airborne concentration of the PAL shown in Figure 7 by the air exchange rate between the PAL and ambient atmosphere (0.38 m^3/min). The source term for any time increment can be estimated by averaging the mass airborne concentration over that time period x time (in minutes) x 0.38 m^3/min. The mass release rate of Pu from the PAL is shown graphically in Figure 8.

2. Substantial Damage Scenario

This scenario addresses the potential airborne release resulting from the loss of essentially all the 102 Building's walls above grade. The vibratory forces and collapse of the first-floor walls plus roof result in:

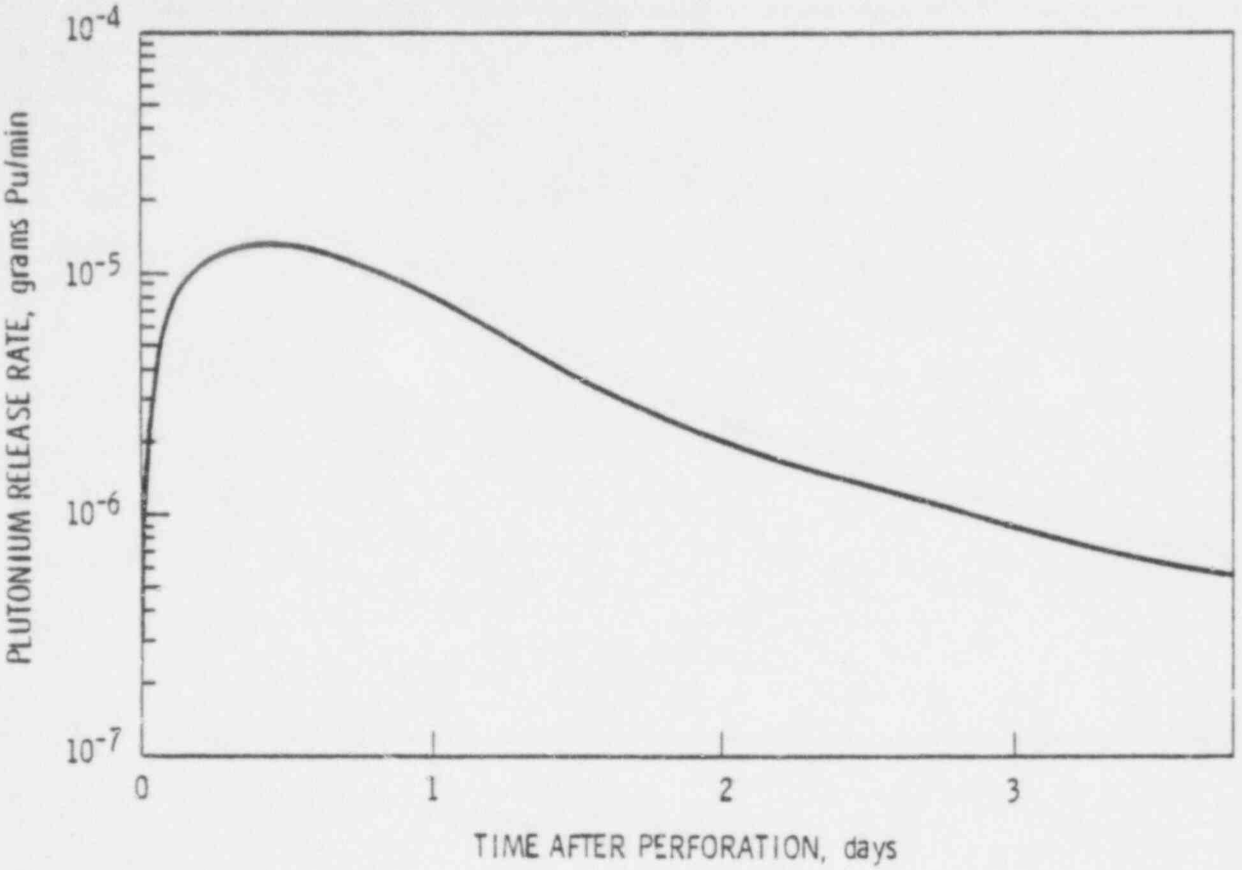

FIGURE 8. Scenario 1 - Mass Airborne Release from Perforated PAL with Time

- Breaking of equipment and bottles in the PAL enclosures, resulting in an instantaneous airborne concentration of 10 mg of solution per cubic meter (see Appendix A). Substantial damage to the enclosure (viewing windows, inlet and exhaust filters, etc.) allows release of all the contained aerosol and unrestricted flow of ambient air.
- The walls and ceiling (12-in. reinforced concrete at minimum) of the AFL remain intact, and first stage HEPA remains functional. Glass equipment within enclosures may be damaged and release their contents, but the enclosures are not breached. The airborne concentration within the enclosure increases, but no significant release occurs due to the lack of motive force to expel the contained atmosphere and the absence of an unfiltered opening.

- The collapse of the walls and roof above grade carry away the inlet ventilation ducts (three 6-in. x 6-in. ducts sealed with furnace-type filters outside each cell) to the Radioactive Materials Laboratory (RML) hot cells. The exhaust outlet and HEPA filters are housed in the massive structure supporting the cells and are assumed to be unaffected, as are the cells themselves. Contamination on cell walls and equipment is assumed suspended in the cell-free volume by the vibratory motion of the earthquake. Airflow through the cells is restricted by the pressure drop across the intact filters.

The airborne release is divided into two phases -- an instantaneous and a long-term source term. The contributions from the three building areas are:

- PAL -- The instantaneous source term is the total release of all the contained aerosol. The total volume of the six enclosures is 17.0 m^3 with an estimated mass airborne concentration of 10 mg solution/m^3. Thus, 0.17 g of solution at a concentration of 200 g/ℓ with an estimated specific gravity of 1.5 is released and contains approximately 22 mg Pu. The long-term source term is the resuspension of liquid spilled onto the floor. A resuspension flux of 10^{-9}/sec (6×10^{-8}/min) (see Appendix A) is used for liquids. Thus, 6 μg/min are made airborne from 100 g Pu that is estimated to be present. The postulated conditions are shown schematically in Figure 9.
- AFL -- All the material made airborne is contained in enclosures that retain their integrity. Any release to the AFL is filtered, reducing its concentration by a factor of 2000. The absence of a mechanism to induce flow for any released material from the AFL to the ambient atmosphere out of the enclosure and across the pressure drop created by the filter or pathways indicates that airborne release of radionuclides from this area would not be significant under these conditions.
- RML -- It is assumed that a fraction of the surface contamination on the walls and equipment of cells 1, 2, 4 and 5 is instantaneously made airborne in the free volume of the cells. A resuspension factor of 10^{-6}/m (see Appendix A) is assumed with a surface area of 82 m^2 and

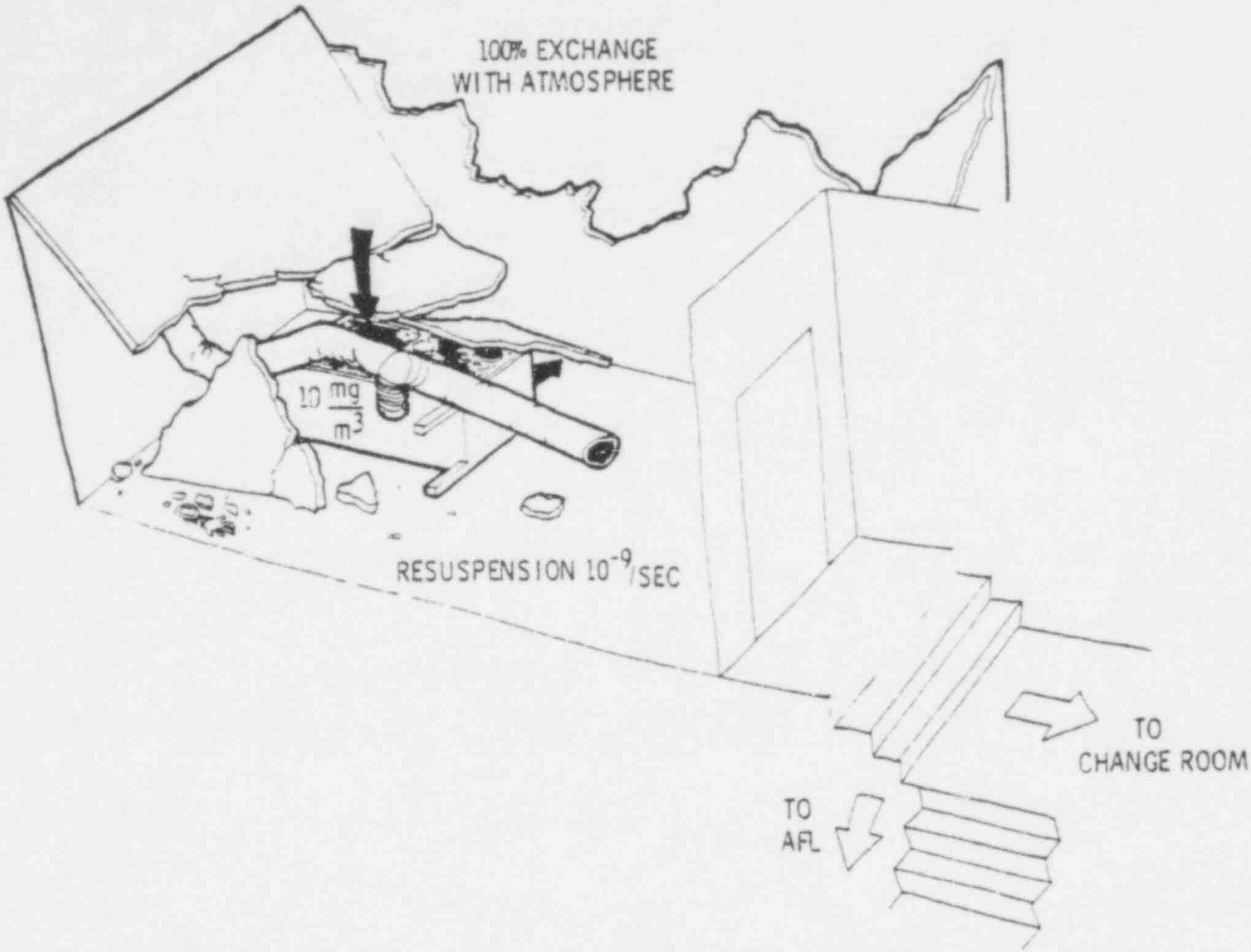

FIGURE 9. Scenario 2 - Schematic Drawing of Leak Path of Particulate Material from Collapsed PAL

a cell volume of 125 m^3, giving an average airborne contamination of 15 µCi FP/m^3 and 0.2 µCi Pu/m^3. The aerosol is assumed to leak from the cells at a rate of 0.1% vol/hr without reduction of the activity concentration. Thus, only a long-term source term contribution is estimated from this area under these conditions of 3×10^{-2} µCi/min with 4×10^{-4} µCi Pu/min.

The presence of other enclosures that may contain radionuclides in other areas of the RML (i.e., Radiochemistry Laboratory, Storage Pools, Cells 6, 9, 10, 11A and 11B) is acknowledged. The quantity of radionuclides in the Radiochemistry Laboratory is small (8 Ci of ^{99}Mo, 0.04 Ci of ^{32}P and 0.1 g of low burn-up mixed oxide fuel solutions) and does not contribute signficantly to the source term. In areas such as the Storage Pool, the material is present primarily as bulk solids in high-integrity containers that should be unaffected by the postulated conditions. The probability of the presence of the inventories assigned to the other cells under a license from the State of California is not known, nor are the characteristics of the cells. The total inventories of radionuclides are small compared to the cells covered, and thus the quantities of radionuclides at risk are assumed proportionally small. It was assumed that airborne releases from these cells would not be significant.

3. Major Damage Scenario

The scenario postulates:

- Total loss of all above-grade walls and roof of the 102 Building. Complete loss of integrity of enclosures in the PAL and RCL.
- Partial collapse of the floor (ceiling of AFL), providing an unrestricted pathway to the ambient atmosphere. Debris causes multiple breachings of some enclosures in the AFL.
- Vibratory motion causes spilling of powders and liquids, creating higher than normal airborne concentrations in the enclosures. A leak rate of 10% of the volume per hour (see Appendix A) is postulated from the enclosure to the AFL and from the AFL to the atmosphere.
- The condition of the RML hot cells is as described in Scenario 2.

The source terms from the three building areas are:

PAL -- As in Scenario 2, the instantaneous source term is 22 mg Pu. The long-term source term is 6 μg Pu/min.

RML Hot Cells -- A long-term source term, 3×10^{-2} μCi, is mixed FP/min with 4×10^{-4} μCi Pu/min.

AFL -- Three enclosures hold the majority of dispersible, undiluted plutonium. Glovebox 37 can contain up to 625 g of PuO_2 powder that is blended with UO_2 in that enclosure. After blending, masses suspended in air will only contain 1/10 to 1/4 the plutonium in undiluted PuO_2 powder. Subsequent operations (slug/granulate) make the powder coarser and thus less likely to form stable aerosols or form into pellets. Undiluted plutonium solutions can be found in gloveboxes 50 and 51 (Scrap Recovery and Nitrate Conversion, respectively). The normal maxima for the two enclosures are 2 and 5 kg Pu as nitrate solutions. The volume of gloveboxes 50 and 51 are estimated to be 17 and 18 m^3 respectively.

The quantity of Pu airborne in each box varies with starting material. Glovebox 37 can contain dry, finely divided PuO_2 powder. Normal maximum inventory during processing is 625 g. The size distribution of the powder is assumed to be that reported by Schwendiman (1977) for a fine PuO_2 used in fuel fabrication and is shown in Figure 10. Quasi-stable mass airborne concentrations greater than 100 mg/m^3 are not anticipated, but due to the transitory nature of the phenomenon described, an airborne concentration of 300 mg PuO_2 (approximately 264 mg Pu) per cubic meter is used (see Appendix A for rationale). Particles greater than 10 μm Aerodynamic Equivalent Diameter (AED)(a) are not normally respirable. [Figure 11 shows several estimations of "respirable fraction" versus AED (Mercer 1977).] Also, particles greater than 10 μm AED are lost due to gravitational settling during transport and do not constitute a significant downwind inhalation hazard. Only 10% of the PuO_2 powder airborne is 10 μm AED or smaller, and thus 53 mg of Pu is used as the instantaneous source term in glovebox 37.

Gloveboxes 50 and 51 can contain concentrated Pu nitrate solution. Their volumes are estimated to be 17 and 18 m^3, respectively. Both are postulated to have instantaneous mass airborne concentrations of 10 mg solution/m^3 (1.33 mg Pu/m^3 -- see Scenario 1), and therefore, the total mass Pu airborne is 47 mg. The postulated conditions are shown schematically in Figure 12.

To simplify the calculational procedure, the 100 mg of Pu were considered airborne in a single enclosure with a volume of 37 m^3 giving an initial assumed airborne mass concentration of 2.7×10^{-3} g Pu/m^3. An air exchange

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(a) Aerodynamic Equivalent Diameter: having aerodynamic behavior equivalent to a sphere of stated size with a density of 1.

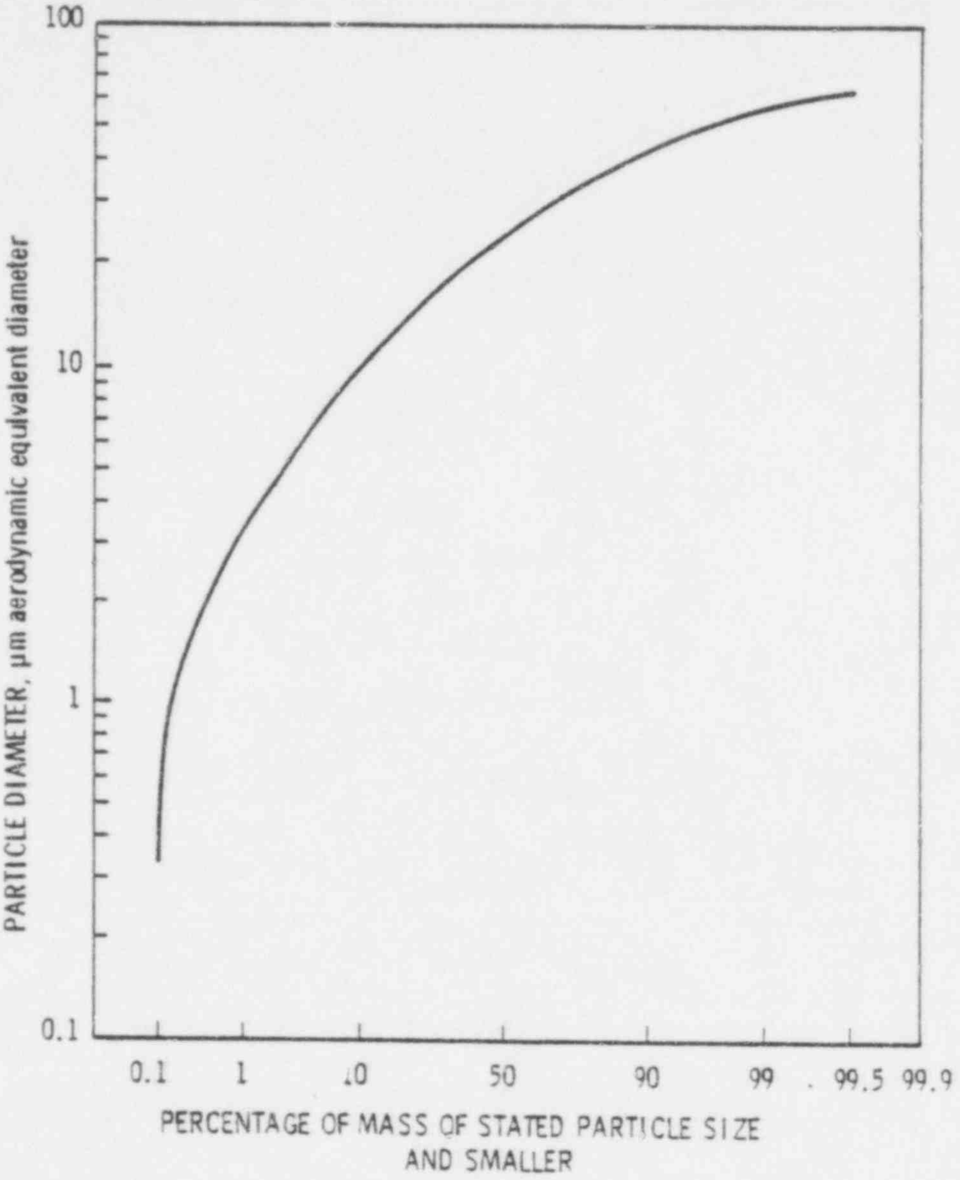

FIGURE 10. Nominal PuO_2 Particle Size Distribution

rate of 10% volume is assumed between the AFL and enclosure (0.06 m^3/min) and between the AFL and ambient atmosphere around the facility (2.1 m^3/min).

The Pu mass airborne concentrations in the enclosure and AFL were estimated by solving the matrix (as shown in Equations 1 and 2 on page 15).

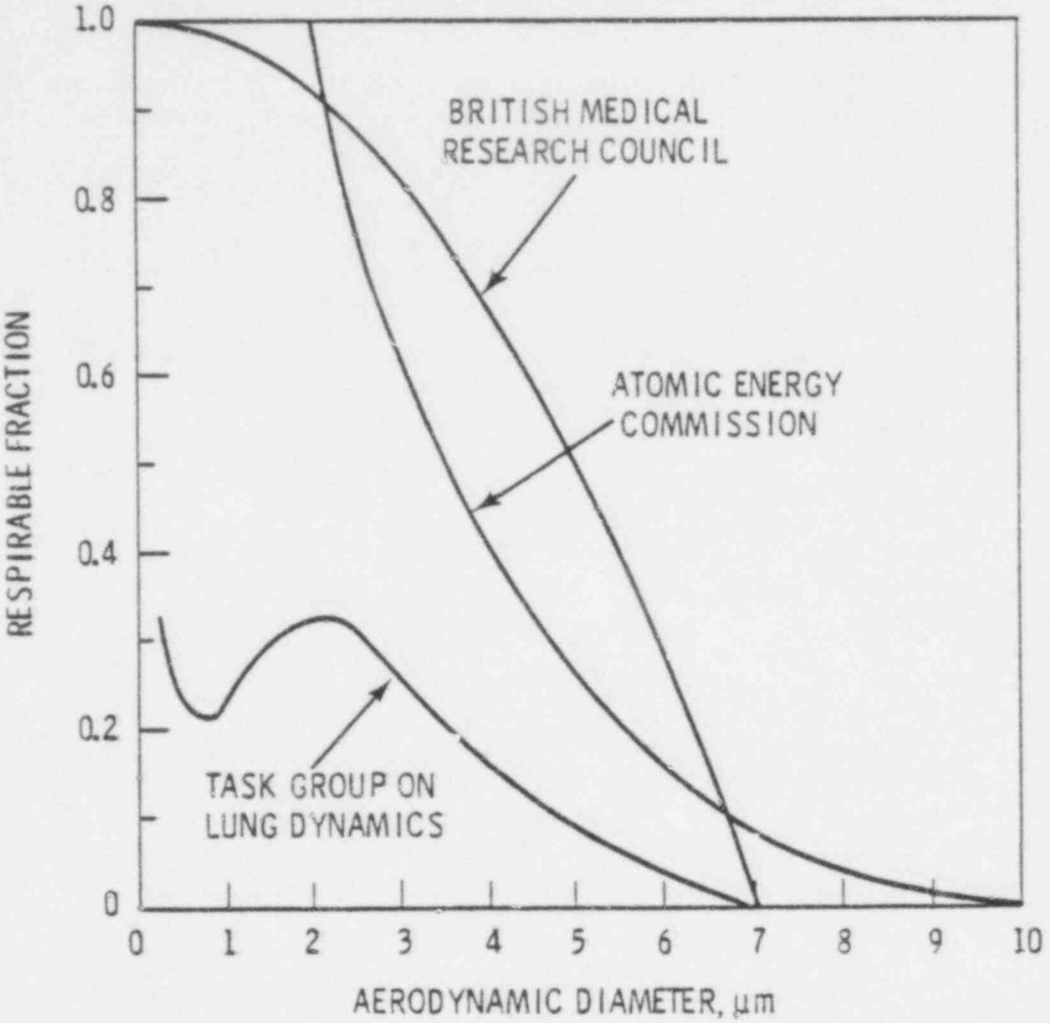

FIGURE 11. "Respirable Fraction" of Airborne Particles (Based on Figure 5 in Mercer 1977)

The Pu mass airborne concentrations as a function of time are shown graphically in Figures 13 and 14. The airborne concentrations in both the enclosure (Figure 13) and AFL (Figure 14) appear to increase with time. The increasing mass airborne concentration in the enclosure is not consistent with the concept that the initial concentration is a maximum value for mass concentration in the enclosed volume and is an artifact of the high resuspension rate chosen for the material on the floor of the enclosure and the small leak rate. Since the artifact leads to a conservative release value (up to a factor of 5 -- see Figure 13), the calculational methodology was not changed.

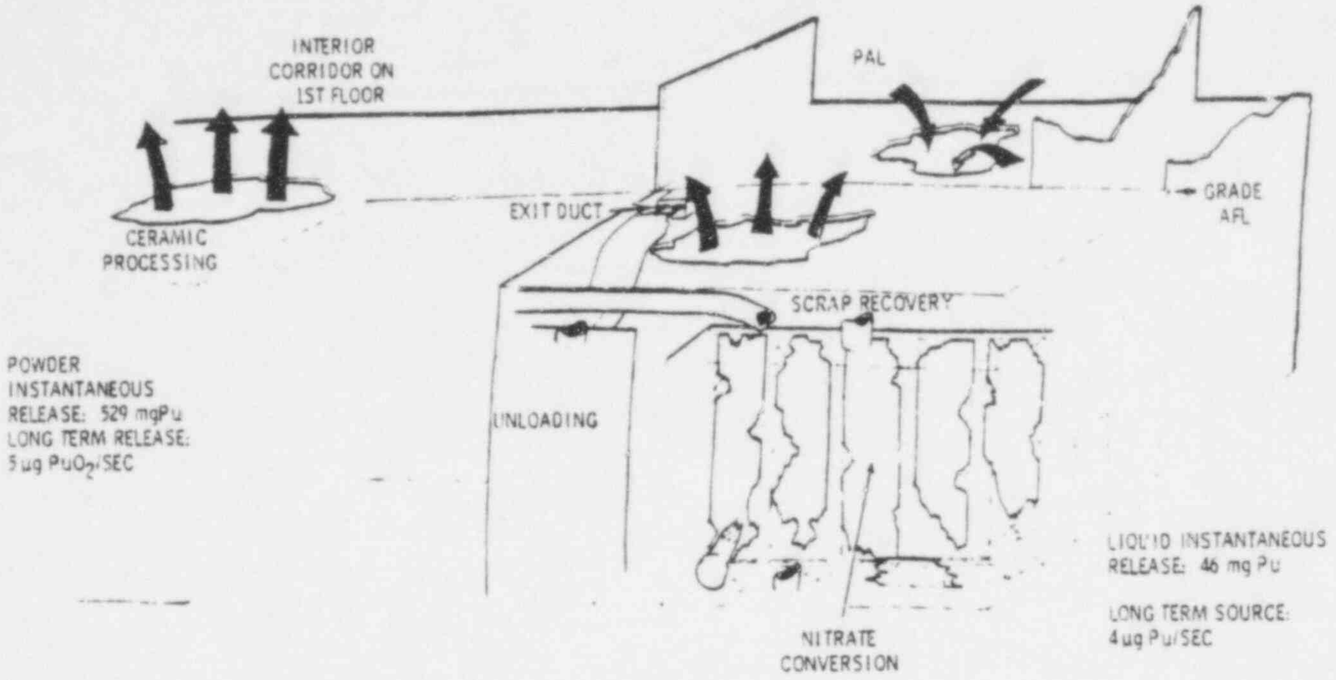

FIGURE 12. Scenario 3 - Schematic Drawing of Leak Path of Particulate Material from Perforated AFL

The release rate as a function of time is shown in Figure 15. The quantity of Pu released over one hour periods was calculated by averaging the Pu mass airborne concentration shown in Figure 15 over the time period and multiplying by 2.1 (the air exchange rate between the AFL and ambient atmosphere in m^3/min). The calculated values are tabulated in Table 3.

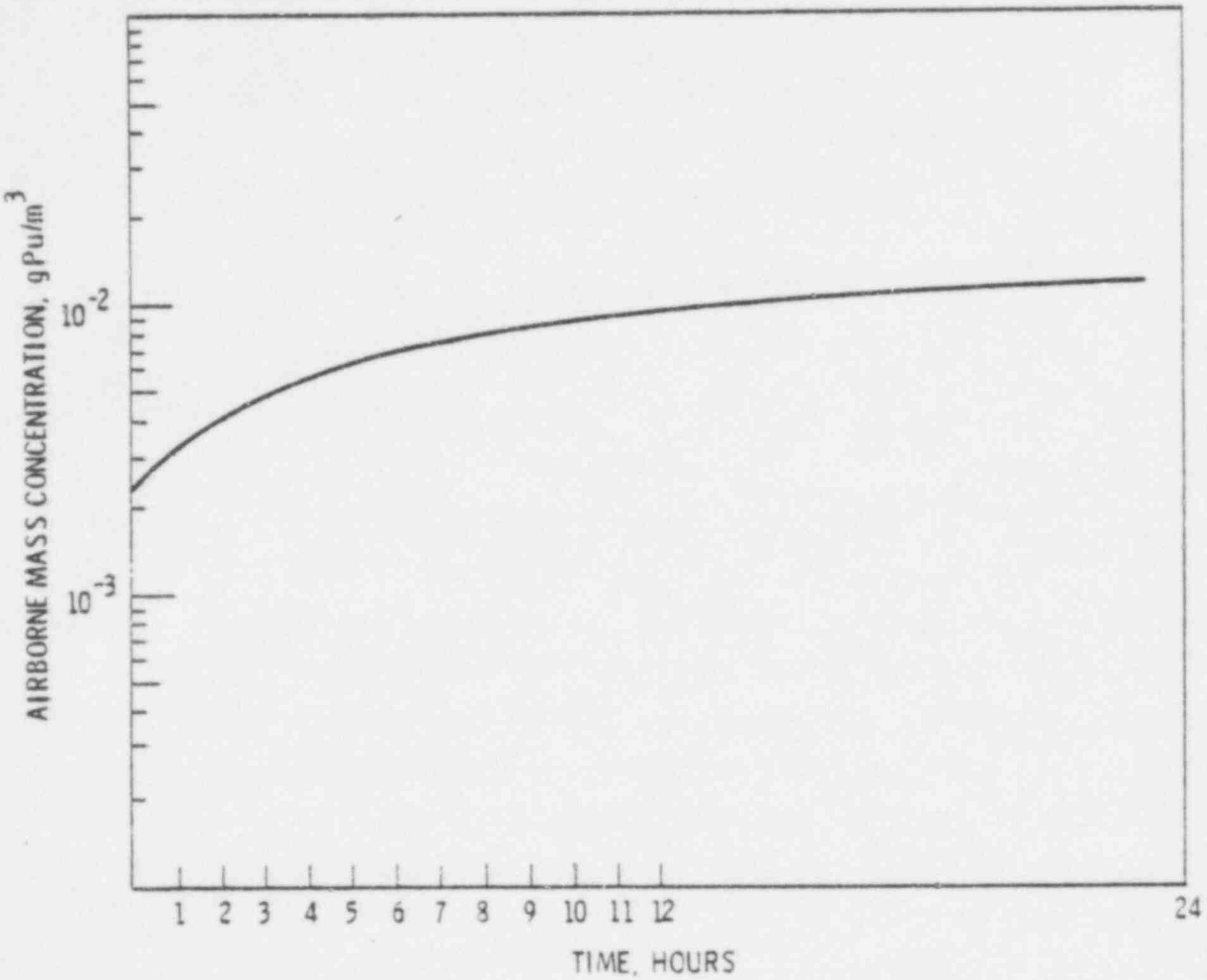

FIGURE 13. Scenario 3 - Airborne Mass Concentration within Perforated AFL Enclosures as a Function of Time

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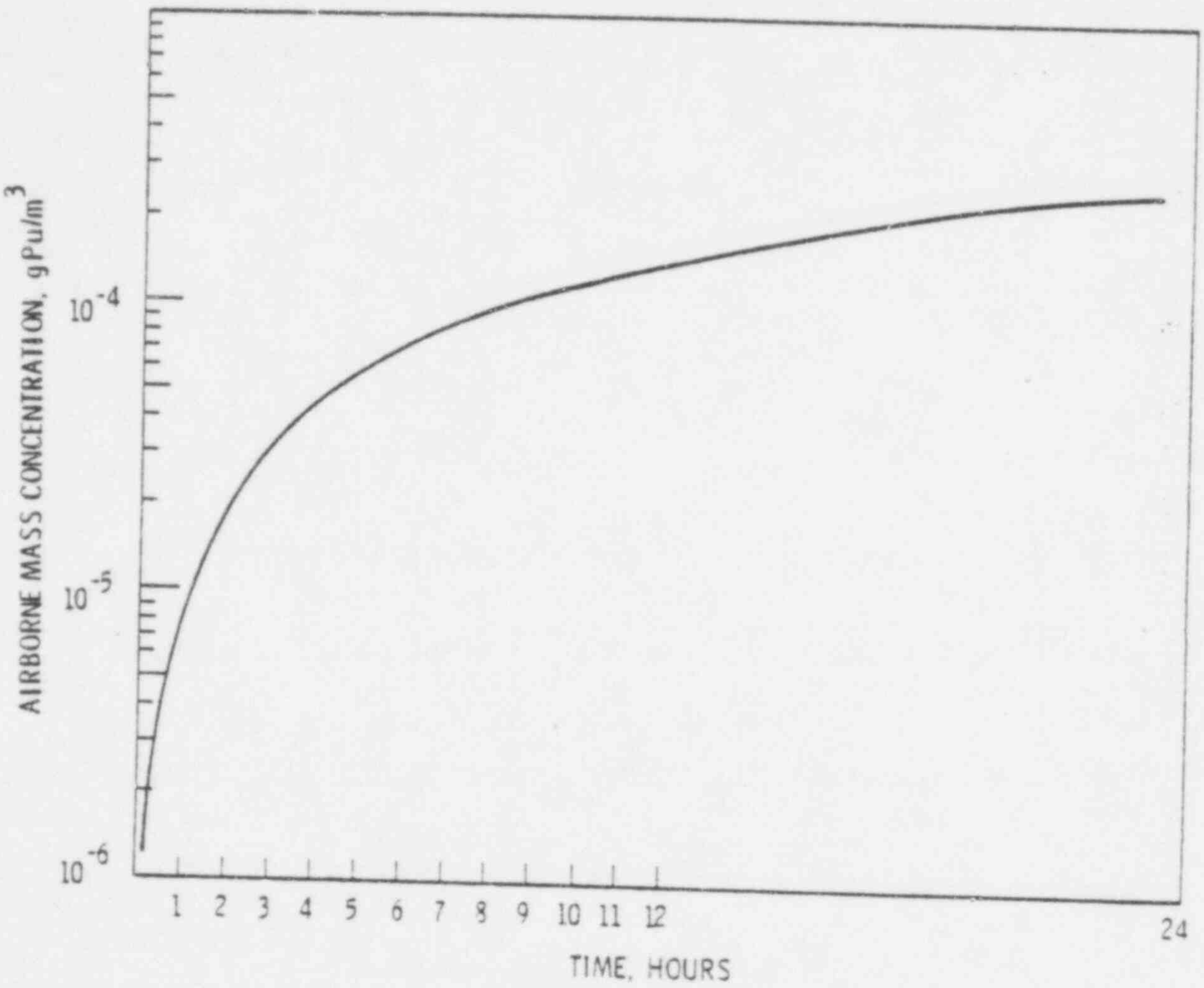

FIGURE 14. Scenario 3 - Airborne Mass Concentration within Perforated AFL as a Function of Time

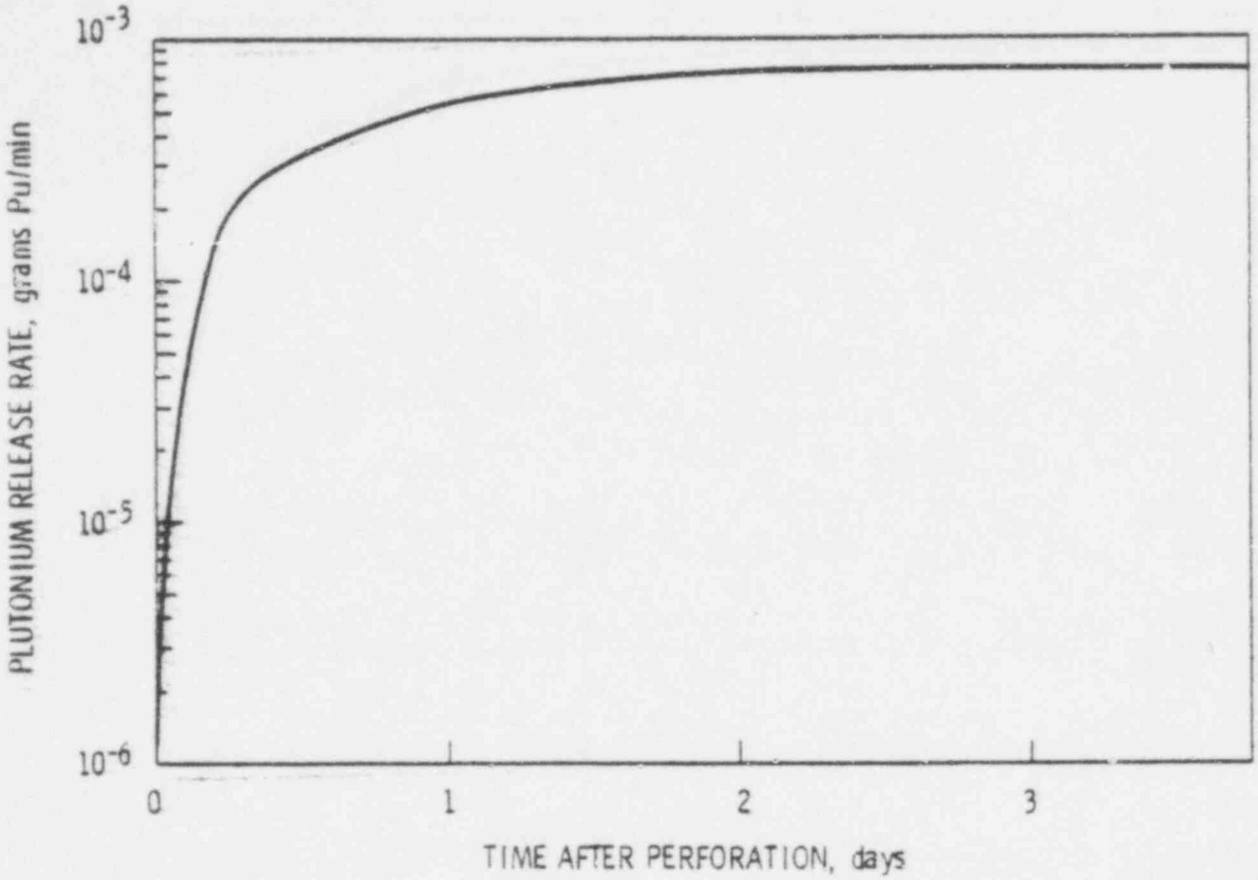

FIGURE 15. Scenario 3 - Mass Airborne Release of Pu from Perforated AFL with Time

TABLE 3. Mass Airborne Release of Pu From Perforated AFL

Time	Average Mass Airborne Concentration in AFL, g Pu/m^3	Mass Pu Release to Ambient Atmosphere, g	Accumulative Mass Pu Release, g
0			
1	8.4×10^{-6}	5×10^{-4}	0.0005
2	2.4×10^{-5}	1×10^{-3}	0.002
3	4.6×10^{-5}	3×10^{-3}	0.005
4	7.8×10^{-5}	5×10^{-3}	0.01
5	1.3×10^{-4}	8×10^{-3}	0.02
6	1.8×10^{-4}	1×10^{-2}	0.03
7	2.1×10^{-4}	1×10^{-2}	0.04
8	2.4×10^{-4}	1×10^{-2}	0.05
9	2.7×10^{-4}	2×10^{-2}	0.07
10	2.8×10^{-4}	2×10^{-2}	0.09
11	3.1×10^{-4}	2×10^{-2}	0.1
12	3.3×10^{-4}	2×10^{-2}	0.1
13	3.4×10^{-4}	2×10^{-2}	0.1
14	3.6×10^{-4}	2×10^{-2}	0.2
15	3.8×10^{-4}	2×10^{-2}	0.2
16	4.0×10^{-4}	2×10^{-2}	0.2
17	4.2×10^{-4}	3×10^{-2}	0.2
18	4.4×10^{-4}	3×10^{-2}	0.3
19	4.5×10^{-4}	3×10^{-2}	0.3
20	4.7×10^{-4}	3×10^{-2}	0.3
21	4.9×10^{-4}	3×10^{-2}	0.4
22	5.1×10^{-4}	3×10^{-2}	0.4
23	5.2×10^{-4}	3×10^{-2}	0.4
24	5.4×10^{-4}	3×10^{-2}	0.4
48	6.6×10^{-4}	1×10^{-2}	1
72	7.4×10^{-4}	1×10^{-2}	2
96	7.5×10^{-4}	1×10^{-2}	3

RADIATION DOSE MODELS FOR AN ATMOSPHERIC RELEASE

The more important potential environmental exposure pathways for plutonium released to the atmosphere are inhalation, cloud submersion, ingestion, and direct ground irradiation. Of these, the only significant exposure pathway for acute atmospheric releases of Pu is inhalation during initial cloud passage and inhalation of resuspended environmental residual contamination (McPherson and Watson 1979).

The equation for calculating committed radiation dose equivalents from acute inhalation is:

$$DC_{ir} = Q_i(E/Q)BR(DCF)_{ir} \qquad (3)$$

where

DC_{ir} · the committed dose equivalent to organ r from acute inhalation of radionuclide i, rem

Q_i · the quantity of radionuclide i released to the atmosphere, μg

E/Q · the accident atmospheric exposure coefficient, μg · sec/m^3 per μg released

BR · the ventilation rate of the human receptor during the exposure period, m^3/sec

$(DCF)_{ir}$ · the acute committed dose equivalent factor, rem per μg inhaled; a number specific to a given nuclide i and organ r which can be used to calculate radiation dose from a given radionuclide intake.

Human ventilation rates for three time periods for this study were derived from International Commission on Radiological Protection (ICRP) recommendations (ICRP 1975): 3.3×10^{-4} m^3/sec for the period 0 to 8 hours; 2.3×10^{-4} m^3/sec for 8 to 24 hours; and 2.7×10^{-4} m^3/sec for greater than 24 hours.

Fifty-year committed dose equivalent factors were calculated using the computer code DACRIN (Houston, Strenge and Watson 1975). This code incorporates the ICRP Task Group Lung Model (TGLM) to calculate the dose commitment to the lung and other organs of interest (Task Group on Lung Dynamics 1966).

The organ masses used in the code have been modified to reflect the changes reported in ICRP Report 23 (1975). The translocation of americium from the blood to the organs of interest has been changed to the values suggested in ICRP Report 19 (1972). Fifty-year committed dose equivalents per unit isotopic mass inhaled for particles with an AMAD(a) of one μm are listed in Appendix C, Tables C-1 and C-2, for each Pu isotope and ^{241}Am. The organs of interest in Pu dosimetry are the total body, kidneys, liver, bone, and lungs.

The Pu postulated to be released to the atmosphere from the Vallecitos Nuclear Center is in the form of Pu oxides. Lung retention, as described by the TGLM, depends upon the chemical nature of the compound inhaled. Compounds of Pu largely fall into Class Y (retained for years) or Class W (retained for weeks). There is no evidence of Pu existing in the environment as Class D (retained for days). Actinides in the oxide form are currently classified as Class Y (ICRP 1972), a classification assumed in this study. Doses for Pu as Class W material, however, are included in Appendix C.

Plutonium particulates that deposit onto the ground surface from a plume can be resuspended to the atmosphere by natural processes and subsequently inhaled by people. Therefore, ground contamination is an important factor when calculating doses via inhalation. Where deposition values were not provided for this study (distances less than 5000 m for the 0 to 2 hr release period), the deposition velocity concept was used to estimate the Pu deposition (Equation 4):

$$W_i = Q_i(E/Q)V_d \tag{4}$$

(a) Activity Median Aerodynamic Diameter.

where

W_i · the concentration of radionuclide i on the ground surface, $\mu g/m^2$

Q_i · the quantity of radionuclide i released to the atmosphere, µg

E/Q · the accident atmospheric exposure coefficient, $\mu g \cdot sec/m^3$ per µg released

V_d · particle deposition velocity, m/sec

The deposition velocity of Pu particles cannot be specified exactly because the velocity will vary, depending on the size distribution of the particles, the nature of the surface on which deposition occurs, the wind speed, and other meteorological variables. The deposition velocity for Pu has been reported to range from 1×10^{-4} to 3×10^{-2} m/sec (Selby et al. 1975; Cohen 1977; Baker 1977; Gudiksen, Peterson, Lange and Knox 1976; Atomic Energy Commission 1974). A value of 1×10^{-3} m/sec is used in this report (Baker 1977).

Resuspension rates for material deposited on the ground are time dependent and tend to decrease with time after initial deposition. Local conditions can be expected to strongly affect the rate, with rainfall, winds, and surface characteristics predominant. The exact relationships are not well-enough understood to account for these effects (Selby et al. 1975). However, the airborne concentration from resuspended material can be estimated using a resuspension factor, K. The resuspension factor is defined as the resuspended air concentration divided by the surface deposition. Values for K in the environment between 10^{-4} and 10^{-13} m^{-1} have been measured and reported (Selby et al. 1975; Cohen 1977; Atomic Energy Commission 1974; Friedman 1976, pp. 49-51; Anspaugh, Shinn, Phelps and Kennedy 1975; EPA 1977; Bennett 1975; Hanson 1975; Martin and Bloom 1975; Sehmel 1977; Healy 1977; Anspaugh 1976, pp.392-395). Until a more general model is available that considers all the important variables affecting the resuspension process, Anspaugh, Shinn, Phelps and Kennedy (1975) recommend using a simple time-dependent model to predict the average airborne concentration of a resuspended contaminant:

$$K(t) = 10^{-4} \exp(-0.15\ t^{1/2}) + 10^{-9} \qquad (5)$$

where

t = time since the material was deposited on the ground, days

10^{-4} = resuspension factor at time $t = 0$, m^{-1}

10^{-9} = resuspension factor after 20 yr, m^{-1}

Figure 16 illustrates the time dependence of the resuspension factor.

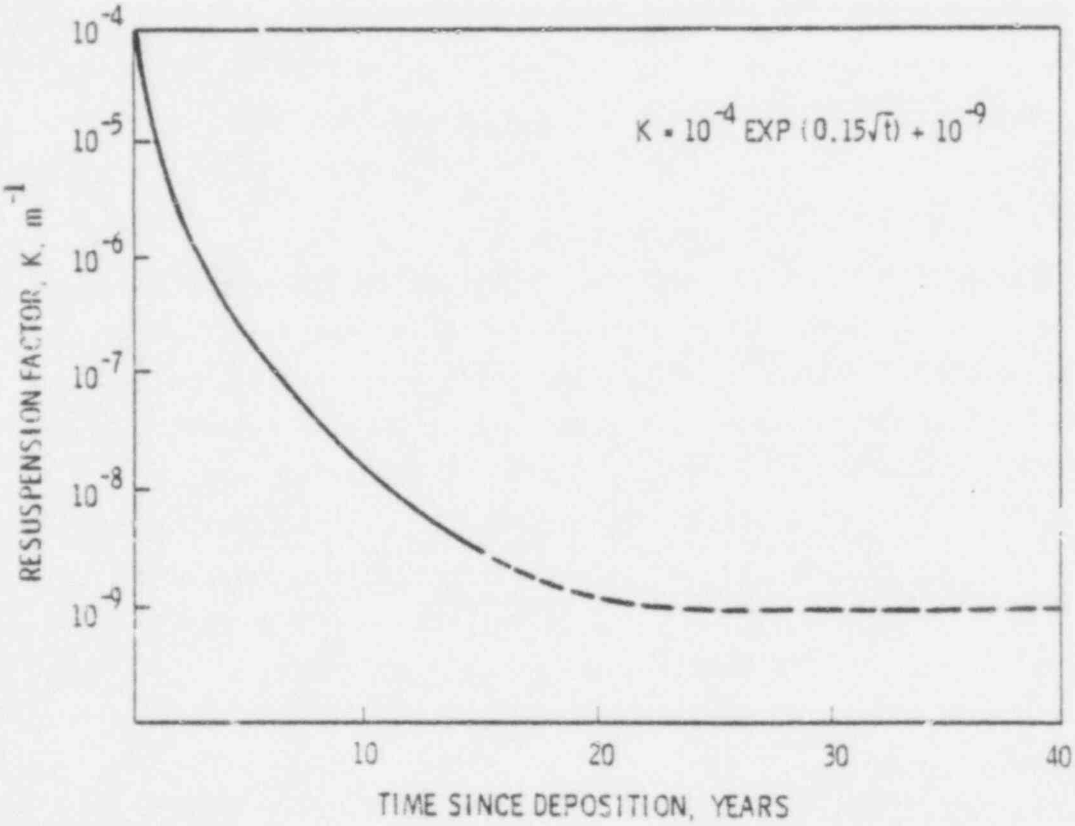

FIGURE 16. Time Dependence of the Environmental Surface Resuspension Factor

Equation 5 was integrated over each year post-deposition and divided by the integrated time period to determine the average resuspension factor for each year considered. Ninety-nine percent of the total 50-yr exposure from resuspension occurs in the first five years. The chronic 50-yr committed dose equivalent factor for inhalation remains relatively constant over this time period. Therefore, the 50-yr committed dose equivalent from 50 years of exposure to resuspended Pu can be estimated using chronic 50-yr committed dose equivalent factors, and only the first five years of exposure to the resuspended material needs to be included. The committed dose equivalent from inhalation of resuspended material was calculated by:

$$DC_{ir} = W_i \, \overline{K}(BR)(DCF)_{ir} \; (3.16 \times 10^7) \qquad (6)$$

where

DC_{ir} · the 50-yr committed dose equivalent to organ r from one yr of inhalation of radionuclide i, rem/yr of inhalation

W_i · the concentration of radionuclide i on the ground surface for the year of consideration, $\mu g/m^2$

$\overline{K}$ · the average resuspension factor for the year of consideration, m^{-1}

(BR) · the ventilation rate of the human receptor (for a duration of greater than 24 hr), m^3/sec

$(DCF)_{ir}$ · chronic committed dose equivalent factor, rem/μg inhaled

3.16×10^7 · conversion factor, sec/yr

Radiological decay of the deposited radionuclides and the buildup of ^{241}Am from the decay of ^{241}Pu were accounted for. Chronic 50-yr committed dose equivalent factors for a one-year intake were calculated using DACRIN and are listed in Appendix C, Tables C-3 and C-4.

DOSE ESTIMATES AND DISCUSSION

Using the source terms given in Table 1, committed radiation dose equivalents to several organs of the human body were calculated for the three damage scenarios postulated for this study. The dose contribution from the postulated fission product (FP) releases is negligible. Therefore, dose results for the FP releases are not included.

The isotopic composition assumed for the Pu mixture is given in Table 4.

TABLE 4. Isotopic Composition of the Pu Mixture

Isotope	Weight Percent[(a)]
^{238}Pu	0.053
^{239}Pu	87
^{240}Pu	12
^{241}Pu	4
^{242}Pu	0.20
^{241}Am	-[(b)]
	100

(a) All isotopic values including the sum have been rounded to two significant figures.

(b) ^{241}Am was not considered in the release. However, the buildup of ^{241}Am from residual ^{241}Pu in the environment is accounted for.

For the 0 to 2 hour time period, accident atmospheric dispersion values for a 5% and 50% condition, calculated by the NRC for the Vallecitos site were used to estimate potential committed dose equivalents to the population and a maximum individual. Annual average atmospheric dispersion and deposition values also calculated by the NRC were used for all other time periods. The calculated committed dose equivalents via inhalation are listed in Tables 5-7 for the three release scenarios. The estimated maximum Pu ground depositions at the site boundary, the nearest residence and the nearest pasture are listed in Tables 8-10.

TABLE 5. Fifty-Year Committed Dose Equivalents from Inhalation Following Damage, Scenario 1 (Class Y)

Organ of Reference	Committed Dose Equivalents for: Population (person-rem)[a] 5% Meteorology	50% Meteorology	Nearest Residence[b] (rem) 5% Meteorology	50% Meteorology
Total Body	1.2E+1[c]	2.9E+0	1.4E-3	3.5E-4
Kidneys	4.9E+1	1.2E+1	5.9E-3	1.5E-3
Liver	1.[illegible]E+2	3.9E+1	1.9E-2	4.7E-3
Bone	2.6E+2	6.4E+1	3.1E-2	7.8E-3
Lungs	1.7E+2	4.3E+1	2.1E-2	5.2E-3

(a) Population within a 50-mile radius of the site.
(b) Located 560 m WSW of the 102 Building.
(c) Notation: 1.2E+1 is equivalent to 1.2×10^1.

TABLE 6. Fifty-Year Committed Dose Equivalents from Inhalation Following Damage, Scenario 2 (Class Y)

Organ of Reference	Committed Dose Equivalents for: Population (person-rem) 5% Meteorology	50% Meteorology	Nearest Residence[a] (rem) 5% Meteorology	50% Meteorology
Total Body	1.8E+1	4.3E+0	2.3E-2	6.0E-3
Kidneys	7.5E+1	1.8E+1	9.8E-2	2.6E-2
Liver	2.4E+2	5.8E+1	3.1E-1	8.1E-2
Bone	3.9E+2	9.5E+1	5.1E-1	1.3E-1
Lungs	2.6E+2	6.3E+1	3.4E-1	8.9E-2

(a) Located 560 m WSW of the 102 Building.

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TABLE 7. Fifty-Year Committed Dose Equivalents from Inhalation Following Damage, Scenario 3 (Class Y)

Organ of Reference	Committed Dose Equivalents for: Population (person-rem) 5% Meteorology	50% Meteorology	Nearest Residence[a] (rem) 5% Meteorology	50% Meteorology
Total Body	1.8E+3	4.5E+2	1.8E-1	4.5E-2
Kidneys	7.6E+3	1.9E+3	7.5E-1	1.9E-1
Liver	2.4E+4	6.0E+3	2.4E+0	6.0E-1
Bone	4.0E+4	9.9E+3	3.9E+0	9.9E-1
Lungs	2.7E+4	6.6E+3	2.6E+0	6.6E-1

(a) Located 560 m WSW of the 102 Building.

TABLE 8. Estimated Maximum Pu Deposition at Significant Locations Following Damage, Scenario 1

Location	Pu Deposition ($\mu Ci/m^2$) 5% Meteorology	50% Meteorology
Site Boundary(a)	5.5E-3	1.4E-3
Residence(b)	2.1E-3	5.2E-4
Pasture(c)	6.8E-3	1.9E-3

(a) Located 370 m SE of the 102 Building.
(b) Located 560 m WSW of the 102 Building.
(c) Located 240 m WNW of the 102 Building.

TABLE 9. Estimated Maximum Pu Deposition at Significant Locations Following Damage, Scenario 2

Location	Pu Deposition ($\mu Ci/m^2$) 5% Meteorology	50% Meteorology
Site Boundary(a)	1.0E-1	2.7E-2
Residence(b)	2.4E-2	6.3E-3
Pasture(c)	1.5E-1	5.1E-2

(a) Located 370 m SE of the 102 Building.
(b) Located 560 m WSW of the 102 Building.
(c) Located 240 m WNW of the 102 Building.

TABLE 10. Estimated Maximum Pu Deposition at Significant Locations Following Damage, Scenario 3

Location	Pu Deposition ($\mu Ci/m^2$) 5% Meteorology	 50% Meteorology
Site Boundary[(a)]	6.9E-1	1.8E-1
Residence[(b)]	2.8E-1	7.0E-2
Pasture[(c)]	8.0E-1	2.1E-1

(a) Located 370 m SE of the 102 Building.
(b) Located 560 m WSW of the 102 Building.
(c) Located 240 m WNW of the 102 Building.

The dose rate from natural background radiation in the State of California is reported to be 120 mrem/yr to the total body (Klement 1972). Therefore, an individual receives a total-body dose of about 6 rem from exposure to natural background radiation during a 50-yr period. The collective dose equivalent from 50 years of exposure to natural background radiation to the total body of the population within a 50-mile radius of the General Electric Vallecitos Nuclear Center is 3×10^7 person-rem. The average annual dose to the total body of an individual from medical x-ray examination is about 20 mrem (United Nations 1977). This average dose corresponds to a 50-yr collective dose equivalent of 5×10^6 person-rem. The dose contribution from fallout is negligible when compared to natural background radiation and medical x-ray exposure. If a radiation worker was involved in an occupational accident and received a maximum permissible bone burden of ^{239}Pu, the 50-yr committed dose equivalent to the bone would be greater than 1000 rem. As can be seen, then, the calculated 50-yr committed dose equivalents to the population for the three scenarios postulated in this report are much lower than the collective dose equivalent from 50 years of exposure to natural background radiation and medical x-rays.

Existing guidelines on acceptable levels of soil contamination from Pu can be found to range from 0.01 $\mu Ci/m^2$ to 270 $\mu Ci/m^2$ (Selby et al. 1975; EPA 1977; Martin and Bloom 1975; Healy 1977; <u>U.S. Code</u> 1976; Healy 1974; Guthrie and Nichols 1964; Hazle and Crist 1975; Kathren 1968; Dunster 1962). The proposed EPA guideline for Pu contamination in the general environment is 0.2 $\mu Ci/m^2$ (EPA 1977). This guideline is based on annual doses of one mrad to the lung from inhalation and three mrad to the bone from ingestion. If the broad range of current guidelines are normalized to these lung and bone doses and the same resuspension factor is used, the guidelines are all in reasonable agreement with 0.2 $\mu Ci/m^2$. The estimated maximum residual Pu contaminants on the ground based on the three damage scenarios are all within the EPA proposed guideline at the significant locations, except for the 5% meteorological condition during scenario 3. The estimated contamination levels for this case range from about 0.3 to 0.8 $\mu Ci/m^2$ at the significant locations. The highest value is estimated at the pasture which is actually inside the outer property fence.

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APPENDIX A

DISCUSSION OF FACTORS USED TO ESTIMATE THE POTENTIAL AIRBORNE RELEASE FROM SEISMIC ACTIVITY AT THE VALLECITOS NUCLEAR CENTER

DISCUSSION OF FACTORS USED TO ESTIMATE THE POTENTIAL AIRBORNE RELEASE FROM SEISMIC ACTIVITY AT THE VALLECITOS NUCLEAR CENTER

AIRBORNE MASS CONCENTRATIONS WITHIN ENCLOSED SPACES

Finely divided solids and liquids can be injected into the air and remain suspended for a finite period of time. Quasi-stable suspensions of solid or liquid particles in a gas are called aerosols. The mass concentration that will remain airborne is dependent upon the size distribution and density of the suspended material and the lifting force present (turbulent eddies). Mass concentrations of 25 to 250 $\mu g/m^3$ are commonly encountered (Dennis 1976); 0.1 to 50 mg/m^3 are representative of industrial atmospheres (Dennis 1976) and can be as high as 5 g/m^3 at 1 to 2 m above the ground in dust devils (Sinclair 1974).

Liquids

The airborne dispersion of bulk liquids requires subdivision and injection of the subdivided material into the air. Film formation and breakup is a subdivision process for liquids. Due to the fluid properties of liquids, very thin films are necessary to produce fine droplets. The viscous energy requirements for atomizer-producing sprays of various particle sizes have been estimated (Monke 1952, p. 288), and the viscous energy required to form 1 cm^3 of spray of 1 µm and 5- to 10-µm particles were calculated to be 10^4 to 10^6 cal and 100 cal, respectively. Additional energy is necessary to inject the particles into the gas stream.

Oak Ridge National Laboratory (1970) has been able to demonstrate an approximate correlation of solution concentration in air or vapors from cooling towers, evaporators, and air-sparged(a) vessels (see Figure A.1). For superficial velocities less than 0.15 fps (0.046 m/sec), the metastable aerosol formed by air sparging was found to have a mass concentration of 10 mg/m^3 (approximately equivalent to fog) and had a size distribution shown in Figure A.2. The situation found during air sparging is more favorable for film formation than by spilling, and use of the mass airborne concentration from air sparging

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(a) Air sparging: bubbling air through a liquid to stir and remove gases entrained in the liquid matrices.

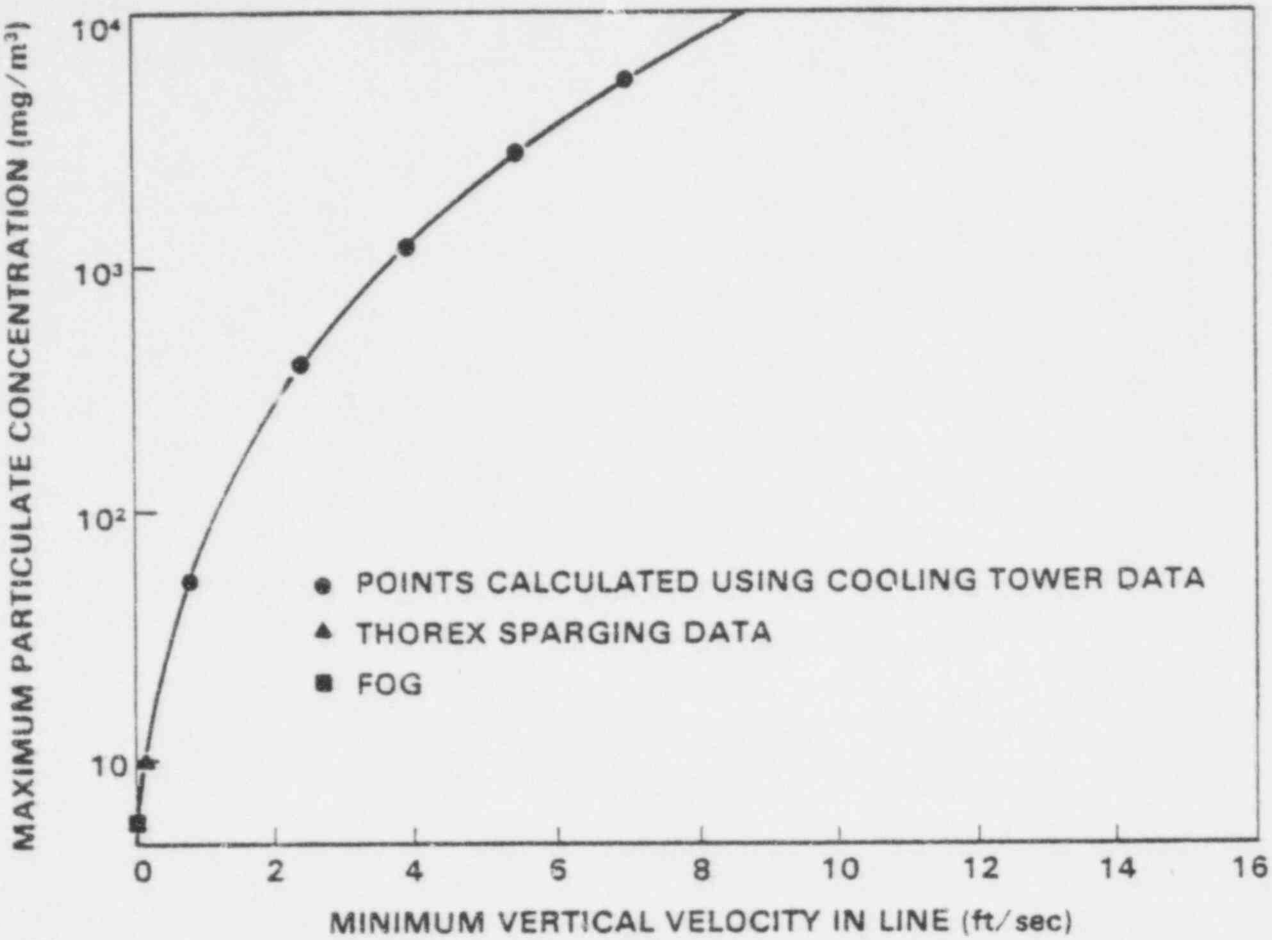

FIGURE A.1. Effect of Minimum Superficial Velocity in an Off-Gas Line on the Concentration of Liquid Solution Particles Resulting from Vigorous Mixing of a Solution with Air (Density of Solution: 1 g/cc)

should be conservative (greater concentrations) for these postulated VNC accident situations. Use of conservative values also compensate for minor contributions from sloshing of the liquid in the enclosure.

An alternate means of estimating airborne mass concentrations for an accident situation is to estimate the mass associated with particles of 10-µm Aerodynamic Equivalent Diameter or less. These size particles are those associated with the quasi-stable aerosol mentioned above, a conservative estimate of "respirable" particles (Mercer 1977), and a conservative estimate of particles supported by normal turbulence levels (Dennis 1976). Data are not

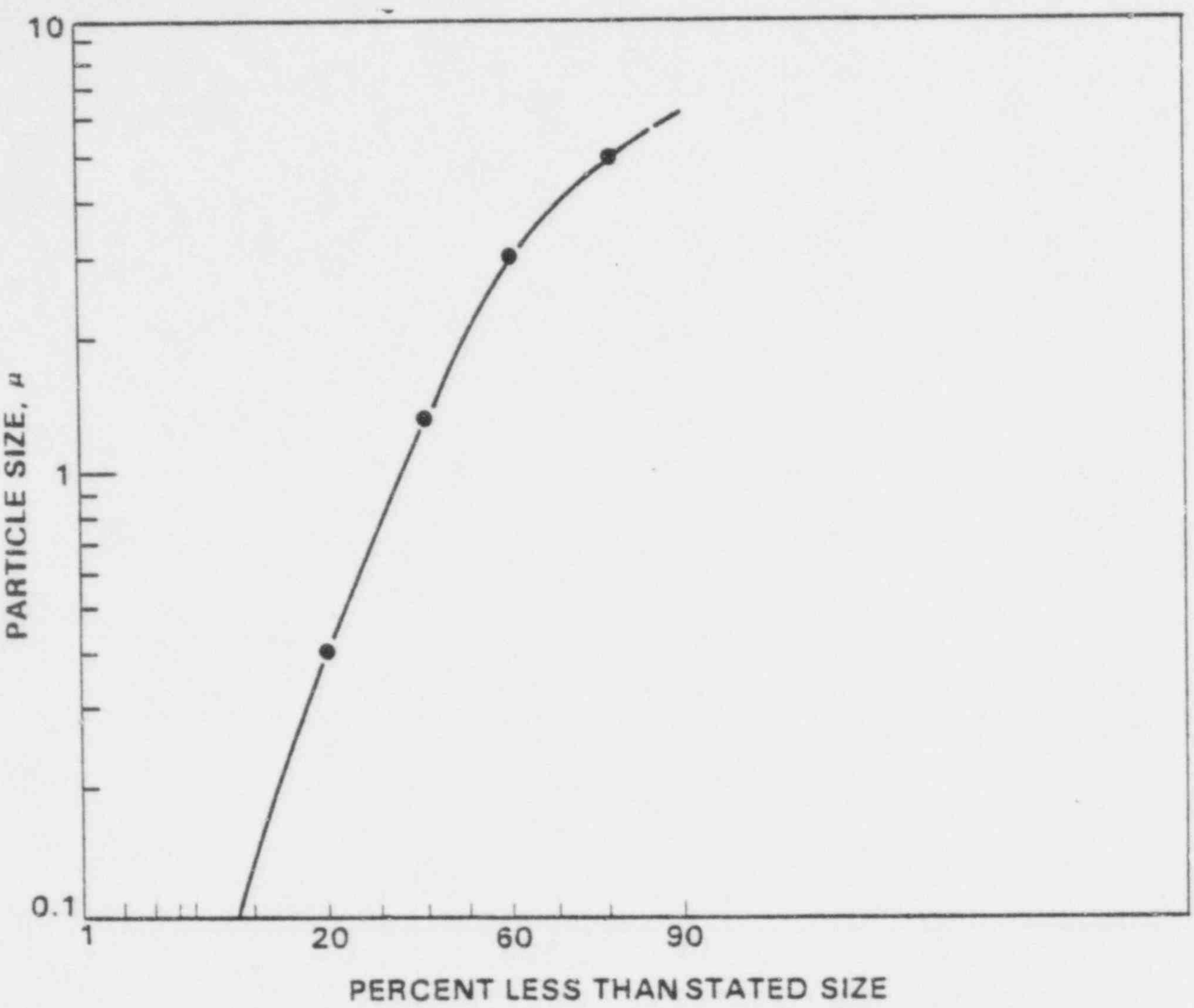

FIGURE A.2. Particle Size Distribution of a Stable Aerosol that has Encountered Several Changes of Direction in a Pipeline

available on the size distribution of droplets formed from bulk liquids under accident conditions. Spray nozzles are designed to generate fine droplets by forcing liquids through small openings, and assuming a similar distribution for accident aerosols would provide conservative airborne mass concentration estimates. Table A.1 shows cumulative masses associated with droplets less than various size ranges for three nozzles with orifice diameters ranging from 0.063 in. (1.6 mm) to 0.128 in. (3.3 mm) at various pressures (Houghton 1943, p. 1990). The size distributions become coarser with increasing orifice

TABLE A.1. Drop Size Distribution of 3 Hollow Cone Nozzles at Various Pressures (Source: Houghton 1943)

Drop Size (μm)	Weight Percent Drops in Size Fraction												Diameter
	0.063"						0.086"				0.128"		Orifice
	50 psi		100 psi		200 psi		100 psi		200 psi		200 psi		Pressure
	1	2	1	2	1	2	1	2	1	2	1	2	
10	.038	.038	.079	.08	.17	.2	.01	.01	.03	.03	.01	.01	
25	.31	.35	.44	.5	.9	1.1	.09	.1	.24	.3	.12	.1	
50	2.0	2.4	2.2	2.7	3.2	4.3	.5	.6	1.3	1.6	.73	.8	
100	5.0	7.4	6.0	8.7	7.0	11.3	2.6	3.2	3.4	5.0	3.5	4.3	
150	9.1	16.5	10.4	19.2	11.8	23.1	4.6	7.8	6.1	11.1	6.5	10.8	
200	15.2	31.7	18.3	37.5	21.5	44.6	7.1	14.9	9.6	20.7	11.3	22.1	
300	21.7	53.4	24.5	62.0	29.9	74.5	13.5	28.4	21.9	42.6	21.1	43.2	
400	12.8	66.2	25.5	87.5	25.5	100.0	25.3	53.8	44.9	87.5	24.6	67.8	
500	12.5	78.7	12.5	100.0	--	--	24.8	78.6	12.6	100.0	32.2	100.0	
600	21.5	100.0	--	--	--	--	21.4	100.0	--	--	--	--	

---

(1) W/o in size fraction.
(2) W/o in all fraction less than stated size.

diameter and decreasing pressure. The fraction of droplets less than 10 μm in diameter for the 0.086-in. orifice at 100 psi and the 0.128-in. orifice at 200 psi is 0.01% of the mass. In addition, this fraction of droplets is 1/4 the fraction of the 0.063-in. orifice at 50 psi. These conditions appear to greatly exceed the pressure and are much finer than openings found for the breakage of glass equipment. Thus, an assumption of 10^{-4} of the inventory made airborne is conservative.

The maximum anticipated inventory in the PAL is 100 g of Pu as a nitrate solution. The maximum solution concentration received is 200 g Pu/ℓ, and such solutions have specific gravities in the range of 1.5. The total free volume of the enclosures in the PAL is 16.6 m^3. If it is assumed that this volume is filled with a mass concentration of 10 mg/m^3, 166 mg of solution containing 22 mg of Pu would be airborne. If the spray nozzle data are used, and 10^{-4} of the total inventory is asssumed to be airborne, a total of 10 mg of Pu would be airborne in the enclosures. Thus, the value of 10 mg/m^3 is used in this study to estimate the accident-generated mass airborne concentration of liquids.

Dry Powders

Swain and Haberman (1961) calculated a mass concentration of 33 mg/m^3 was a "reasonable value" for PuO_2 accident-generated aerosols. Their basis was 10^6 particles per cm^3 of PuO_2 particles of density 2. The particles ranged from 0.04 to 10 μm in diameter with a log-normal distribution with a slope of 2.

Schwendiman (1977) reports rapidly decaying concentrations for UO_2 dispersed in a rt. cylinder 6 in. in diameter x 10 in. long. Four-and-a-half kilograms of fine uranium dioxide powder (see Figure A.3 for the size distribution) were made airborne by rapidly rotating the cylinder, and a sample was extracted via a hypodermic needle that was inserted into the air space equipped with a Swinney adapter. The airborne concentration versus time for the four experiments (shown in Figure A.4) indicates an airborne mass concentration of 10^{-6} g/cm^3 (or 1 g/m^3) in 46 sec and decreases to 10^{-8} g/cm^3 (10 mg/m^3) in 200 sec (3.3 min). Mishima (1973) assigns an upper-limit mass concentration of 100 mg/m^3 for quasi-stable, accident-generated, airborne concentrations.

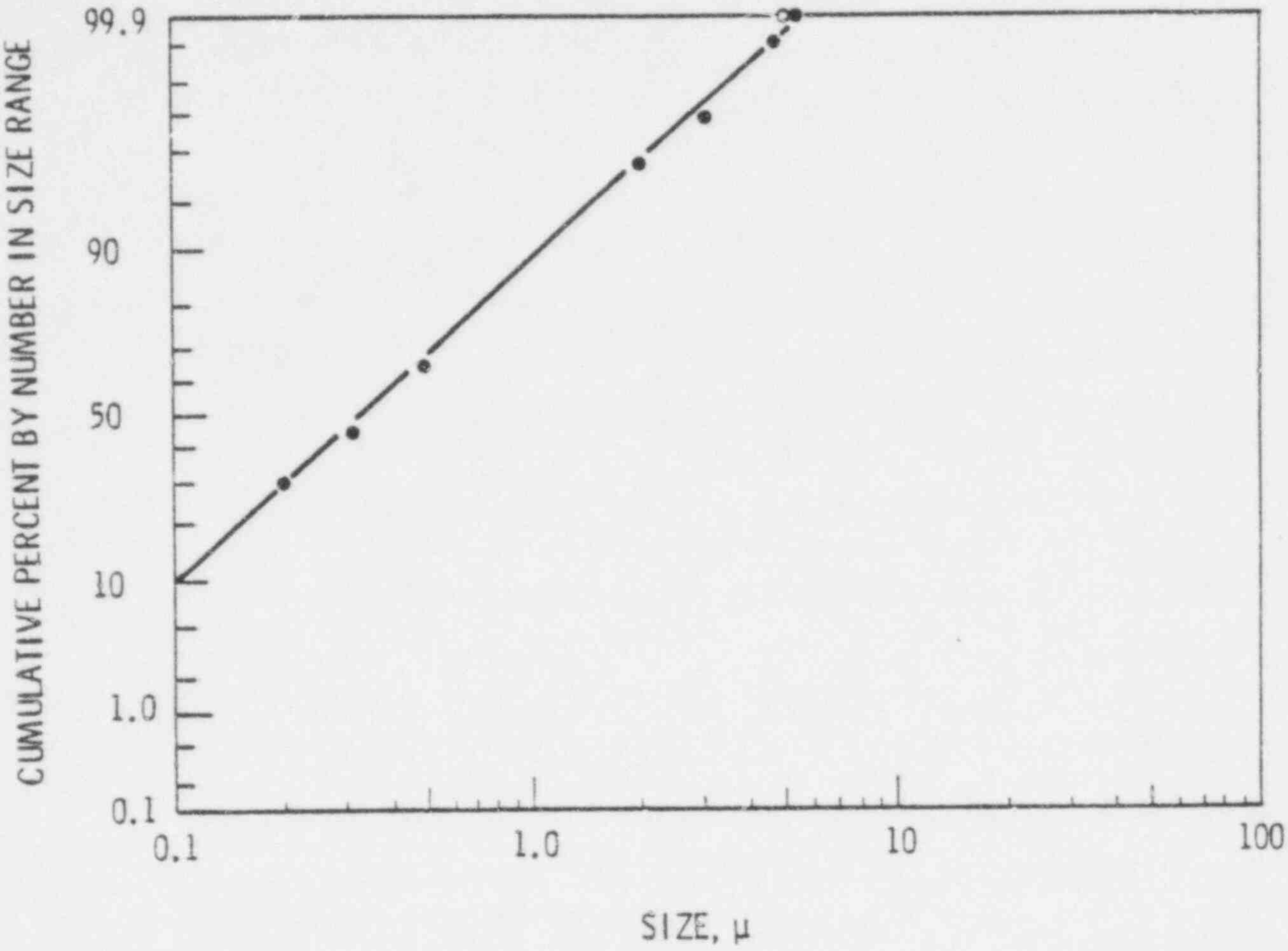

FIGURE A.3. Geometric Size Distribution of UO_2

For aerosols that have not had an opportunity to stabilize, but are not immediately released by the dispersing action, a mass concentration of 300 mg/m^3 was arbitrarily assigned.

ALTERATION OF AIRBORNE MASS CONCENTRATIONS WITHIN ENCLOSED VOLUMES

Once generated, the characteristics of aerosols change with time. "Within the confines of a closed chamber, the concentration, c, is continuously decreasing owing to 1) loss of particles to the floor by sedimentation, 2) loss of particles to the walls and floor by diffusion, and 3) loss of particles by coagulation" (Dennis 1976). Diffusional effects become small above 1 μm, whereas sedimentation is not as significant for particles less than 1 μm in

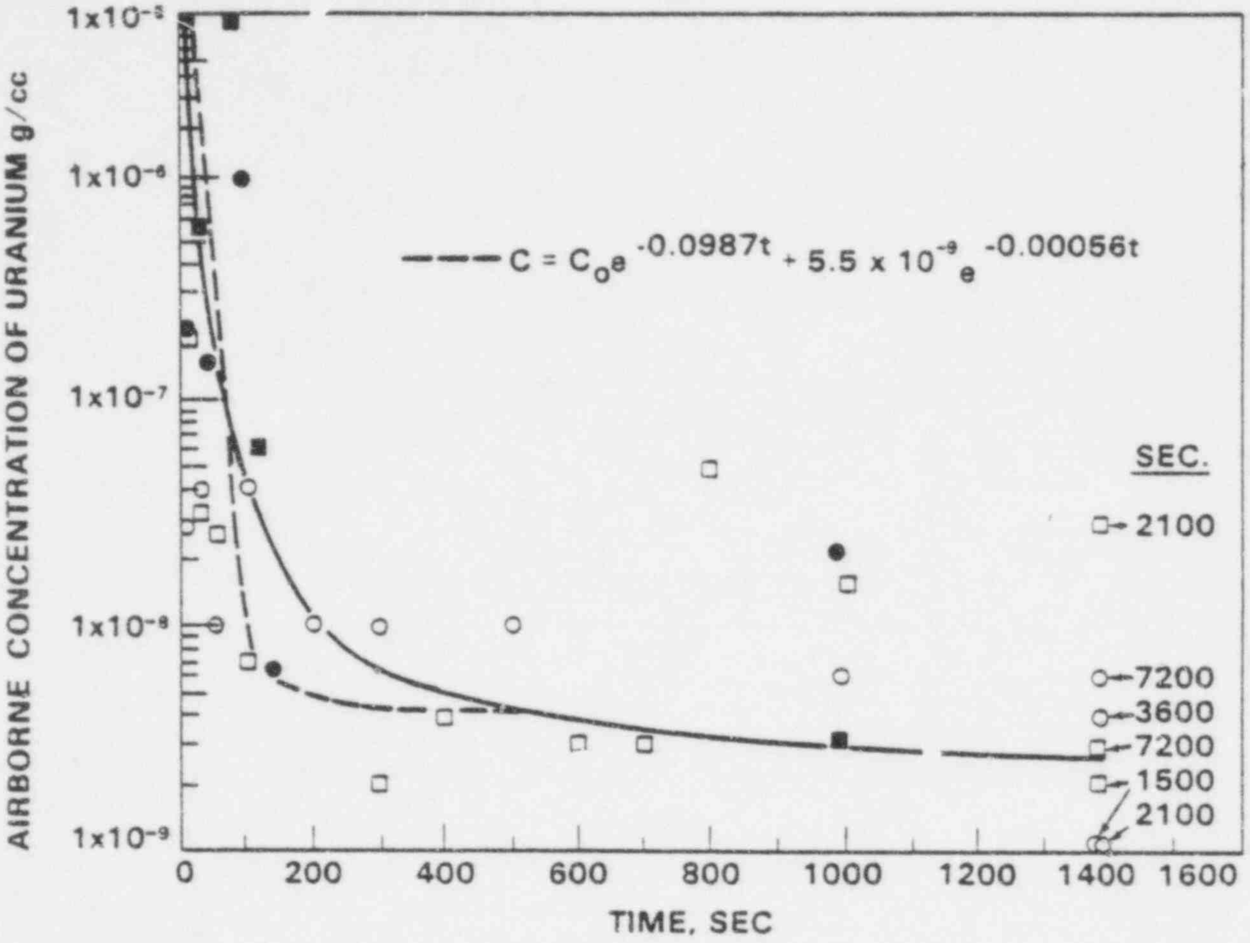

FIGURE A.4. Uranium Oxide Airborne Over the Bulk Powder Following Disruption

diameter in still air (Dennis 1976). Terminal velocities are shown in Figure A.5. Unfortunately, in most cases the air is not still, and normal turbulence provides sufficient mixing energy to support some particles up to 10 µm (Dennis 1976). The convective flow velocity in a chamber one meter high at a temperature difference of 0.01°C can reach 1 cm/sec (the terminal velocity of a 20-µm unit density sphere) (Fuchs 1964). Therefore, limiting the discussion of airborne aerosols to the fraction less than 10-µm AED provides a reasonable, though conservative, estimate of the fraction that constitutes the quasi-stable aerosol.

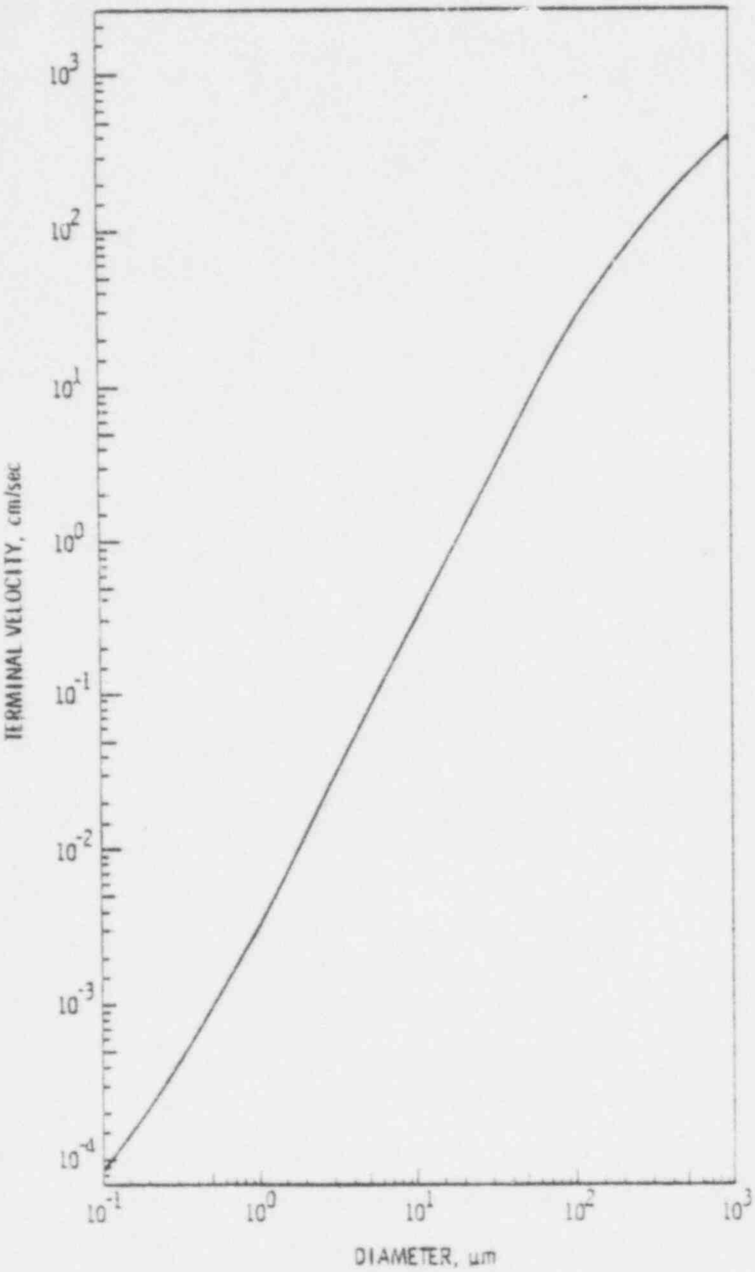

FIGURE A.5. Terminal Velocity of Unit-Density Spheres at 1 Atm and 20°C (Adapted from Dennis 1976, p. 122)

An additional conservative factor is introduced by not considering the loss of airborne mass concentration with time by natural processes. Even particles that can be stirred by the existing turbulence can be removed by natural processes if they are very near the walls and floor (Dennis 1976; Fuchs 1973). Assuming that the mean velocity of the convective currents in an enclosed space is much greater than the settling velocity of the particles of interest and, therefore, that the aerosol concentration is practically constant throughout the chamber except near the walls (stirred settling), the concentration (c) of particles of radius (r) at time (t) is

$$c(r) = c_0(r) \exp\left(-\frac{V_s(r)t}{H}\right) \qquad \text{(Fuchs 1964)}$$

where

$c_0(r)$ · initial concentration of radius (r)
$V_s(r)$ · settling velocity of particles of radius (r), cm/sec
t · time, sec
H · height of enclosed space, cm

The fraction of various-diameter particles of density 10 remaining airborne after various time increments is shown in Table A.2. After 500 sec (8.3 min), almost all of the particles with physical diameters greater than 10 µm (equal to particles 33 µm AED) have been deposited on the floor. After 1000 sec (16.7 min), all particles greater than 20-µm AED are no longer airborne. In the one hour that this study has assumed would require the exchange of the 10% contaminated volume with the outside atmosphere, only particles less than 10 µm will remain airborne. Using the mass fraction associated with each size of particles, and using the fraction deposited for the smallest size particle in the group (a conservative assumption), the mass airborne concentration would decrease to less than 3 mg/m^3 in the one-hour period (see Figure A.6) -- an order of magnitude less than the 30 mg/m^3 assumed. The airborne concentrations are based on a chamber height of 10 ft (approximately the height of the PAL and AFL) and would be less for heights less than 10 ft, such as gloveboxes.

TABLE A.2. Fraction of Various-Sized Particles (ρ = 10 g/cm^3) Remaining Airborne in Rectangular Chamber (Stirred Settling) 10-ft Tall

$$\frac{C}{C_o} = e^{-\frac{V_s t}{H}}$$

Diameter (μm)	V_s Settling Velocity, cm/sec	$\frac{V_s}{H}$	C/C_o 500 sec	1000 sec	6000 sec
0.5	0.0100	3.28×10^{-5}	0.9837	0.068	0.821
1	0.0350	1.15×10^{-4}	0.944	0.891	0.502
2	0.1304	4.28×10^{-4}	0.807	0.652	0.077
3	0.285	9.35×10^{-4}	0.626	0.393	0.0037
4	0.515	1.68×10^{-3}	0.432	0.186	4.19×10^{-4}
5	0.777	2.53×10^{-3}	0.282	0.0796	-
6	1.11	3.64×10^{-3}	0.162	0.0263	-
7	1.51	4.85×10^{-3}	0.088	0.0078	-
8	1.96	6.43×10^{-3}	0.040	0.0016	
9	2.48	8.14×10^{-3}	0.017	0.00029	-
10	3.06	0.010	0.0067	0.00004	-
12	4.57	0.015	0.00055	-	-
14	6.10	0.020	-	-	-
16	9.14	0.030	-	-	-
18	10.70	0.035	-	-	-
20	12.10	0.040	-	-	-

Thus, limiting the estimates of the plutonium airborne to particles or drops less than 10-μm AED provides airborne mass concentrations for release periods in excess of 20 min that are overstated and for release periods greater than one hour, are an order of magnitude too high.

RESUSPENSION OF DEPOSITED MATERIAL

Particles deposited upon surfaces can be re-injected into the airstream by aerodynamic or mechanical forces. Under most circumstances, mechanical transfer of force is a much more effective means of resuspension of material

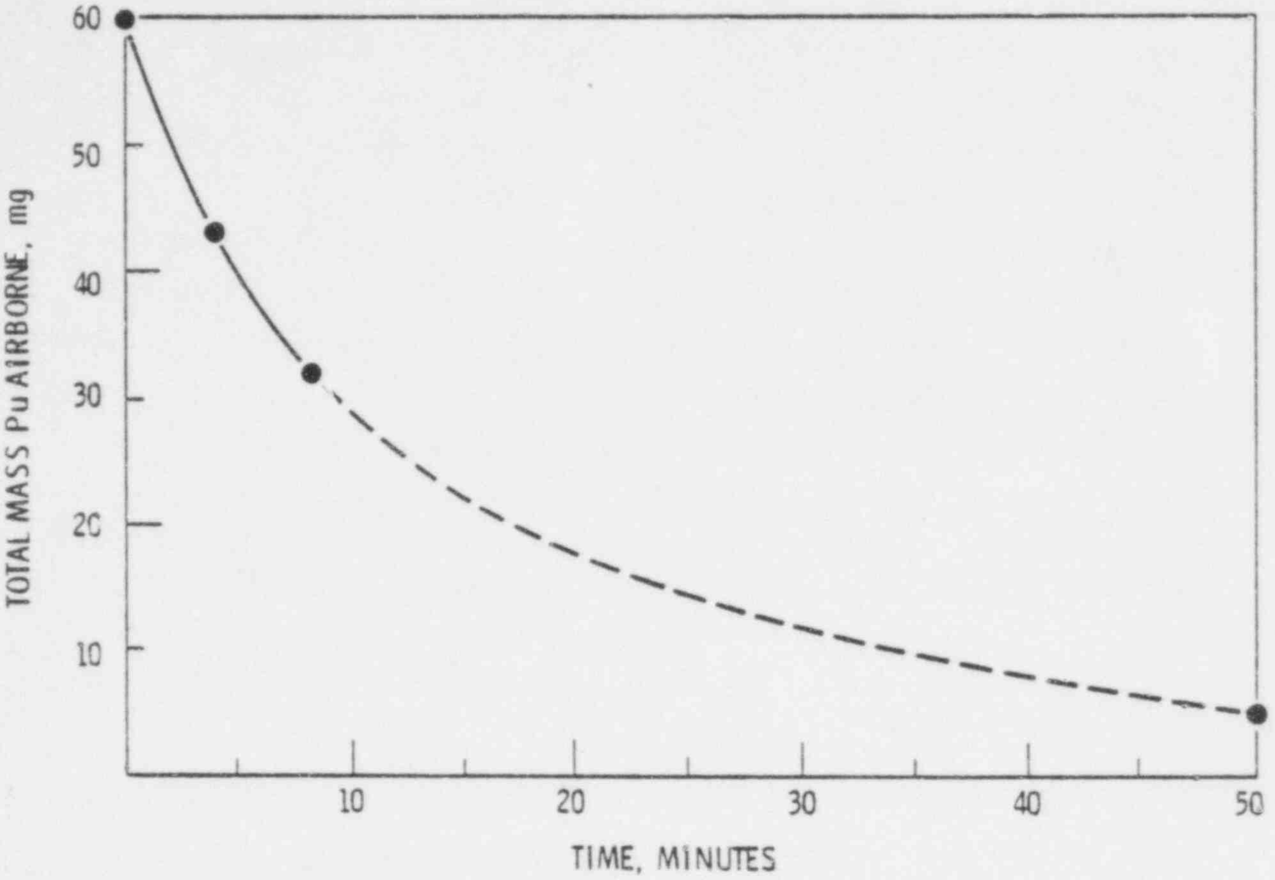

FIGURE A.6. Decrease in Mass Airborne Concentration versus Time (Assumed Stirred Settling Only), C_o = 300 mg/m^3

than aerodynamic forces. Aerodynamic forces can be effective under certain conditions (Fish et al. 1967). Resuspension factors[a] (k, m^{-1}) have been reported for a variety of conditions and range over roughly 11 orders of magnitude (Mishima 1964). The values cover aerodynamic, mechanical, and a combination of aerodynamic-mechanical forces, but quantitative assessment of the influence of various parameters (wind speed, mechanical forces, etc.) and other essential information (height above the surface and the time period for which airborne concentrations are measured) are not available and make extrapolation of the data difficult.

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[a] Resuspension factor: $k = \frac{\text{airborne concentration (units/m}^3\text{)}}{\text{surface concentration (units/m}^2\text{)}}$

Mishima and Schwendiman (1973) have reported the resuspension of UO_2 powder and UNH solutions from various surfaces at two air velocities in a wind tunnel. The data are tabulated in Table A.3. Under the conditions of these experiments, the resuspension of material is not linear with time (see Figure A.7). For UO_2 powder from sandy soil, a large fraction was resuspended within the first hour at 20 mph and within 8 hr at 2.5 mph with little or no resuspension for the remainder of the 24-hr sampling period. A substantial fraction of UO_2 powder is suspended from stainless steel in the first hour at 20 mph with a decreasing fraction of suspension with time. Assuming a linear rate for the resuspension would be conservative for time periods greater than 24 hr. Resuspension fluxes calculated from the values in Table A.3 are shown in Table A.4. Mishima, Schwendiman and Radasch (1968) measured the plutonium entrained in air drawn across concentrated plutonium nitrate solutions (250 g Pu/ℓ) held in a stainless steel dish at velocities up to 100 cm/sec and at temperatures up to 100°C (see Table A.5). The data, recalculated as resuspension fluxes assuming a linear rate, are shown in Table A.6. Orgill, Peterson

TABLE A.3. Aerodynamic Entrainment of Uranium Particles in the Respirable Size Range from Various Surfaces (Mishima and Schwendiman 1973)

	Percent Airborne							
	Uranium Dioxide Powder				Uranium Nitrate Solution			
Surface	2.5 mph		20-23 mph		2.5 mph		20-23 mph	
Smooth, sandy soil	0.24	(6)*	1.7	(24)	0.0051[a]	(24)	0.20[a]	(24)
	0.023	(24)	9.8	(24)	0.0042[a]	(24)	0.70[a]	(24)
	0.005	(24)[b]	0.68	(24)	0.037	(6)	0.027	(28)
					0.010	(24)		
Vegetation cover	0.0038	(24)	0.4	(24)	---		---	
Stainless steel	0.075	(4.8)[b]	1.1	(24)	0.017[b]	(6)	0.78	(5)
			0.29[b]	(24)				
Asphalt Road-Like Surface	0.087[b]	(6)	---		0.033[b]	(6)		

(a) Solid residues from air-dried UNH solutions.
(b) Solid residues remaining after a gasoline fire.
* Numbers in parentheses are hours sample collected.

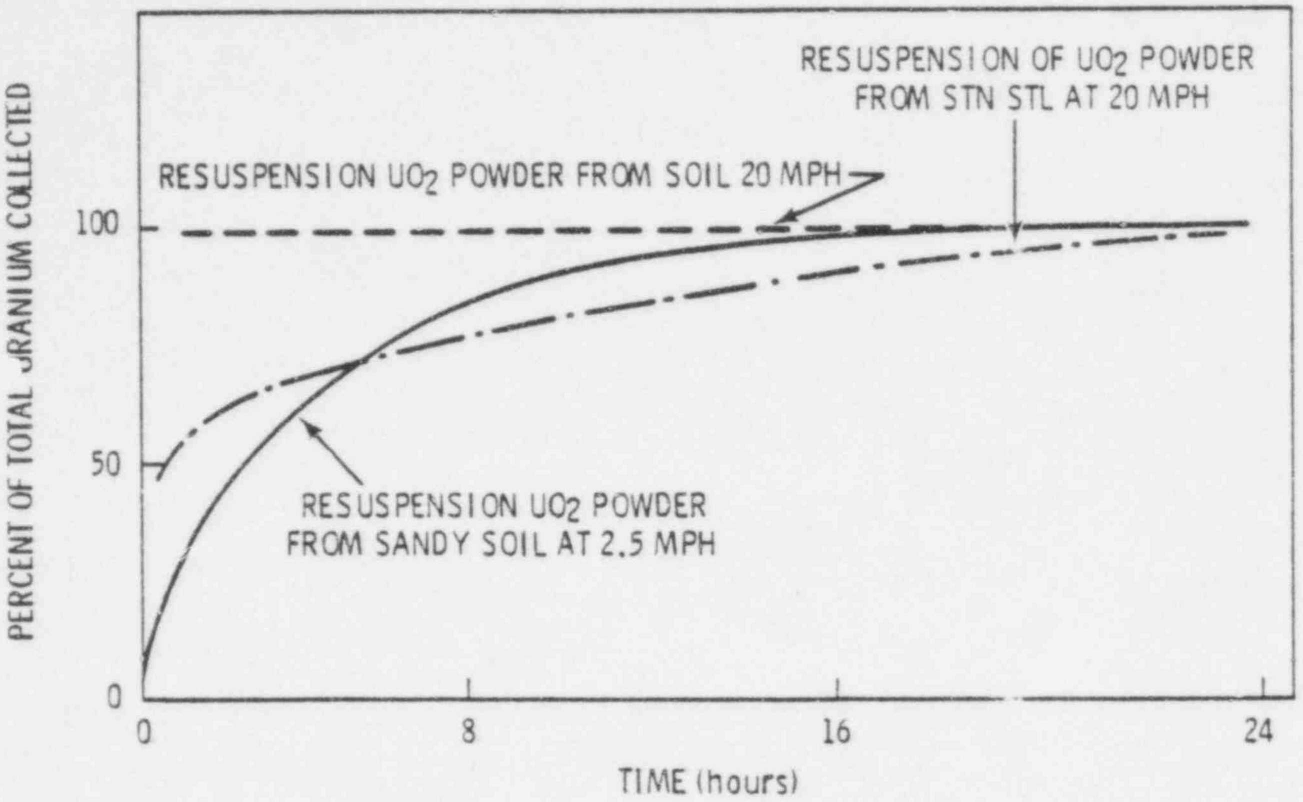

FIGURE A.7. Aerodynamic Entrainment of UO_2 Powder from Various Surfaces

TABLE A.4. Resuspension Fluxes (Mass Fraction UO_2 <10 μm AED Per Second) From Various Surfaces (Mishima and Schwendiman 1973)

	Uranium Dioxide Power		UNH Solution	
Surface	2.5 mph	20 mph	2.5 mph	20 mph
Smooth, sandy soil	6.7×10^{-6} 1.6×10^{-7} 2.5×10^{-8}	1.2×10^{-5} 6.8×10^{-5} 4.7×10^{-6}	1.1×10^{-6} 6.9×10^{-8} $3.5 \times 10^{-8(a)}$ $2.9 \times 10^{-8(a)}$	1.6×10^{-7} $1.4 \times 10^{-6(a)}$ $4.9 \times 10^{-6(a)}$
Vegetation cover	2.6×10^{-8}	2.8×10^{-6}	---	---
Stainless steel surface	2.6×10^{-6}	7.6×10^{-6}	---	2.6×10^{-6}

(a) Solid residues from air-dried UNH solutions.

TABLE A.5. Fractional Release During Air Drying of Concentrated Plutonium Nitrate Solutions (Using 0.72 g Plutonium as a Source) (Mishima, Schwendiman and Radasch 1968)

					Weight Percent Plutonium Found In:			
		Air	Sampling Time				Sweep Air	Sweep Air
Run No.	Temp. (°C)	Velocity (cm/sec)	Evap. (hr)	Residue (hr)	Containment Vessel Wash	Condensate + Wash	During Evaporation	Following Evaporation
N1(a)	Ambient	10	24	--	0.0033	8.7×10^{-3}	$<10^{-7}$	--
N2(a)	75	10	5	20	0.00027	9.5×10^{-8}	$<10^{-6}$	$<10^{-6}$
N3	100	10	2	4	0.0046	1.7×10^{-6}	0.001	3×10^{-7}
N4	Ambient	50	24	24	0.00035	4.5×10^{-7}	2.5×10^{-7}	1×10^{-7}
N5	100	50	1-1/2	3	0.027	1.4×10^{-4}	0.003	6×10^{-7}
N6	90	50	2	4-1/2	0.00051	5.4×10^{-6}	5.3×10^{-5}	1×10^{-6}
N7	Ambient	100	24	24	0.020	7.5×10^{-8}	$<2 \times 10^{-8}$	$<2 \times 10^{-8}$
N8	50	100	2	4	0.00045	9.4×10^{-6}	1.3×10^{-5}	$<2 \times 10^{-8}$
N9	90	100	1-1/2	4	0.00013	9.4×10^{-5}	5.7×10^{-5}	3×10^{-6}

(a) 0.86 g plutonium used during these runs.

TABLE A.6. Calculated Resuspension Fluxes for Plutonium Nitrate from Stainless Steel (Mass Fraction/Second) (Mishima, Schwendiman and Radasch 1968)

Air Velocity cm/sec	Temperature	Plutonium Nitrate Solution	Air-Dried Residue From Plutonium Nitrate Solution
10	Ambient	$<6.9 \times 10^{-13}$	$<8.3 \times 10^{-12}$
	75°C	$<3.3 \times 10^{-11}$	$<1.2 \times 10^{-11}$
	100°C	8.3×10^{-8}	
50	Ambient	1.7×10^{-12}	6.9×10^{-13}
	90°C	4.4×10^{-4}	3.7×10^{-11}
	100°C	3.3×10^{-7}	3.3×10^{-11}
100	Ambient	$<1.4 \times 10^{-13}$	$<1.4 \times 10^{-13}$
	50°C	1.0×10^{-9}	$<8.3 \times 10^{-13}$
	90°C	3.8×10^{-7}	1.2×10^{-10}

and Sehmel (1974) reported resuspension fluxes of 1 to 7.7×10^{-8}/sec of DDT deposited in wooded areas. Sehmel and Lloyd (1974) measured the resuspension fluxes of an inert, submicron powder deposited on sandy soil with a light cover of vegetation. Fluxes ranged from 10^{-8} to 10^{-10}/sec for all material in the cowled cascade impactor and were a nonlinear function of wind speed. Average rate during the four-month experimental period was 10^{-10}/sec.

The choice of a resuspension flux for powders and liquids released but not made airborne is difficult. The material could be distributed on a variety of surfaces (metal, concrete, soil with or without vegetation, etc.). The roughness of the surfaces can vary greatly (smooth concrete slabs to very coarse rubble) providing varying degrees of shielding for the deposited material. If the deposited material is buried under debris and equipment, the quantity resuspended could be negligible.

Sehmel and Lloyd's (1974) value of 10^{-8} fraction/sec seems most useful for powders. This value represents the higher fluxes obtained at a variety of wind speeds over an appreciable time period. The value is in the range of the DDT values that represent particulates that are deposited on vegetation in the canopy layer. Mishima, Schwendiman and Radasch's data (1968) are for air velocities at one foot above the surface and should be considered to be equivalent data for much higher velocities measured at the usual height. The data for resuspension from soil agree in general with Sehmel and Lloyd's data in the same wind speed range. The data presented by Mishima and Schwendiman (1973) also indicate higher resuspension fluxes from hard, impermeable surfaces (stainless steel and asphalt) but, under the situations considered, such surfaces are either enclosed and have greatly diminished air velocities) or have a high potential to be covered by debris. Thus, a resuspension flux of 10^{-8} fraction/sec was chosen for powders under air conditions limited by this study.

The choice of an overall resuspension flux for liquids for this study is more difficult. There are no directly measured fluxes as there are for solid particles. The mobility of the material means greater or lesser accessibility to air passing over the surface, depending upon the characteristics of the substrate. The resuspension rates for liquids (concentrated uranium and plutonium nitrate solutions) span seven orders of magnitude--from 1×10^{-6}/sec for UNH from smooth, sandy soil at 2.5 mph, to $<1 \times 10^{-13}$/sec for plutonium nitrate from a stainless steel dish at 100 cm/sec (2.2 mph). Both velocities are much lower than wind speeds measured at the normal height (10 m). It is anticipated that the resuspension rate for liquids should be lower than for a dry powder under comparable conditions due to the liquid surface tension. Thus, a value of 10^{-9} fraction/sec was selected. The rate is believed to be conservative by up to orders of magnitude and is applicable to the air-dried residues for spilled solutions.

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APPENDIX B

CALCULATION OF RELEASE TO THE ATMOSPHERE FROM PERFORATED ENCLOSURES AND ROOMS

by T. C. Kerrigan

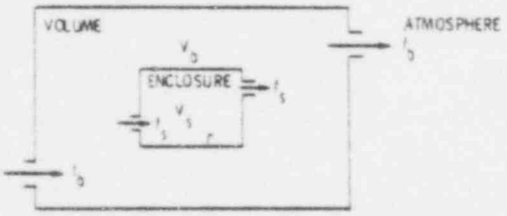
CALCULATION OF RELEASE TO THE ATMOSPHERE FROM PERFORATED ENCLOSURES AND ROOMS

by T. C. Kerrigan

The release rate and source term (total quantity of Pu released) from Scenarios 1 and 3 are estimated by circulating the Pu mass airborne concentration in the PAL and AFL as a function of time and of the exchange rate from the areas in question to the atmosphere. For the purposes of this study, an exchange rate of 10% of the enclosed volume per hour was assumed in the absence of any strong force (such as mechanical blowers) to induce flow.

The Pu airborne concentration in an area surrounding a breached enclosure was calculated from the quantity of Pu released from the enclosure (which is again the airborne concentration of Pu in the enclosure times the exchange rate) minus the quantity released to the atmosphere divided by the volume of the room. The airborne concentration within the enclosure was calculated from the quantity of Pu initially suspended plus the quantity carried into the enclosure from the room and resuspended from the surface minus the quantity released to the room air divided by the volume of the enclosure.

The system can be represented as a small box (enclosure) in a big box (room) with air from the big box flowing through the little box, and air from the big box being exchanged with the atmosphere. The system is shown schematically in Figure B.1.



V_s = VOLUME OF THE SMALL BOX, m^3
V_b = VOLUME OF THE BIG BOX, m^3
f_s = FLOW IN AND OUT OF THE SMALL BOX, m^3/min
f_b = FLOW IN AND OUT OF THE BIG BOX, m^3/min
r = RATE OF RESUSPENSION IN THE SMALL BOX, g Pu/min

FIGURE B.1. Flow Paths from Enclosure and PAL Structure

Let $C_s(t)$ and $C_b(t)$ denote the concentrations in the small and big boxes at time t. These concentrations can be estimated by solving the following system of equations:

$$\begin{aligned} \frac{d}{dt}\left[V_s C_s(t)\right] &= r + f_s C_b(t) - f_s C_s(t) , \\ \frac{d}{dt}\left[V_b C_b(t)\right] &= f_s C_s(t) - f_s C_b(t) - f_b C_b(t) \end{aligned} \tag{1}$$

These equations are simplified statements of the mass balance in the boxes. Rewriting in matrix notation,

$$\frac{d}{dt}\begin{bmatrix} C_s(t) \\ C_b(t) \end{bmatrix} = \begin{bmatrix} -f_s/V_s & f_s V_s \\ f_s/V_b & -(f_s + f_b)/V_b \end{bmatrix} \begin{bmatrix} C_s(t) \\ C_b(t) \end{bmatrix} + \begin{pmatrix} r/V_s \\ 0 \end{pmatrix}$$

Next, make the following substitutions in order to cast this system in general form. Set

$$x_1 = C_s, \quad x_2 = C_b, \quad y_1 = r/V_s, \quad y_2 = 0, \quad a = -f_s/V_s,$$

$$b = f_s/V_s, \quad c = f_s/V_b, \quad d = -\left(f_s + f_b\right)/V_b$$

Thus,

$$\dot{x} = Ax + y$$

where

$$x = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}, \quad y = \begin{pmatrix} y_1 \\ y_2 \end{pmatrix}, \quad \text{and} \quad A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

The solution of this system is an easy application of the theory of systems of linear ordinary differential equations (Rabenstein 1966, p. 431). In order to expedite this application, we simply hypothesize a solution of the form

$$x(t) = c_1 e^{\lambda_1 t} \begin{pmatrix} v_{11} \\ v_{12} \end{pmatrix} + c_2 e^{\lambda_2 t} \begin{pmatrix} v_{21} \\ v_{22} \end{pmatrix} + \begin{pmatrix} w_1 \\ w_2 \end{pmatrix}$$

and proceed to evaluate the parameters in terms of given information.

- <u>To find λ_1, λ_2:</u>

Define $\mathrm{Tr} = a + d$ and $\mathrm{Det} = ad - bc$. Then λ_1 and λ_2 are known to be the solutions of the equation

$$\lambda^2 \quad \mathrm{Tr}\,\lambda + \mathrm{Det} = 0$$

These solutions are given by

$$\frac{\mathrm{Tr} \pm \sqrt{\mathrm{Tr}^2 - 4\,\mathrm{Det}}}{2}$$

- <u>To find v_{i1}, $v_{i2}(i = 1,2)$:</u>

The vector $\begin{pmatrix} v_{i1} \\ v_{i2} \end{pmatrix}$ is known to satisfy

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} v_{i1} \\ v_{i2} \end{pmatrix} = \lambda_i \begin{pmatrix} v_{i1} \\ v_{i2} \end{pmatrix}$$

Thus,

$$v_{i1} = \frac{b}{\lambda_i - a} = \frac{\lambda_i - d}{c} \text{ and } v_{i2} = 1$$

- <u>To find w_1 and w_2:</u>

  $\dot{x}(t) = Ax(t) + y$ implies that

$$A \begin{pmatrix} w_1 \\ w_2 \end{pmatrix} + y = 0$$

Thus,

$$\begin{pmatrix} w_1 \\ w_2 \end{pmatrix} = - A^{-1} y$$

where

$$A^{-1} = \frac{1}{DT} \begin{pmatrix} d & -b \\ -c & a \end{pmatrix}$$

- <u>To find c_1, c_2:</u>

$$x(t) = c_1 e^{\lambda_1 t} \begin{pmatrix} v_{11} \\ v_{12} \end{pmatrix} + c_2 e^{\lambda_2 t} \begin{pmatrix} v_{21} \\ v_{22} \end{pmatrix} - A^{-1} y$$

implies that

$$x(0) = c_1 \begin{pmatrix} v_{11} \\ v_{12} \end{pmatrix} + c_2 \begin{pmatrix} v_{21} \\ v_{22} \end{pmatrix} - A^{-1} y ,$$

or

$$x(0) + A^{-1}\ y = \begin{pmatrix} v_{11} & v_{21} \\ v_{12} & v_{22} \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$$

Thus,

$$\begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} v_{11} & v_{21} \\ v_{12} & v_{22} \end{pmatrix}^{-1} \left[x(0) + A^{-1}\ y\right] ,$$

where

$$\begin{pmatrix} v_{11} & v_{21} \\ v_{12} & v_{22} \end{pmatrix}^{-1} = \frac{1}{v_{11}v_{22}-v_{12}v_{21}} \begin{pmatrix} v_{22} & -v_{21} \\ -v_{12} & v_{11} \end{pmatrix}$$

In conclusion,

$$C_s(t) = C_{s1}\ e^{\lambda_1 t} + C_{s2}\ e^{\lambda_2 t} + C_{s3}$$

and

$$C_b(t) = C_{b1}\ e^{\lambda_1 t} + C_{b2}\ e^{\lambda_2 t} = C_{b3}$$

where

$$C_{s1} = c_1 v_{11}, \quad C_{s2} = c_2 v_{21}, \quad C_{s3} = w_1$$

and

$$C_{b1} = c_1 v_{12}, \quad C_{b2} = c_2 v_{22}, \quad C_{b3} = w_2$$

C_{si}, C_{bi} for i = 1, 2, 3 and λ_i for i = 1, 2 were computed using the computer program shown in Table B.1. The input values for Scenarios 1 and 3 are given in Table B.2.

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TABLE B.1. Symoblic Reference MAP (R=1)

```
PROGRAM MISH          74/74    OPT=1

                PROGRAM MISH (INPUT,OUTPUT)
                DO 5 J=1,2
                READ *,VS,VB,FS,FB,R,CS0,CB0
                A=-(FS/VS)
                B= FS/VS
                C=FS/VB
                D=-((FS+FB)/VB)
                Y1=R/VS
                Y2=0.
                X10=CS0
                X20=CB0
                TR=A+D
                DET=A*D-B*C
                DISC=SQRT(TR*TR-4.*DET)
                XLAM1=0.5*(TR+DISC)
                XLAM2=0.5*(TR-DISC)
                V11=(XLAM1-D)/C
                V12=1.
                V21=(XLAM2-D)/C
                V22=1.
                DUM=1./DET
                AI=DUM*D
                BI=-DUM*B
                CI=-DUM*C
                DI=DUM*A
                S=-(AI*Y1+BI*Y2)
                T=-(CI*Y1+DI*Y2)
                DUM=1./(V11*V22-V12*V21)
                V11I=DUM*V22
                V12I=-DUM*V12
                V21I=-DUM*V21
                V22I= DUM*V11
                XS=X10-S
                XT=X20-T
                COF1=V11I*XS+V21I*XT
                COF2=V12I*XS+V22I*XT
                CS1=COF1*V11
                CS2=COF2*V21
                CS3=S
                CB1=COF1*V12
                CB2=COF2*V22
                CB3=T
                PRINT 1,XLAM1,XLAM2
              1 FORMAT(1H0,*LAM1,LAM2=*,2E12.6)
                PRINT 2,CS1,CS2,CS3
              2 FORMAT(1H0,*CS1,CS2,CS3=*,3E12.6)
              5 PRINT 3,CB1,CB2,CB3
              3 FORMAT(1H0,*CB1,CB2,CB3=*,3E12.6)
                END
```

TABLE B.2. Program Input

Definitions	Scenario 1	Scenario 3
V_s • Volume of small box m^3	16.6 m^3	37 m^3
V_B • Volume of big box, m^3	226 m^3	1250 m^3
F_s • Flow through small box, m^3/min	0.028 m^3/min	0.062 m^3/min
F_s • Flow through big box, m^3/min	0.38 m^3/min	2.08 m^3/min
R • Resuspension rate, g Pu/min	6 x 10^{-6} g Pu/min	7.5 x 10^{-4} g Pu/m
C_{so} • Initial Pu concentration in small box, g Pu/m^3	1.3 x 10^{-3} g Pu/m^3	2.4 x 10^{-3} of Pu/m^3
C_{Bo} • Initial Pu concentration in big box, g Pu/m^3	0	0

REFERENCES

Rabenstein, A. L. 1966. *Introduction to Ordinary Differential Equations*. Academic Press, New York.

APPENDIX C

DOSE FACTORS FOR INHALATION AND DOSE CALCULATION RESULTS FOR CLASS W PLUTONIUM

DOSE FACTORS FOR INHALATION AND DOSE CALCULATION
RESULTS FOR CLASS W PLUTONIUM

TABLE C.1. Fifty-Year Committed Dose Equivalent Factors from Acute Inhalation for Class W Material(a)

	(rem per µg inhaled)				
Isotope	Total Body	Kidneys	Liver	Bone	Lungs
^{238}Pu	1.2E+3(b)	4.8E+3	1.5E+4	2.4E+4	9.2E+2
^{239}Pu	4.6E+0	1.9E+1	5.9E+1	9.7E+1	3.0E+0
^{240}Pu	1.7E+1	6.9E+1	2.2E+2	3.6E+2	1.1E+1
^{241}Pu	1.3E+2	6.1E+2	1.8E+3	3.2E+3	1.8E+0
^{242}Pu	2.8E-1	1.1E+0	3.6E+0	5.7E+0	1.8E-1
^{241}AM	2.0E+2	1.5E+3	3.2E+3	5.2E+3	1.7E+2

(a) Committed dose equivalent factors calculated using DACRIN for 1-µm AMAD (Activity Median Aerodynamic Diameter) size particles. Organ masses are those reported in ICRP-23.

(b) Notation: 1.2E+3 is equivalent to 1.2×10^3.

TABLE C.2. Fifty-Year Committed Dose Equivalent Factors from Acute Inhalation for Class Y Material

	(rem per µg inhaled)				
Isotope	Total Body	Kidneys	Liver	Bone	Lungs
^{238}Pu	4.3E+2	1.8E+3	5.8E+3	8.9E+3	9.0E+3
^{239}Pu	1.7E+0	7.1E+0	2.3E+1	3.7E+1	3.0E+1
^{240}Pu	6.3E+0	2.6E+1	8.3E+1	1.3E+2	1.1E+2
^{241}Pu	4.3E+1	2.0E+2	6.0E+2	1.1E+3	9.6E+1
^{242}Pu	1.0E-1	4.3E-1	1.4E+0	2.2E+0	1.8E+0
^{241}Am	7.8E+1	5.6E+2	1.2E+3	1.9E+3	1.7E+3

TABLE C.3. Fifty-Year Committed Dose Equivalent Factors from One-Year Chronic Inhalation for Class W Material

	(rem per μg inhaled in first year)				
Isotope	Total Body	Kidneys	Liver	Bone	Lungs
^{238}Pu	1.2E+3	4.8E+3	1.5E+4	2.4E+4	9.2E+2
^{239}Pu	4.5E+0	1.9E+1	5.8E+1	9.7E+1	3.0E+0
^{240}Pu	1.7E+1	6.8E+1	2.2E+2	3.6E+2	1.1E+1
^{241}Pu	1.3E+2	6.1E+2	1.8E+3	3.2E+3	1.8E+0
^{242}Pu	2.8E-1	1.1E+0	3.6E+0	5.7E+0	1.8E-1
^{241}Am	2.0E+2	1.5E+3	3.2E+3	5.1E+3	1.7E+2

TABLE C.4. Fifty-Year Committed Dose Equivalent Factors from One-Year Chronic Inhalation for Class Y Material

	(rem per μg inhaled in first year)				
Isotope	Total Body	Kidneys	Liver	Bone	Lungs
^{238}Pu	4.3E+2	1.8E+3	5.7E+3	8.8E+3	9.0E+3
^{239}Pu	1.7E+0	7.0E+0	2.2E+1	3.6E+1	3.0E+1
^{240}Pu	6.2E+0	2.6E+1	8.2E+1	1.3E+2	1.1E+2
^{241}Pu	4.3E+1	2.0E+2	6.0E+2	1.0E+3	9.6E+1
^{242}Pu	1.0E-1	4.3E-1	1.4E+0	2.1E+0	1.8E+0
^{241}Am	7.7E+1	5.6E+2	1.2E+3	1.9E+3	1.7E+3

TABLE C.5. Fifty-Year Committed Dose Equivalents from Inhalation Following Damage, Scenario 1 (Class W)

Organ of Reference	Committed Dose Equivalents for: Population (person-rem) 5% Meteorology	Population (person-rem) 50% Meteorology	Nearest Residence[a] (rem) 5% Meteorology	Nearest Residence[a] (rem) 50% Meteorology
Total Body	3.2E+1	8.0E+0	3.8E-3	9.8E-4
Kidneys	1.4E+2	3.4E+1	1.6E-2	4.1E-3
Liver	4.2E+2	1.1E+2	5.0E-2	1.3E-2
Bone	7.0E+2	1.8E+2	8.4E-2	2.1E-2
Lungs	1.7E+1	4.2E+0	2.0E-3	5.2E-4

(a) Located 560 m WSW of the 102 Building.

TABLE C.6. Fifty-Year Committed Dose Equivalents from Inhalation Following Damage, Scenario 2 (Class W)

Organ of Reference	Committed Dose Equivalents for: Population (person-rem) 5% Meteorology	Population (person-rem) 50% Meteorology	Nearest Residence[a] (rem) 5% Meteorology	Nearest Residence[a] (rem) 50% Meteorology
Total Body	4.9E+1	1.2E+1	6.4E-2	1.7E-2
Kidneys	2.1E+2	5.0E+1	2.7E-1	7.1E-2
Liver	6.4E+2	1.6E+2	8.4E-1	2.2E-1
Bone	1.1E+3	2.6E+2	1.4E+0	3.7E-1
Lungs	2.6E+1	6.3E+0	3.4E-2	8.8E-3

(a) Located 560 m WSW of the 102 Building.

TABLE C.7. Fifty-Year Committed Dose Equivalents from Inhalation Following Damage, Scenario 3 (Class W)

	Committed Dose Equivalents for:			
	Population (person-rem)		Nearest Residence[a] (rem)	
Organ of Reference	5% Meteorology	50% Meteorology	5% Meteorology	50% Meteorology
Total Body	5.0E+3	1.2E+3	4.9E-1	1.2E-1
Kidneys	2.1E+4	5.2E+3	2.1E+0	5.2E-1
Liver	6.5E+4	1.6E+4	6.4E+0	1.6E+0
Bone	1.1E+5	2.7E+4	1.1E+1	2.7E+0
Lungs	2.6E+3	6.6E+2	2.6E-1	6.6E-2

(a) Located 560 m WSW of the 102 Building.

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