**Increment of Analysis
An Estimate of Airborne Release of
Plutonium from Babcock and
Wilcox Plant as a Result of Severe
Wind Hazard and Earthquake**

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October 1978

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Increment of Analysis

AIRBORNE RELEASE OF PLUTONIUM FROM BABCOCK AND WILCOX PLANT AS A RESULT OF SEVERE WIND HAZARD AND EARTHQUAKE

INTRODUCTION

This increment of analysis is a portion of an interdisciplinary study sponsored by United States Nuclear Regulatory Commission to estimate the potential radiological hazard to the general population as a result of the impact of natural phenomena upon existing commercial mixed oxide fabrication plants. This report covers the potential release of radionuclides from the Babcock and Wilcox Plant at Leechburg, Pennsylvania, due to wind hazard and earthquake.

Engineering Decision Analysis Company (EDAC) provided the description and condition of the facility.⁽¹⁾ Features whose failure might have a significant effect on the release of radioactive material were identified.⁽²⁾ The probability of various levels of wind hazard at the site was assessed by Fujita,⁽³⁾ while TERA provided the same service for the seismic potential.⁽⁴⁾ The potential response of the structure and contained equipment to the various degrees of wind hazard was provided by Texas Tech.⁽⁵⁾ and EDAC provided the analysis for the response to seismic events.⁽⁶⁾ These last two analyses provided the "damage scenarios" upon which the estimates of the potential airborne release of the contained radioactive material from the facility (source term) are based.

OBJECTIVE

The objective of this increment is to provide "realistic" estimates of the quantity of plutonium that may be made airborne as a result of the postulated damage scenarios and released to the ambient atmosphere around the facility. The estimated airborne releases form the basis for the calculated dose which is one component of the risk analysis that is the objective of the entire study. The primary concern in the calculation of downwind dose for this study is inhalation,⁽⁸⁾ and the primary emphasis in this increment will be the release of plutonium particulate material of a size range that can be carried downwind and inhaled. Particles 10 μ m Aerodynamic Equivalent Diameter^(a) (AED) or less are conservatively assumed to be the respirable fraction. Such an assumption overstates the potential effect by a factor of 1.5 to greater than an order of magnitude, depending upon the lung deposition model chosen.⁽⁷⁾ Finally, although a "realistic" estimate is desired, much of the behavior of the structure and equipment in accident situations is not precise and, faced with such uncertainties, the estimates of airborne releases tend to be conservative.

(a) Aerodynamic Equivalent Diameter - particles exhibiting the aerodynamic behavior of a unit density sphere of the stated size.

SUMMARY AND CONCLUSIONS

As part of an interdisciplinary study to evaluate the potential radiological consequences of wind hazard and earthquake upon existing commercial mixed oxide fuel fabrication plants, the potential mass airborne releases of plutonium (source terms) from such events are estimated. The postulated source terms become the basis for the estimation of potential dose by inhalation to the maximum individual and to the total population living within a prescribed radius of the plant. The "respirable fraction" of airborne particles is thus of principal concern.

The estimated source terms are based upon the fraction of enclosures damaged to three levels of severity (crush, puncture penetrate, and loss of external filter, in order of decreasing severity), called damage ratio, and the airborne release if all enclosures suffered that level of damage. In an attempt to provide a realistic range of potential source terms to include the vast majority of normal processing conditions, a "best estimate" bounded by an "upper" and "lower" limit is provided. The range of source terms was calculated by combining a "high," "best estimate," and "low" damage ratio based upon a decreasing fraction of enclosures suffering crush, with the airborne release from enclosures based upon an "upper limit," "on-the-average," and "lower limit" inventory of dispersible materials at risk. Factors used to evaluate the fractional airborne release of material and the exchange rates between enclosures and exterior atmospheres are discussed.

The discussion of damage scenarios and source terms is divided into wind hazard and earthquake scenarios in order of increasing severity.

The largest airborne releases from the building were for cases involving the catastrophic collapse of the roof over the major production areas--wind hazard at 110 mph and earthquakes with peak ground accelerations of 0.20 to 0.29 g. Wind hazards at higher air velocities and earthquakes with higher ground acceleration do not result in significantly greater source terms. The source terms were calculated as additional mass of respirable particles released with time up to 4 days; and, under these assumptions, approximately 98% of the mass of material of concern is made airborne from 2 hr to 4 days

after the event. The overall building source terms from the damage scenarios evaluated are shown in Table 1. The contribution of individual areas to the overall building source term is presented in order of increasing severity for wind hazard and earthquake.

TABLE 1. Estimated Mass Airborne Release of Plutonium from the Babcock and Wilcox Pu Plant in Leechburg, Pennsylvania, as a Result of Postulated Wind Hazard and Earthquake

Postulated Occurrence	Mass Airborne Release of Plutonium, mg, $\leq 10 \mu\text{m AED}$		
	Upper Limit WIND HAZARD	Best Estimate	Lower Limit
<ul style="list-style-type: none"> Nominal windspeed of 85 mph (38 m/sec), 1×10^{-2} per year probability of occurrence <ul style="list-style-type: none"> instantaneous additional mass released in next 2 hr additional mass released in next 6 hr additional mass released in next 16 hr additional mass released in next 3 days 	$1 \times 10^1, 1 \times 10^{1+}$ 3×10^1 8×10^1 2×10^2 9×10^2	$1 \times 10^1, 1 \times 10^{1+}$ 5×10^0 1×10^1 4×10^1 1×10^2	$1 \times 10^1, 1 \times 10^{1+}$ 5×10^0 1×10^1 4×10^1 1×10^2
<ul style="list-style-type: none"> Nominal windspeed of 95 mph (42.5 m/sec), 3×10^{-3} per year probability of occurrence 	(a)	(a)	(a)
<ul style="list-style-type: none"> Nominal windspeed of 110 mph (49 m/sec), 4×10^{-4} per year probability of occurrence <ul style="list-style-type: none"> instantaneous additional mass released in next 2 hr additional mass released in next 6 hr additional mass released in next 16 hr additional mass released in next 3 days 	$3 \times 10^2, 2 \times 10^{3+}$ 1×10^3 5×10^3 1×10^4 6×10^4	$1 \times 10^2, 3 \times 10^{2+}$ 1×10^2 4×10^2 5×10^2 2×10^3	$5 \times 10^1, 5 \times 10^{1+}$ 7×10^1 2×10^2 2×10^2 4×10^2
<ul style="list-style-type: none"> Nominal windspeed of 130 mph (58 m/sec), 2×10^{-5} per year probability of occurrence 	(a)	(a)	(a)

TABLE 1. (Contd.)

Postulated Occurrence	Mass Airborne Release of Plutonium, mg, $\leq 10 \mu\text{m AED}$		
	Upper Limit	Best Estimate	Lower Limit
	EARTHQUAKE		
• Peak ground acceleration levels of 0.015 to 0.04 g, 1.8×10^{-2} per year probability of occurrence at 0.025 g	(b)	(b)	(b)
• Peak ground acceleration levels of 0.08 to 0.16 g, 3.4×10^{-4} per year probability of occurrence at 0.13 g			
- instantaneous	-	-	-
- additional mass released in next 2 hr	5×10^{-3}	1×10^{-3}	6×10^{-4}
- additional mass released in next 6 hr	1×10^{-2}	3×10^{-3}	2×10^{-3}
- additional mass released in next 16 hr	2×10^{-2}	8×10^{-3}	3×10^{-3}
- additional mass released in next 3 days	-	-	-
• Peak ground acceleration levels of 0.20 to 0.29 g, 7.1×10^{-3} per year probability of occurrence at 0.21 g			
- instantaneous	$3 \times 10^2, 2 \times 10^{3\dagger}$	$1 \times 10^2, 3 \times 10^{2\dagger}$	$5 \times 10^1, 5 \times 10^{1\dagger}$
- additional mass released in next 2 hr	1×10^3	1×10^2	7×10^1
- additional mass released in next 6 hr	5×10^3	4×10^2	2×10^2
- additional mass released in next 16 hr	1×10^4	5×10^2	2×10^2
- additional mass released in next 3 days	6×10^4	2×10^3	4×10^2
• Peak ground acceleration levels greater than 0.3 g, less than 3.5×10^{-5} per year probability of occurrence	(a)	(a)	(a)

† mass Pu released from facility as airborne particulate material

(a) no additional damage postulated that results in the airborne release of significant quantities of plutonium

(b) no damage postulated, resulting in the airborne release of significant quantities of plutonium

FACILITY DESCRIPTION AND AREAS OF CONCERN

The two radioactive materials involved in the process in significant quantities are plutonium and normal uranium. Of the two, plutonium is by far the more radiologically significant.⁽²⁾ The process operations involving plutonium are located in FAB-1 and FAB-6⁽²⁾ (see Figure 1). Nuclear materials not involved in the process are stored in the NMV storage area (vault). Packaged contaminated materials are temporarily stored in Warm Equipment Storage prior to disposal.

The quantity of plutonium at all locations within the facility is shown in Table 2. Additional pertinent information is also tabulated for the various areas, and the table is more definitive and informative than that given in reference (2). The normal quantity and the chemical and physical form of the plutonium in the FFTF line in the FAB-1 area are also tabulated. Since the FFTF line is a production line, the quantity and hours that quantity are manipulated per month to attain a production rate of 1000 rods are used to calculate a "duty cycle" -- an indication of the probability of plutonium in jeopardy from inadvertent events. But the "duty cycle" alone cannot be used as an index of relative hazard. The objective of the study is to assess the potential radiological impact to the downwind population and, thus, the "dispersibility" (ability to be entrained and transported downwind) and the relative radiological importance of the material in jeopardy must be considered. The boxes holding undiluted plutonium are of greater significance than those holding mixed oxides since the radiological impact of the material injected into the air is much larger if these boxes are subjected to the same forces as the same boxes holding the same quantity of mixed oxides in the same forms. Under most circumstances, pre-formed powders are more easily injected into the air than other physical forms when subjected to equal force. For the boxes listed in the FFTF line, manipulation of undiluted, pre-formed plutonium dioxide powder are conducted only in box #110A (inlet to transfer channel to the blending box). Operations in all other boxes involve a diluted $\text{PuO}_2(\text{MO})$ powder or a diluted PuO_2 in a form more difficult to disperse.

FIGURE 1. Plan View of Babcock and Wilcox's Pu Plant

TABLE 2. Identification of Work Areas and Enclosures (Duty Cycle for Plutonium)

FAB-1 FFTF LINE

Box No.	Criticality Control Limit (kg)		Normal Amount (kg)	Material at Risk Form	1000 Rods/Mo Production Rate		
					Kg Pu at Risk	Total Hr/Mo	Kg Hr/Mo
110A	15.9	PuO ₂	14.0	PuO ₂	6.2	22.5	139.5
110B	Geometry control		19.0	PuO ₂	0	0	0
175	12.5 fissile		11.0	MO	3.3	26.8	89.8
176A	45	MO	28.0	MO	1.3	63.3	81
176B	68	MO	56.0	MO	7.3	32.0	233.6
176C	Geometry control		(b)	MO	0	0	0
177	53	MO	9.3	MO	1.2	32	38.4
178	68	MO	56	MO	7.3	32	233
179	68	MO	56	MO	6.7	9	60
180	53	MO	8	MO & pellets	2.5	144	364.5
181	53	MO	33.5	MO pellets	2.9	16	45.6
182	53	MO	11.5	MO pellets ^(a)	0	0	0
183	53	MO	25.0	MO pellets ^(a)	0	0	0
1	53	MO	25	MO pellets	0	0	0
184	53	MO	34	Sintered MO pellets	8.6	96	824
185/185A	53	MO	0.3	Sintered MO pellets	0.3	135	38.6
186	53	MO	1.4	Sintered MO pellets	1.4	160	229

(a) Pellets in moly boats with boat covers are not considered as exposed material at risk.

(b) Material in storage vaults range in size from 55 to 275 kg of MO.

TABLE 2. (Contd.)

FAB 1-FFTF LINE

Box No.	Criticality Control Limit (kg)		Normal Amount (kg)	Material at Risk Form	1000 Rods/Mo Production Rate		
					Kg Pu at Risk	Total Hr/Mo	Kg Hr/Mo
187	53	MO	48	Sintered MO pellets	.27	.33	.09
188	53	MO	30	Sintered MO pellets	1.4	207	280
189	53	MO	50	Sintered MO pellets	.27	.33	.09
190	53	MO	50	Sintered MO pellets	2.3	133	304
124B	Geometry control		(b)	0	0	0	0
124A	53	MO	5	0	0	0	0
126	11	MO	5	Sintered MO pellets	0.75	48	36
135	Glovebox	Not in use ^(a)		0	0	0	0
171	Geometry control		.5 Pu	MO sintered powder	2.5	4	10
40 41	Geometry control		1.4 Pu	MO pellets in rods	1.44	80	115.2
42 46	Geometry control		.7 Pu	MO pellets in rods	1.4	40	57.5
43	Geometry control		3.6 Pu	MO pellets in Rods	3.6	128	461

(a)Glovebox 135, not in use to process FFTF fuel. Box was used to sieve mixed oxide, has since been eliminated as a process requirement.

(b)Material in storage vaults range in size from 5 to 30 kgs MO.

TABLE 2. (Contd.)
FAB-1 CONVERSION FACILITY(a)

Glovebox No.	Criticality Control Limit (kg)	Normal Amount (kg)	Material at Risk Form	8 kg Pu/Mo Production Rate		
				Kg Pu at Risk	Total Hr/Mo	Kg Hr/Mo
123	Geometry control	3 Pu	0	0	0	0
105	Geometry control	.4 Pu	Pu Oxalate	.4	31.5	12.6
168	2.6 fissile	.5 Pu	Pu Oxalate ^(b) in stainless steel filters			
104		1.5 Pu	PuO ₂	1.5	3.5	5.25
106		3 Pu	PuO ₂	3	7	21
107		3 Pu	PuO ₂	3	7	21
108	Glovebox not in use --		0	0	0	0

(a) The material at risk shown in this table is based on operating the Conversion Facility on a one shift operation. When used in conjunction with the Scrap Recovery plant to recover scrap from the FFTF fuel, the operating time of the facility is dependent on how much scrap is reprocessed. Typically, the FFTF fuel contract for 35,000 fuel pins will generate 25 kg of Pu for scrap recovery. Hence, the Conversion Facility would operate about 3 months out of 3 years. Scrap Recovery and Conversion would not operate at the same time but alternate on a month-to-month basis.

(b) Pu oxalate is contained in stainless steel filter canisters. Normally 6 canisters are accumulated before processing for a calcine run. Average residence time is 2 days (48 hr). Since material is contained in the filter canister, material is not considered at risk.

TABLE 2. (Contd.)

CHEMICAL LABORATORY

<u>Box Number</u>	<u>Criticality Fissile Limit (kg)</u>	<u>Normal Amount Fissile (kg)</u>	<u>Kg-Hr(1) Fissile</u>
Assay room bench	.025	.015	.120
Hood 912, 913, 914, GB 165	.250 total	.100	.80
Chem Lab bench Boxes 162, 163, 164, hood 917	.075 .100 total	.050	.40
901 thru 910	.025	.015	.120
150	.250	.075	.6
153 & 154	.250	.075	.6
152 & hood 916	.250	.050	.4
Sample bench	.250	.025	.2

(1) Normal amount present at all times during production.
Kg-hr for an 8-hr day.

TABLE 2. (Contd.)

FAB-2

<u>Box No.</u>	<u>Limit (kg Fissile)</u>	<u>Normal Amt. (kg Pu)</u>	<u>At Risk (kg Pu)</u>
200	0.50	.025	.025
TG	.100	.025	.025

FAB-3

(155+169)	0.250	0.100	0.100
(310+311)	0.250	0.100	0.100
313	0.250	0.100	0.100
Met Lab	0.250	0.100	0.100
Radio Chem	Low level waste	0	0

FAB-7

Tables	Geom. control	1.0	0.0
Leak det.	Geom. control	3.0	0.0
701	11.3	5.0 ⁽⁰⁾	0.0
702	11.3	5.0 ⁽⁰⁾	0.0

(1)Gloveboxes 701 and 702 are only used about 4 shifts per month during FFTF production.

TABLE 2. (Contd.)
FAB-6 SCRAP RECOVERY^(a)

<u>Box No.</u>	<u>Limit (kg Fissile)</u>	<u>Normal Amount (kg Pu)</u>	<u>Kg-Hr Duty Cycle</u>
601	2.6	2.6 (Fissile)	.3 (Pu) ^(b)
602 + 603	5.0 (MO)	5.0 (MO)	0.0
604	Geom. control (0.1 kg/L)	1.1/column	0.0
605	Geom. control (0.215 kg/L)	3.0	0.0
607	Geom. control (0.215 kg/L)	0.0	0.0
Wall columns	Geom. control (0.215 kg/L)	1.5/column	0.0
Ring filled	0.220 kg/L	25 mg/[47 g/tank]	0.0
610	Geom. Control	0.100	0.0

(a) Scrap Recovery normally will operate to process FFTF scrap. Typical quantities of scrap generated for a 35,000 fuel pin contract in 25 kgs of Pu. For a one-shift operating schedule total operating time would be 2.5 months for a contract period (typically 3 years).

(b) Charge make-up per shift. 1 kg charge at 20% Pu, 1/2 hr to make up 3 charges, make up 6 charges per day.

TABLE 2. (Contd.)

FABS-8 & -9

<u>Box No.</u>	<u>Limit (kg Fissile)</u>	<u>Normal Amt. (kg Pu)</u>	<u>At Risk (kg Pu)</u>
Warm equipment	0.250	0.250	0.0
Warm maintenance	0.250	0.250	0.0
Room 110	0.250	0.250	0.0
Room 105	2.6 kg/cubicle	2.6 kg/cubicle	0.0
Room 106 (CB)	5.0 (MO)	5.0 (MO)	0.0
Room 106 (drums)	0.064 g/drum	0.064/drum	0.0
Ship. cont. (24)	120 pin/cont.	120 pin/cont.	0.0
Ship load	120 pin	120 pin	0.0
QC insp. table	Geom. control	100 pin/table	0.0
Counting table	Geom. control	100 pins	0.0
Room 129	Geom. control	1500 pins	0.0
131-W	Geom. control	100 pins	0.0
Room 120	Geom. control	100 pins	0.0
Shipping	12 Ship. Cont.	120 pins/cont.	0.0

The conversion facility is located in the north end of the FAB-1 area (see Figure 2) and is normally operated on an alternating basis with the scrap recovery facility in the FAB-6 area. For a typical FFTF run, both areas would operate 3 months in 3 years or 1 month each year. The "duty cycle" in Table 2 is for that month of operation and should be reduced by a factor of 12 for proper perspective. Boxes #106 and #107 both handle PuO_2 powders and show the highest "duty cycle" in this process step. Neither approaches the "duty cycle" for box #110A.

The quantities present in the Chem. Lab. west of the FAB-1 area (see Figure 1) are small but constant. The "duty cycle" listed is for a normal 8-hr day and would be a factor of 20 higher calculated on a per month basis. The forms range from PuO_2 powder to mixed oxide (MO) solutions. The indication is that a small quantity of plutonium would be in jeopardy at any time during the normal 8-hr work day, but the quantity and form present indicate this area is of less significance than the production areas.

FAB-2, -3, -4, and -5 enclosures are used infrequently or hold very limited quantities of fissile material.

Scrap Recovery is conducted in the gloveboxes located in the south end of FAB-6 area (see Figure 3). The operating period for production (FFTF) scrap is estimated to be 2-1/2 months (8-hr work day) in 3 years on an alternating basis with the Conversion Facility in the FAB-1 area. The activity within the enclosures is limited, but the wall columns that are used for storage of plutonium solutions are in use at a higher frequency during the limited operational cycle.

Solid scrap (greater than 95% MO powders and pellets with the remainder PuO_2 powder) enters the process in glovebox #601. After a charge (1 kg) is accumulated, the material is transferred to box #602 and dissolved in a stainless steel dissolver. Dissolved MO is termed "nitrate solution." The liquid is vacuum transferred to box #603, where the valence is adjusted for the ion exchange separation of uranium and plutonium. The liquid is then pumped via box #606 (Wall Tank Valve Glovebox) to one of 3 sets of 3 wall tanks at the north end of the 13 vessels on the east wall. The tanks are

FIGURE 2. Babcock and Wilcox Pu Plant, FAB-1 Floor Plan

FIGURE 3. Babcock and Wilcox Pu Plant, FAB-6 Floor Plan

5" diam 304 stainless steel sch 10 pipe 11' 10" tall with piping connections at the top and bottom. The tanks are attached to pedestals which elevate them 1.5 ft above the floor and are supported by attachment at their midpoint to a metal frame secured to the wall. It appears that the tanks would tend to act as a single unit under most circumstances. The capacity of a bank of 3 is 120 liters, but the tanks are set to alarm at 80% and thus the operational capacity is 96 liters. The solution is then fed to 3 ion exchange columns in box #604, where the plutonium is absorbed on the resin and the depleted solution and rinses are sent to the stainless steel concentrator in box #607 (Recycle Concentrator). The wastes, after analysis, are sent to the ring filled-tanks on the mezzanine or in the basement. The plutonium eluted from the resin columns is concentrated in the titanium vessel in box #605 (Product Evaporator) and the concentrated plutonium nitrate loaded into 10-liter polyethylene bottles held in appropriate containers for recycle through the system. The vacuum system for the facility is housed in glovebox #609. Box #610 is in the basement and is unaffected by the natural phenomena considered in this analysis.

The four wall tanks on the south end of the bank were initially used to store product solution (concentrated plutonium nitrate). The wall tanks shared piping, pumps, and valves with the feed tanks and resulted in contaminated product. These 4 tanks are no longer in service and only contain Pu contamination fixed to the interior surfaces.

The plutonium shown in other areas is contained (substantial outer containers plus inner packaging in the vault), as an encapsulated, difficult-to-disperse form (sintered pellet) of mixed oxide (fuel pins), as contamination on combustible materials, or as fixed contamination on non-combustible surfaces. All the aforementioned situations present much less vulnerability to airborne release than plutonium involvements in the process portion of the facility.

Other features in the facility were also noted in reference (2) as cause for concern-- the hydrogen and natural gas lines traversing the FAB-1 area,

all exhaust ducts, and the 1A gas cylinders. Both the hydrogen and natural gaslines have been removed.^(9,10) The failure of the other two items would be initiated by the failure of the structure.⁽⁴⁾

The gloveboxes in the FAB-1 and FAB-6 areas provide the primary containment for most of the plutonium of concern in this study. The plastic windows are the glovebox feature most susceptible to damage from falling debris (the flexibility and limited area for impact of the gloves makes them less susceptible than windows). The window area in the FAB-1 and FAB-6 areas are limited. The faces of the gloveboxes in FAB-6 are stainless steel with approximately 8" x 8" windows. The light windows on the top of the boxes appear to be their most vulnerable point. Approximately 1/8" thick lead sheets with 8" square cut-outs have been attached to the faces of all the gloveboxes in the FAB-1 area. Although of limited structural strength, the plasticity of the lead provides some protection from impact and some containment capability. Thus, although the windows remain the most vulnerable feature of gloveboxes, the probability of damage that could lead to the airborne release of contained materials is diminished.

APPROACH AND METHOD USED IN ESTIMATING SOURCE TERMS

The objective of this increment of analysis is to arrive at "realistic" estimates of the airborne plutonium release (in the respirable size range) that may result from the postulated damage scenarios for various severities of wind hazard and earthquake. The quantity of plutonium released to the ambient atmosphere is related to the quantity of plutonium made airborne in the enclosure by the event and the fraction of the material made airborne which is then released as a result of the loss of integrity of containment and the attenuation by other physical barriers separating the airborne material from the ambient atmosphere.

The quantity of material made airborne by the event depends on the type and level of stress imposed on the material, the quantity and characteristics of the material in jeopardy, and the mixing energy in the air volume in which the material is dispersed. The types and levels of force imposed are described in the damage scenarios^(5,6) and results in 3 levels of damage to the primary physical barriers (predominantly gloveboxes) that in turn are used as indices of stress applied to the contained material. The levels of damage also determine the fraction of airborne material released to the ambient environment.

DAMAGE LEVELS AND RATIOS

The three damage levels sustained by the enclosures are crush, puncture-penetrate, and loss of external High Efficiency Particulate Air (HEPA) filter. Crushing is considered the catastrophic failure mode for enclosures and is defined as an essentially complete loss of containment. For the responses described for this facility, the force required to crush an enclosure is generally only available when an enclosure is directly impacted by a metal roof joist bearing the weight of a significant part of the roof over its entire length (from side to side or end to end). Some of the force of such an impact is absorbed by the deformation of the metal with the remainder tearing or slicing the enclosure apart. If the deformation of the metal is sufficient, the windows of gloveboxes (especially in the FAB-1 gloveboxes with larger windows) can be "popped out" or lost, resulting in

essentially complete loss of containment even if the remainder of the glovebox remains intact. Since the enclosures are not anchored to the floor, impacts other than direct blows tend to cause the boxes to slide or topple rather than be crushed. If the metal roof joist strikes the wall prior to impact with the enclosure, a portion of the energy is absorbed by the contact and the energy remaining is probably insufficient to cause total loss of containment.

The "best estimate" for the fraction of enclosures within an area that are crushed is $1/4$ with a range of $1/8$ to $1/2$ for events resulting in the complete collapse of the roof over an area.⁽¹¹⁾

The moderate level of damage is termed puncture-penetrate and assumes a significant breach of integrity of an enclosure. Enclosures which are punctured or penetrated are assumed to have at least 2 openings of significant dimensions, one of which is the connection to which the external HEPA filter was attached. The other opening(s) can range in size from a part or all of a small window to a single puncture in which the projectile remains lodged. For the situations where collapse of the roof is postulated, all enclosures not assumed to be crushed nor having lost their external HEPA filter are considered to be punctured or penetrated.

The minimum level of damage postulated for an enclosure in an area suffering collapse of its roof is loss of its external HEPA filter resulting in a single unfiltered pathway with the dimension of the connection from the enclosure to the ambient atmosphere around the enclosure. The "best estimate" of the fraction of enclosures in an area that lose their external filters is $1/10$ with a range of $1/20$ to $1/5$.⁽¹¹⁾

INVENTORIES AT RISK

The quality and characteristics of the plutonium bearing materials in the enclosures in the four areas where plutonium is routinely manipulated were listed in Table 2. Some of the forms listed are not considered dispersible under the conditions postulated (i.e., pellets, sintered pellets, and pellets in rods) and their inventories are not considered at-risk. Furthermore, the duty cycles shown for the four areas are computed on 3 different bases--
1) the kg Pu normally present x the number of hours per month the inventory is

found in that enclosure for a continuous operation (FFTF Line), 2) the kg Pu normally present x the number of hours per month the inventory is found in that enclosure for the 1 month per year operational cycle (Conversion Facility and Scrap Recovery) and, 3) the normal inventory present x the number of hr per 8-hr shift the inventory is present in the enclosure (Analytical Laboratory). As an index of the availability of dispersible plutonium, the values listed in Table 2 can be deceptive. The inventories of dispersible plutonium-bearing material, the form of the dispersible material, and the duty-cycles calculated on the same basis for all enclosures in the four areas are listed in Tables 3a, 3b, 3c, and 3d. The values for duty-cycle have not been adjusted for non-operational periods (housekeeping, maintenance and repair, inventory clean-outs, etc.,) and are therefore conservative.

FRACTIONAL AIRBORNE RELEASE OF DISPERSIBLE MATERIAL

The quantity of materials injected into the air is a function of the physical form and characteristics of the dispersible material and the type and level of force imposed upon the material. The damage levels to enclosures and the type of forces are defined by the damage scenarios. The physical forms of the dispersible materials in the enclosures are listed in Table 2. Since it is postulated that the same incident (such as a metal roof joist striking an enclosure, etc.,) results in making the dispersible material airborne and compromising the integrity of the enclosure, it was postulated that the material is initially dispersed into the enclosed space and then released. The volume of all enclosures is assumed to be 2 m^3 (approx. 72 ft^3).

- Crushed Enclosures

It was assumed that all the material airborne in a crushed enclosure was released to the ambient atmosphere around that enclosure within minutes of the loss of containment (designated hereafter as an instantaneous release) and that the total inventory of dispersible materials at risk is subject to resuspension by the ambient wind field. The quantity of material for the various types of material present is described below.

TABLE 3a. Inventories at Risk, Duty-Cycles, and Airborne Releases for FFTF Line (FAB-1) Enclosures

Box No.	Form Dispersible Material at Risk	Pu at Risk(a) kg	Duty Cycle(b) kg Pu-hr/mo	Surface Contamination(c) g Pu	Airborne Release of Plutonium, mg		
					Instantaneous(d)	Time Dependent	Resuspension(e)
110A	PuO ₂ powder	6.2	139.5	49.3	52.8 ^(f)	52.8	223/hr
110B	PuO ₂ surface contamination	-	-	49.3	13.2	13.2	1.8/hr
175	MO powder	3.3	89.8	12.3	13.2 ^(g)	13.2	119/hr
176A	MO powder	1.3	81.	12.3	13.2 ^(g)	13.2	40.8/hr
176B	MO powder	7.3	233.6	12.3	13.2 ^(g)	13.2	263/hr
176C	MO surface contamination	-	-	12.3	13.2 ^(g)	13.2	0.4/hr
177	MO powder	1.2	38.4	12.3	13.2 ^(g)	13.2	43.2/hr
178	MO powder	7.3	233.	12.3	13.2 ^(g)	13.2	263/hr
179	MO powder	6.7	60.	12.3	13.2 ^(g)	13.2	241/hr
180	MO powder	2.5	364.5	12.3	13.2 ^(g)	13.2	90/hr
181	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
182	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
183	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
1	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
184	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
185/185A	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
186	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
187	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
188	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
189	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
190	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
124A	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
124B	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
126	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
135	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
171	MO powder	2.5	10.	12.3	13.2	13.2	90/hr
40	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
41	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
42	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
43	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr
46	MO surface contamination	-	-	12.3	3.3	3.3	0.4/hr

(a) Normal inventory for product rate of 1000 rods/mo.

(b) Based upon 3 shifts/day, 365d/year operation.

(c) Assume total interior contaminated area of 80 ft²/enclosure.

(d) Respirable fraction.

(e) Mass release for normal inventory.

(f) Total mass Pu release of 528 mg.

(g) Total mass Pu release of 132 mg.

TABLE 3b. Inventories at Risk, Duty-Cycles, and Airborne Releases for Conversion Facility (FAB-1) Enclosures

Box No.	Form Dispersible Material at Risk	Pu at Risk(a) kg	Duty Cycle(b) kg Pu-hr/mo	Surface Contamination(c) g Pu	Airborne Release of Plutonium, mg		
					Instantaneous(d)	Time Dependent	Resuspension(e)
123	PuO ₂ surface contamination	-	-	49.3	13.2	13.2	1.8/hr
105	Pu oxalate	0.4	1.05	49.3	52.8(f)	52.8	14.4/hr
168	PuO ₂ surface contamination	-	-	49.3	13.2	13.2	1.8/hr
104	PuO ₂ powder	1.5	0.44	49.3	52.8(f)	52.8	54/hr
106	PuO ₂ powder	3.	1.75	49.3	52.8(f)	52.8	108/hr
107	PuO ₂ powder	3.	1.75	49.3	52.8(f)	52.8	108/hr
108	PuO ₂ surface contamination	-	-	49.3	13.2	13.2	1.8/hr

(a) Normal inventory during operational cycle.

(b) Based upon 3 shifts/day, during 1 month operational cycle per year.

(c) Assumes total interior contaminated area of 80 ft²/enclosure.

(d) Respirable fraction.

(e) Mass release for normal inventory.

(f) Total mass Pu release of 528 mg.

TABLE 3c. Inventories at Risk, Duty-Cycles, and Airborne Releases for Analytical Laboratory Enclosures

Box No.	Form Dispersible Material at Risk	Pu at Risk(a) kg	Duty Cycle(b) kg Pu-hr/mo	Surface Contamination(c) g Pu	Airborne Release of Plutonium, mg		
					Instantaneous(d)	Time Dependent	Resuspension(e)
AB(f)	"nitrate solution"(i)	0.015	1.2	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
912	"nitrate solution"(i)	0.1	8.	21.7(k)	1.7(g)	1.7(j)	1.5/hr(l)
913	"nitrate solution"(i)	0.1	8.	21.7(k)	1.7(g)	1.7(j)	1.5/hr(l)
914	"nitrate solution"(i)	0.1	8.	21.7(k)	1.7(g)	1.7(j)	1.5/hr(l)
615	"nitrate solution"(i)	0.1	8.	21.7(k)	1.7(g)	1.7(j)	1.5/hr(l)
C.L.B.(g)	dried nitrate solution surface cont.	-	-	21.7(k)	5.8	5.8	0.78/hr
162	"nitrate solution"(i)	0.05	4.	21.7(k)	1.7(g)	1.7(j)	0.96/hr(l)
163	"nitrate solution"(i)	0.05	4.	21.7(k)	1.7(g)	1.7(j)	0.96/hr(l)
164	"nitrate solution"(i)	0.05	4.	21.7(k)	1.7(g)	1.7(j)	0.96/hr(l)
917	"nitrate solution"(i)	0.05	4.	21.7(k)	1.7(g)	1.7(j)	0.96/hr(l)
901	"nitrate solution"(i)	0.015	1.2	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
902	"nitrate solution"(i)	0.015	1.2	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
903	"nitrate solution"(i)	0.015	1.2	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
904	"nitrate solution"(i)	0.015	1.2	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
905	"nitrate solution"(i)	0.015	1.2	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
906	"nitrate solution"(i)	0.015	1.2	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
907	"nitrate solution"(i)	0.015	1.2	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
908	"nitrate solution"(i)	0.015	1.2	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
909	"nitrate solution"(i)	0.015	1.2	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
910	"nitrate solution"(i)	0.015	1.2	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
150	"nitrate solution"(i)	0.075	6.	21.7(k)	1.7(g)	1.7(j)	1.0/hr(l)
153	"nitrate solution"(i)	0.075	6.	21.7(k)	1.7(g)	1.7(j)	1.0/hr(l)
154	"nitrate solution"(i)	0.075	6.	21.7(k)	1.7(g)	1.7(j)	1.0/hr(l)
152	"nitrate solution"(i)	0.05	4.	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
916	"nitrate solution"(i)	0.05	4.	21.7(k)	1.7(g)	1.7(j)	0.83/hr(l)
SB(h)	"nitrate solution"(i)	0.025	2.	21.7(k)	1.7(g)	1.7(j)	0.87/hr(l)

(a)Normal inventory during operational periods.

(b)Based upon 1 shift/day, 365d/year.

(c)Assume total interior contaminated area of 80 ft²/enclosure.

(d)Respirable fraction.

(e)Mass release for normal inventory.

(f)Assay Room Bench.

(g)Chemical Laboratory Bench.

(h)Sample Bench.

(i)Nitric acid solution of average composition 0.44 Pu + 0.56 U.

(j)Release respirable fraction less than for surface contamination. Use surface contamination value (5.8 mg Pu). Total mass Pu release of 85 mg.

(k)Represents approx. 200 ml of "nitrate solution" and exceeds normal maximum inventory of half the enclosures in area.

(l)Mass release for normal inventory and surface contamination.

TABLE 3d. Inventories at Risk, Duty-Cycles, and Airborne Releases for Scrap Recovery (FAB-6) Enclosures

Box No.	Form Dispersible Material at Risk	Pu at Risk(a) kg	Duty Cycle(b) kg Pu-hr/mo	Surface Contamination(c) g Pu	Airborne Release of Plutonium, mg		
					Instantaneous(d)	Time Dependent	Resuspension(e)
601	MO powder	2.6	0.025	12.3	13.2 ⁽¹⁾	13.2	94/hr
602	MO surface contamination	(5.0) ^(g)	(3.0) ^(j)		3.3	3.3	18/hr
603	MO surface contamination				3.3	3.3	0.4/hr
604	MO surface contamination	-	-		3.3	3.3	0.4/hr
605	PuO ₂ surface contamination	(3.0) ^(h)	(18.) ^(j)	49.3	13.2	13.2	10.8/hr
606	MO surface contamination	-	-		3.3	3.3	0.4/hr
607	U surface contamination	-	-	-	-	-	-
609	MO surface contamination	-	-		3.3	3.3	0.4/hr
IX FEED(f)	Nitric acid solution of MO	(2.88) ⁽¹⁾	(18.) ^(j)	(k)	(m)	1.6	1.2/hr
PROD(f)	PuO ₂ surface contamination	-	-	(k)	(m)	0.27	(k)

(a) Normal inventory during operational periods.

(b) Based upon 3 shifts/day, during 1 month operation per year.

(c) Assumes total interior contaminated area of 80 ft²/enclosure.

(d) Respirable fraction.

(e) Mass release for normal inventory.

(f) Wall storage column, 9 IX FEED + 4 PROD.

(g) Nitric acid solutions of MO in stainless steel dissolver. Solution can leak from vessel.

(h) Nitric acid solution of Pu in titanium evaporator. Solution can leak from vessel.

(i) Nitric acid solution of MO, 320 g Pu per column.

(j) Estimated upon assumption material present 10% of time during operational periods.

(k) Wall columns not crushed but contents may leak out.

(1) Total mass airborne release Pu of 132 mg.

- Powders:

The quantity of plutonium made airborne during the crushing of a glovebox containing an exposed powder is estimated by:

$$\text{mg Pu released} = 300 \text{ mg/m}^3 \times \text{fraction Pu} \times \text{volume enclosure} \\ \times \text{fraction powder in respirable size range.}$$

A value of 300 mg/m^3 was selected for the transient airborne mass loading of enclosures during crushing. Mishima assigned a value of 100 mg/m^3 as the maximum quasi-stable airborne mass loading for plutonium dioxide within a few minutes.⁽¹²⁾ An airborne mass concentration of 10 g/m^3 was measured 5 sec after a container holding a fine UO_2 powder was tumbled (see Figure 4).⁽¹³⁾ The enclosures could be severely shaken by the impact of debris during and prior to crushing, but shaking is not nearly as effective a mechanism to inject particles into the air as tumbling. Since the situation is transient, a value 3 times larger than Mishima's quasi-stable value was selected.

Since the densities and size distributions of PuO_2 and UO_2 are relatively close, the same mass airborne loading can be used for enclosures holding PuO_2 and MO powders. Pu is the radiologically significant material and the plutonium contents of each are:

- PuO_2 , 0.88 Pu
- MO, $0.88 \times 0.20 = 0.176 \text{ Pu}$

The volume of the average enclosure is assumed to be (3 ft. x 8 ft. x 3 ft. = 72 ft^3) 2 m^3 . The size distribution for the PuO_2 powder is assumed to be adequately represented by the distribution reported by Schwendiman for the PuO_2 used in fuel fabrication and shown in Figure 5.⁽¹³⁾ The mass fraction of material $10 \text{ } \mu\text{m}$ A.E.D. (a conservative estimate of respirable particles) is 0.1. Therefore, the instantaneous release during the crushing of enclosures are:

FIGURE 4. Uranium Oxide Airborne over the Bulk Powder Following Disruption

FIGURE 5. Nominal PuO_2 Particle Size Distribution

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Pu • $300 \text{ mg/m}^3 \times 2 \text{ m}^3 \times 0.88 = 528 \text{ mg}$ Pu of which 52.8 mg is associated with particles $10 \text{ }\mu\text{m}$ AED or less

MO • $300 \text{ mg/m}^3 \times 2 \text{ m}^3 \times 0.176 = 132 \text{ mg}$ Pu of which 13.2 mg is associated with particles $10 \text{ }\mu\text{m}$ AED or less.

- Liquids:

All liquids in enclosures are held in some type of container (glass, plastic, metal, etc.). Liquids which are held in fragile containers (those that could be ruptured by the impact of debris) are assumed to be subdivided and made airborne. Those liquids held in more substantial containers (stainless steel dissolver, titanium evaporator, etc.,) are not assumed to be significantly subdivided but are assumed to leak from their containers and be available for resuspension. For the liquids held in fragile containers, it is assumed the entire volume of the enclosure is filled with a mass of respirable particles equivalent to the maximum mass concentration formed in nature--fog, 10 mg/m^3 --and size distribution is that of a coarse spray. Figure 6 is a plot of the cumulative mass fraction vs droplet diameters for hollow cone nozzles of orifice diameters ranging from 0.063" (1.6 mm) to 0.178" (3.25 mm) at various liquid upstream pressures.⁽¹⁴⁾ The orifice diameters appear small and the pressures high for the conditions envisioned for most situations resulting in the breaking of fragile containers. The distribution of the coarsest spray (0.128" diameter at 200 psig) indicates the mass of droplets $100 \text{ }\mu\text{m}$ or less is 50 times the mass of droplets $10 \text{ }\mu\text{m}$ and less. Particles $100 \text{ }\mu\text{m}$ in diameter could be carried beyond the remnants of the structure for the wind hazard scenarios and it was assumed that the airborne mass concentration of particles $100 \text{ }\mu\text{m}$ AED and less in the enclosure was 500 mg/m^3 . The volume of the enclosures is assumed to be 2 m^3 and, therefore, the mass of respirable and releasable particles are 20 and 1000 mg, respectively. *respirable = .02*

Plutonium separated from uranium is present in solution in only one enclosure (glovebox #605, Product Evaporation) and is not in jeopardy of airborne dispersal (the liquid is held in a titanium vessel). In all other enclosures, the plutonium and uranium are found together. The concentrations of Pu and U can vary, but assuming a more concentrated solution--a higher proportion of Pu and U to solvent in the mass airborne--is conservative.

FIGURE 6. Mass Fraction vs Droplet Diameters for Sprays as a Function of Orifice Diameter and Upstream Pressure

The most concentrated solutions of Pu and U routinely encountered contain in the range of 200 to 300 g of metal per liter. A concentration of 250 g metal per liter was chosen. The densities of such solutions are generally in excess of 1.3 g/cm^3 . A mass of 20 mg (respirable fraction) represents a volume of 0.015 cm^3 and would contain 3.85 mg of metal. The total airborne release of 1.0 g represents a volume of 0.769 cm^3 and represents a total mass release of metal of 192 mg. Routine process mixed oxides are assumed to have a Pu to U ratio of 1:3 and the Pu mass airborne release in the respirable fraction and total are 1.0 mg and 48 mg, respectively. The materials processed in the Analytical Laboratory are 75% routine process mixed oxides (MO) and 25% Pu compounds. Solutions in the Analytical Laboratory are assumed to contain 0.44 Pu instead of 0.25 to reflect the average plutonium mass present in area. The two airborne releases are 1.7 mg and 84.5 mg Pu, respectively.

- Surface Contamination

Airborne particulate material deposits on exposed surfaces due to various natural mechanisms--sedimentation, turbulent diffusion, electrophoresis, etc. For nuclear fuel cycle facilities in use for some period of time, the quantity of radioactive materials routinely found on contaminated surfaces can range from that which can only be removed by harsh, corrosive techniques to that which is readily visible to the unaided eye. Enclosures in fuel cycle facilities are periodically cleaned for housekeeping, maintenance and repair of equipment, and as a regulatory requirement to account for nuclear materials. Pu surface contamination levels of 0.3 to 0.5 g Pu/ft^2 have been measured in mixed oxide facilities after chemical decontamination and a value of $0.7 \text{ g PuO}_2/\text{ft}^2$ ($7.5 \text{ g PuO}_2/\text{m}^2$) has been reported as just visible.⁽¹⁵⁾ For the purposes of this study, the conservative assumption is made that the average enclosure is contaminated to the visible level. It is further conservatively assumed that the MO has the same particle size distribution as PuO_2 and exhibits the same aerodynamic behavior. Thus an average surface contamination level of 7.5 g MO/m^2 (1.65 g Pu/m^2) is also applied for enclosures used for MO processing. Each enclosure is postulated to have 80 ft^2 of internal, contaminated area yielding a total inventory of 49.3 g Pu for Pu processing enclosures and 12.3 g Pu for MO processing enclosures as a powder lying on the surface.

The ratio of the contamination dislodged and made airborne during the crushing of an enclosure in the respirable fraction to the surface contamination level was estimated to be 10^{-3} m^{-1} . The surface contamination is assumed to have accumulated over an extended period of time and is mixed with foreign material (litter generated in the enclosure, condensed trace organic vapors in the air, etc.). Dislodgement and deagglomeration of such deposits are difficult. Furthermore, 1/2 to 3/4 of the deposited material appears to be absorbed into the surfaces and requires harsh, corrosive treatment for removal. A resuspension factor^(a) of 10^{-6} m^{-1} has been suggested for the resuspension of materials deposited on surface due to aerodynamic stress alone⁽¹⁶⁾ and as great as 10^{-2} m^{-1} for a combination of aerodynamic and mechanical stresses.⁽¹⁷⁾ The conditions postulated for the crushing of an enclosure are severe but do not appear to be as effective a resuspension mechanism as mechanical re-entrainment. Therefore, a value of 10^{-3} m^{-1} is used. The Pu mass airborne concentration would be 6.6 mg/m^3 in enclosures contaminated with PuO_2 and 1.7 mg/m^3 in enclosures contaminated with MO. The volume of the enclosures is 2 m^3 and the instantaneous airborne releases are 13 mg Pu and 3.3 mg Pu, respectively. The conservative assumption was made that all the material generated was in the respirable size range.

- Toppling of the Wall Storage Columns (IX FEED)

The nine IX FEED wall storage columns in the Scrap Recovery area (FAB-6) contain nitric acid solutions of dissolved MO and stored feed solution for the ion exchange columns in glovebox #604. The normal Pu concentration of such solutions does not exceed 10 g/liter and the operational capacity is 32 liters. A Pu inventory of 320 g Pu for each storage column is used.

Crushing of the wall storage tanks is not postulated in any damage scenario, but an instantaneous release may be generated if the columns topple. If the piping connections are sheared, liquid droplets can be

(a) Resuspension factor, K:

$$K = \frac{\text{airborne concentration (units/m}^3\text{)}}{\text{surface contamination (units/m}^2\text{)}}$$

generated by the release of liquids through the openings during the fall and impact of the column with the ground. The generation of fine droplets requires considerable viscous force⁽¹⁸⁾ and the energy available in this situation is limited. The liquid pressure and size of openings are not conducive to the formation of small droplets as in a spray nozzle--most of the liquid gushes out as a large diameter stream. It is postulated that no more than 1/10th the liquid under these conditions may be converted to the equivalent of a coarse spray (see Figure 4) and 0.5% of the mass is converted to droplets 100 μm AED or smaller (160 cm^3) with 0.001% of the mass as droplets in the respirable size fraction (0.32 cm^3). Thus, the instantaneous release from the toppling of an IX FEED wall storage column is estimated to be 1.6 g Pu total airborne release with 32 mg Pu in the respirable fraction.

- Punctured or Penetrated Enclosures

This mode encompasses all degrees of damage to enclosures between minimal (loss of external filter) to catastrophic (crush). It is assumed that enclosures in this category have at least 2 unfiltered openings of significant dimensions but have not suffered a complete loss of containment. Therefore, air can flow through the enclosure but its atmosphere is not instantaneously released to the ambient atmosphere around the enclosure, as in the case of the crushed enclosure. This form of release is designated as time dependent.

The enclosures in this damage mode are also assumed to have been subjected to a range of forces as reflected by the range of damage suffered. The forces may range from tumbling of an enclosure dislodged from its stand to mild shaking from the impact of debris on the walls of the enclosures. Although the quantities of dispersible materials initially made airborne may approach the maximum mass airborne concentration, the release of airborne material to the ambient atmosphere is diminished by natural depletion mechanism (sedimentation, electrophoresis, agglomeration and more rapid sedimentation of the larger particles, etc.,) prior to release. It is conservatively assumed that the mass airborne concentration of respirable particles in punctured and penetrated enclosures is equal to that found in crushed enclosures and that this fraction is not depleted during the time period required to release this material to the ambient atmosphere.

- Powders:

Over the entire time period of release the mass airborne releases of Pu for enclosures with PuO₂ and MO powders are 52.8 mg and 13.2 mg, respectively.

- Liquids:

The mass airborne release of Pu for enclosures containing dissolved routine process MO and enclosures in the Analytical Laboratory are 1.0 mg and 1.7 mg, respectively.

- Surface Contamination:

The mass airborne release of Pu for enclosures contaminated with PuO₂, enclosures containing MO, and enclosures in the Analytical Laboratory are 13 mg, 3.3 mg, and 5.8 mg, respectively.

ATMOSPHERE EXCHANGE RATES

The rate at which the enclosed volume is exchanged with the ambient atmosphere is dependent upon the size of the openings and the velocity of the air striking an opening. Determining the real velocity under the conditions postulated is difficult. For the damage scenarios postulated, portions of the surrounding structures remain intact in FAB-1 and FAB-6, providing some shielding from the external windfield. The orientation of the opening in relation to the wind direction in the remnants of the facility (which may be different than the external wind direction) also affects the velocity of air striking the opening. The opening(s) can be shielded from the full impact of the external windfield by the large amounts of debris in the areas and, for the roof collapse in FAB-6, the entire area can be shielded from the external windfield by a cover. Finally, the enclosure can topple, and if it comes to rest on a side containing an opening, this situation will limit the exchange rate. Thus the exchange rate can potentially vary from virtually nothing (controlled by diffusion) to the release of airborne material in minutes to days.

Directional air flow is used in nuclear facilities to control particulate materials generated. An air exchange rate of ten changes per hour is used in

operating areas and requires substantial motive force (blowers). Fans are required to attain rates as low as one change per hour. At these rates, the particulate material is not removed in plug flow but is diluted. Using the exponential dilution model, ~60% of the particles are removed with the exchange of one volume. (This ignores the depletion of particles from the volume by natural mechanisms during release.) Nearly five volumes must be exchanged before the release exceeds 99%. Thus, an exchange rate of 10%/hr was selected as an average for the FAB-1 enclosures in the wind hazard scenarios and 5%/hr for all other conditions.

- Enclosures That Have Lost Their External Filters

The release of material airborne in enclosures that lose only their external filters is assumed to be governed by diffusion and is negligible compared to the other sources present. Their contribution is lost in the uncertainties of the analysis and is not included.

RESUSPENSION

The plutonium-bearing material released from containment and exposed to the ambient windfield can be entrained by the aerodynamic stress imposed upon the deposited material.

- Powders:

Sehmel has reported a resuspension rate of 10^{-8} /sec as a conservative value for the resuspension of a fine powder from prairie land for the wind velocity variations over a year's duration at that locale.⁽¹⁹⁾ Although the types of surface involved here are different, the cover over most of the released material (debris and remnants of the enclosure) makes Sehmel's value still conservative for these situations.

- Liquids:

Liquids have greater physical mobility than powders and adhere more tenaciously to surfaces. Values for the entrainment of nitric acid solutions of uranium have been reported,⁽²⁰⁾ indicating a resuspension rate of 10^{-9} /sec is conservative, and appearing consistent with Sehmel's resuspension flux for powders.⁽¹⁹⁾

SOURCE TERM RANGE

Three values were calculated for each potential source term--a "best estimate" with an upper and lower bound. The "best estimate" was derived by determining the potential release using the best estimate damage ratio and the "on-the-average" inventory at risk. The on-the-average inventory at risk was calculated by dividing the sum of duty cycles for all dispersible materials for an area by 720 (the number of hr in a month). The result is the average quantity of plutonium that would be present in that area on any given hr. For the scenarios involving a roof collapse in an area, the best estimate damage ratio was given as 0.25 of the enclosures crushed - 0.65 of the enclosures punctured or penetrated - 0.1 of the enclosures lost their external filters. The on-the-average inventory at risk was distributed into the largest number of enclosures possible, using the normal weight of Pu at risks listed in Table 3. Finally, all other enclosures were assumed to contain surface contamination only. The coefficients from the damage ratio were applied to the total releases calculated on the basis of all the enclosures crushed (instantaneous and resuspension) or puncture-penetrated.

This approach was not feasible or did not result in the largest airborne release in all cases. In the Conversion Facility and Scrap Recovery, the on-the-average inventories at risk (7 and 90 g Pu, respectively) were so low that their significance in the release terms other than in the resuspension term was minimal and therefore not used. Release estimates based on liquids (primarily water) being made airborne were less than the release estimate assuming the pressure of only surface contamination. Since resuspension⁽⁸⁾ forms the greatest part of total mass airborne releases, the effect of the on-the-average inventory at risk and surface contamination were included in the resuspension term, but the instantaneous and time-dependent releases were based upon the surface contamination only.

The "upper limit" release was based upon the "high" damage ratios and the "upper limit" inventory of dispersible materials at risk. The "upper limit" inventory was taken to be the normal process inventory of dispersible material in all enclosures. The assumption is believed to be conservative, since some of the process steps are sequential and the chance that the full inventory

would be simultaneously found in all enclosures appears remote. Applying the high damage ratio to the upper bound of inventory should generate an upper limit for airborne releases.

The "lower limit" for airborne releases was generated in a similar fashion. The "lower limit" for inventories of dispersible materials at risk was taken to be the presence of a visible level of surface contamination in all enclosures. It was assumed that other conditions giving lower levels of inventories represented the unusual cases.

Since the Conversion Facility and Scrap Recovery areas operate sequentially (off standard material is stored, separated, and then converted for recycle), the airborne releases from an operational and non-operational facility were estimated for both areas. The total postulated airborne releases of Pu with either facility operational and the other non-operational were calculated and the higher releases, based on the respirable fraction released over the 4-day period, chosen to represent the release from the building for each scenario. In the case of the wind hazard at 85 mph, the Scrap Recovery is the only area affected. In all other cases (the wind hazard at 110 mph and the 0.08 to 0.16 g and 0.20 to 0.29 g earthquakes), the "upper limit" releases were based upon an operational Conversion Facility and the "best estimate" releases were based upon an operational Scrap Recovery area. The "lower limit" releases were the same for either assumption--all areas are essentially non-operational.

DAMAGE SCENARIOS AND AIRBORNE RELEASES

The response of the Babcock and Wilcox facility and selected equipment contained within the facility to various levels of wind hazard⁽⁵⁾ and earthquakes⁽⁶⁾ has been described. The following section recapitulates germane portions of the damage scenarios and assigns the quantities of radioactive materials that could be released to the ambient atmosphere around the facility based upon the response and behavior of the materials involved. The analysis is divided in two parts -- wind hazard and earthquakes.

The cumulative mass of plutonium estimated to be released to the ambient atmosphere around the facility as a result of the postulated events is shown in Table 3. Although both the total mass and the mass in the respirable fraction (mass associated with particles or droplets 10 μm AED or less) are given for the instantaneous releases, the material in the respirable fraction is of greater radiological consequence since dose assessments are based upon the quantity deposited in the lungs. As discussed before, assuming that the mass associated with material 10 μm AED or less is respirable is conservative. The format used is to provide data more directly applicable to existing transport and dose calculational models.

A "best estimate" with an upper and lower limit is listed for each source term to provide an estimate of the range anticipated. The assumptions used and the contribution of the four areas (FFTF Line, Conversion Facility, Scrap Recovery, Analytical Laboratory) to the overall source term are given in the following sections covering the individual scenarios.

Illustrations used in the analysis show the type and range of damage that could be inflicted upon the structure and selected features within the facility. In most cases, the data available and state-of-the-art are not sufficient to predict precisely where failure might be initiated nor the precise level of damage that would be inflicted upon each item. Thus, the damage shown is not intended to represent exactly what happens, but, rather, the types of things that can happen.

The glovebox arrangement in the north end of the FAB-1 area is depicted in Figure 7 as a basis for comparison of subsequent illustrations used to

FIGURE 7. Glovebox Arrangement, North End of FAB-1 Area (Conversion Facility)

indicate level of damage. The area contains all the enclosures in FAB-1 that are used for operations involving undiluted PuO_2 powder. The illustration is not intended as an exact representation of the area. Many of the features have been omitted for clarity -- only a single roof joist is shown and all the piping in the ceiling region is not shown, the exhaust ducting is not shown nor is the service piping to the gloveboxes, the exhaust filter arrangement is only shown for box #107 but is present on all boxes (and is a particularly vulnerable feature of the containment system), etc. Figure 8 illustrates the arrangement of the pertinent features in the south end of the FAB-6 area (Scrap Recovery).

SOURCE TERMS FROM WIND HAZARDS

- Source term for nominal windspeed of 85 mph (38 m/sec), probability of occurrence: 1×10^{-2} per year. No significant damage postulated in the FAB-1 area at this level of wind hazard. A 9-foot section of the east wall and the exposed portion of the south wall of the FAB-6 area are likely to collapse outward. Collapse of the south wall is limited by the cross wall at the bottom of the stairway attached to the south wall. A 9-foot section of the roof could collapse downward as a unit, crushing gloveboxes in that area and toppling the liquid storage tanks (2) located in that area along the east wall. Windborne debris might penetrate a few gloveboxes and crush a few HEPA filters. The situation is illustrated in Figure 9.

In this case the area damaged can be reasonably confined to a 9-foot section of roof and east wall and the portion of the south wall east of the stairway wall. The liquid storage tanks area assumed to be pulled outward by the collapse of the wall to which they are attached. Most of the debris is not depicted in the illustration for the sake of clarity. The two enclosures lying under the collapsed roof section are boxes #601 and #605. Since the roof collapse is initiated by the unseating of the roof from the east wall, the roof would collapse from east to west. A glovebox must be struck by the full force of the roof section to be crushed; and, therefore, it is postulated that box #605 is crushed and box #601 is punctured. Other enclosures not under the collapsed roof section may suffer loss of containment due to puncture or loss of exhaust HEPA filters. Although the threshold windspeed for the failure of the FAB-6 penthouse housing the final filters is 102 mph, collapse of the roof would rupture a portion of the exhaust ducting and the

FIGURE 8. Glovebox Arrangement, South End of FAB-6 Area (Scrap Recovery)

FIGURE 9. Range and Type of Responses in FAB-6 Area to Wind Loading of Nominal Windspeed.
85 mph Wind, 1×10^{-2} per Year Probability of Occurrence

loss of directional flow through the enclosures is assumed. These enclosures are not postulated to lose containment and in the absence of a motive force to expel the contained atmosphere do not contribute to the airborne release. The "duty-cycle" for all other enclosures in the FAB-6 area is zero, meaning fissile materials are not normally exposed in these boxes. Loss of exhaust filters would result in the opening of an unfiltered pathway from the glovebox atmosphere (containing minute quantities of airborne radioactive materials resuspended from contaminated surfaces) to the ambient atmosphere with minimal flow out of the box.

The three sources for the airborne release of plutonium are:

1. the two Product wall storage columns at the south end of the bank (#11 and #12 in Figure 3) toppled as a result of the collapse of a portion of the east wall,
2. the crush of glovebox #605,
3. the puncture or penetration of glovebox #601.

The two wall storage columns are no longer used in the process and are assumed to contain PuO_2 surface contamination. Glovebox #605 houses the Product Evaporator and is assumed to contain PuO_2 surface contamination. Furthermore, any Pu solution held in the titanium evaporator is assumed to leak from the vessel as a result of the crush and be available for resuspension. Glovebox #601 is assumed to contain dispersible MO powder during its operational phase and MO surface contamination during its non-operational periods.

Since the damage scenario defines specific areas, damage to specific pieces of equipment could be postulated and damage ratios were not applied. Source terms were calculated based on fractional airborne releases outlined in the section on Approach and Methods Used in Estimating Source Terms using the "upper limit," "on-the-average," and "lower limit" inventories at risk. The mass airborne releases from enclosure for an operational Scrap Recovery area are shown in Table 3d. The source terms derived are shown in Table 4. The source term for the Scrap Recovery area is the overall source term from the building inasmuch as no other portion of the facility suffers any significant damage at this windspeed.

TABLE 4. Estimated Source Term for Wind Hazard, 85 mph

Airborne Release of Plutonium, mg in respirable fraction					
	Building	FFTF Line	Conversion Facility	Scrap Recovery	Analytical Laboratory
	• Upper Limit				
Instantaneous	$1 \times 10^1, 1 \times 10^{1+}$	-	-	$1 \times 10^1, 1 \times 10^{1+}$	-
Additional mass in next 2 hr	3×10^1	-	-	3×10^1	-
Additional mass in next 6 hr	8×10^1	-	-	8×10^1	-
Additional mass in next 16 hr	2×10^2	-	-	2×10^1	-
Additional mass in next 3 days	9×10^2	-	-	9×10^2	-
	• Best Estimate				
Instantaneous	$1 \times 10^1, 1 \times 10^{1+}$	-	-	$1 \times 10^1, 1 \times 10^{1+}$	-
49 Additional mass in next 2 hr	5×10^0	-	-	5×10^0	-
Additional mass in next 6 hr	1×10^1	-	-	1×10^1	-
Additional mass in next 16 hr	4×10^1	-	-	4×10^1	-
Additional mass in next 3 days	1×10^2	-	-	1×10^2	-
	• Lower Limit				
Instantaneous	$1 \times 10^1, 1 \times 10^{1+}$	-	-	$1 \times 10^1, 1 \times 10^{1+}$	-
Additional mass in next 2 hr	5×10^0	-	-	5×10^0	-
Additional mass in next 6 hr	1×10^1	-	-	1×10^1	-
Additional mass in next 16 hr	4×10^1	-	-	4×10^1	-
Additional mass in next 3 days	1×10^2	-	-	1×10^2	-

+Mass total airborne release

The conservatisms in the above analysis are:

1. A PuO_2 surface contamination level for operational enclosures is used to represent the surface contamination present on the interior surfaces of the wall storage tanks after chemical decontamination. The value used of 7.5 g Pu/m^2 is at least a factor of 2 high and could be orders of magnitude high.
2. The surface contamination on the wall storage tanks should be tightly bound to the metal surfaces following chemical decontamination and is not as readily suspended as contamination lying on the surface. The factor used (10^{-3} m^{-1}) is probably an order of magnitude high.
3. All the material resuspended from surfaces is assumed to be of the size that will remain airborne for at least 10 hr in an enclosure and constitute an inhalation hazard for the downwind population.
4. No credit is taken for the deposition or plate out of material released under the collapsed roof.

The quantity of plutonium in the Warm Equipment area exists as contamination on equipment or combustible waste collected on HEPA filters. All the materials have at least one layer of non-porous packaging and the combustible waste is handled in metal 55-gallon drums. The east wall could collapse inward and the debris could crush other than metal items within 14 feet of the wall. The only contaminated items in this category are the HEPA filters. The radioactive material held in the filters is impacted on or embedded in a glass fiber mat encased in a pressed board frame. Even if the filters are crushed, it is anticipated that only a small fraction of the contained materials could be released. There the quantities release from this area would be insignificant compared to the release from FAB-1 and FAB-6.

- Source term for nominal windspeed of 95 mph (42.5 m/sec), 3×10^{-3} per year probability of occurrence.

No significant additional damage results at this windspeed other than described in the previous section for 85 mph. Therefore, no additional source term is postulated.

- Source term for nominal windspeed of 110 mph (49 m/sec), probability of occurrence: 4×10^{-4} per year.

FAB-1: The loadbearing west wall could collapse inward, resulting in the downward collapse of the entire roof. The precast concrete roof planks are likely to disengage from their anchorage to the roof joist during collapse. The weight of the concrete blocks, the roof planks and the steel joists is sufficient to crush gloveboxes, filters and other items in FAB-1 area. The material inside gloveboxes and the filter material outside of the gloveboxes could be exposed to the atmosphere. The penthouse which contains the final filters for the FAB-1 area would also collapse. The filters are likely to be crushed and could be exposed to the atmosphere.⁽²⁾

The type and range of damage that can occur is shown graphically in Figure 10. The drawing is not an attempt to predict what happens to each box (which is not possible with the current analytical tools) but to show that some boxes are crushed, others are punctured or penetrated and almost all will lose their external HEPA filters. It is anticipated that much of the equipment shown will be covered to some extent by debris (concrete blocks from the east and west walls, concrete roof planks, piping passing along the ceiling area, etc.,) most of which is not shown so that damage to the gloveboxes is not obscured. Also, no attempt was made to reproduce exactly the dimensions or location of any feature. Exact descriptions of the features are in reference (1). Finally, only the north end of the FAB-1 area (Conversion Facility) is shown.

FFTF Line

The pertinent information for the 32 enclosures that make up the FFTF line is shown in Table 3a. The source terms (upper limit, best estimate, lower limit) were calculated by applying the appropriate damage ratio to the sum of the postulated airborne releases from all enclosures for each damage level for the various anticipated inventories. The "on-the-average" inventory at risk was calculated to be 1.7 kg and dispersible powders were assumed to be in gloveboxes #176A and #177 that have normal inventories of 1.3 kg Pu and 1.2 kg Pu, respectively.

FIGURE 10. Range and Type of Response in FAB-1 Area to Windloading of Nominal Windspeed 110 mph, 4×10^{-4} per Year Probability of Occurrence

The values are listed in Table 5.

Conversion Facility

A larger overall building upper limit source term resulted from the assumption of an operational Conversion Facility, and the "upper limit" source term was calculated on that basis. The calculated "on-the-average" inventory of dispersible materials at risk was 7 g Pu and is essentially a non-operational facility, and the best estimate source term was calculated on that basis. The source terms were calculated as outlined in the previous section and are listed in Table 5. The pertinent data on the seven enclosures in this area are shown in Table 3b.

Analytical Laboratory

Originally situated in FAB-1, the Analytical Laboratory is currently located in FAB-5. Although the damage to FAB-5 is not covered in detail, the area is assumed to behave in general as the rest of the structure of which it is part. The pertinent information on the 26 enclosures in this area is listed in Table 3c. The source terms were calculated as outlined in section for the FFTF and are shown in Table 5. The source term from the Analytical Laboratory does not exert a significant influence on the "upper limit" value for the overall building source term. For the "best estimate" and "lower limit" source terms, the values are largely a function of surface contamination, and the large number of enclosures assumed to be in this area makes the Analytical Laboratory a strong contributor to the overall building source term.

FAB-6: At this windspeed the entire east wall could collapse inward, resulting in the downward collapse of the entire roof. The roof is likely to collapse as a unit with the metal deck remaining attached to the steel joists. The weight of the concrete blocks and the roof joists is sufficient to crush gloveboxes, filters, and other items in FAB-6 area. Since the roof is likely to remain as a unit, only a part of the material in the gloveboxes and the filter material are likely to be exposed to the atmosphere. The penthouse may be uplifted or may collapse downward. In either case, the filters are likely to be crushed and exposed to the atmosphere.

Figure 11 illustrates the type and range of structural and equipment responses that may occur under the postulated wind loading in the FAB-6 area.

TABLE 5. Estimated Source Term for Wind Hazard, 110 mph

	Airborne Release of Plutonium, mg, $\leq 10 \mu\text{m AED}$				
	Building	FFTF Line	Conversion Facility	Scrap Recovery	Analytical Laboratory
	• Upper Limit				
Instantaneous	$3 \times 10^2, 2 \times 10^3^+$	$1 \times 10^2, 8 \times 10^2^+$	$1 \times 10^2(a), 1 \times 10^3^+$	$2 \times 10^1(b), 2 \times 10^1^+$	$8 \times 10^1, 3 \times 10^1^+$
Additional mass in next 2 hr	1×10^3	1×10^3	3×10^2	6×10^0	3×10^1
Additional mass in next 6 hr	5×10^3	4×10^3	9×10^2	2×10^1	1×10^2
Additional mass in next 16 hr	1×10^4	1×10^4	2×10^2	4×10^1	2×10^2
Additional mass in next 3 days	6×10^4	5×10^4	1×10^4	1×10^2	7×10^2
	• Best Estimate				
Instantaneous	$1 \times 10^2, 3 \times 10^2^+$	$4 \times 10^1, 1 \times 10^2^+$	$2 \times 10^1(b), 2 \times 10^1^+$	$1 \times 10^1(a), 9 \times 10^1^+$	$4 \times 10^1, 4 \times 10^1^+$
Additional mass in next 2 hr	1×10^2	6×10^1	2×10^1	5×10^0	3×10^1
Additional mass in next 6 hr	4×10^2	2×10^2	6×10^1	1×10^1	9×10^1
Additional mass in next 16 hr	5×10^2	3×10^2	6×10^1	3×10^1	6×10^2
Additional mass in next 3 days	2×10^3	1×10^3	2×10^2	1×10^2	2×10^2
	• Lower Limit				
Instantaneous	$5 \times 10^1, 5 \times 10^1^+$	$2 \times 10^1, 2 \times 10^1^+$	$1 \times 10^1(b), 1 \times 10^1^+$	$4 \times 10^0(a), 4 \times 10^0^+$	$2 \times 10^1, 2 \times 10^1^+$
Additional mass in next 2 hr	7×10^1	2×10^1	2×10^1	2×10^0	3×10^1
Additional mass in next 6 hr	2×10^2	6×10^1	5×10^1	1×10^1	8×10^1
Additional mass in next 16 hr	2×10^2	5×10^1	4×10^1	2×10^1	6×10^1
Additional mass in next 3 days	4×10^2	1×10^2	1×10^2	4×10^1	2×10^2

imass total airborne release

(a)source term for operational facility

(b)source term for non-operational facility

FIGURE 11. Range and Types of Responses in FAB-6 Area to Wind Loading of Nominal Windspeed 110 mph, 4×10^{-4} per Year Probability of Occurrence

The response illustrated for the building is the maximum anticipated (complete collapse) but the actual damage could range downward to that shown later for severe earthquakes. The observations as to the responses shown are the same as stated for the FAB-1 illustrations.

The Scrap Recovery facility is the only operation housed in the FAB-6 area involving significant quantities of plutonium. Pertinent data on the enclosures and equipment used in this operation are shown in Table 3d. The three levels of source terms were calculated following the outline given in the FFTF Line section. Since the upper limit value for an operational Conversion Facility is larger than the same value for an operational Scrap Recovery, the "upper limit" source term was calculated on the basis of a non-operational Scrap Recovery facility. The best estimate was calculated using an "on-the-average" inventory of dispersible at risk of 25 g Pu in an IX FEED wall storage column. The values are listed in Table 5.

Overall Building Source Terms

The estimated airborne release of plutonium (source term) from the building at this level of wind hazard is shown in Table 5. The areas generating the larger contributions are the FFTF Line (approx. 80%) and the Conversion Facility (approx. 20%). More than 98% of the mass of Pu release from the FFTF Line occurs after the initial 2 hr. The FFTF Line is still the leading contributor to the "best estimate" source term, but its portion is on the order of 50%. The Analytical Laboratory (because of its increased Pu content and number of enclosures) contributes approx. 50% of the lower limit source term.

Some of the conservatisms incorporated in the above analysis are:

1. All the conservatisms listed for the nominal 85 mph (38 m/sec) wind.
2. The Pu oxalate is assumed to behave as a fine, dry PuO_2 , while in fact the oxalate is much coarser and can be damp.

3. 10 μ m AED or less particles are assumed to be respirable but existing models show 100% of the 2 μ m particles are respirable with decreasing fraction at lesser and greater diameters.⁽⁷⁾ Conservative by more than an order of magnitude.
 4. The mass of liquid which remains airborne in an enclosure is assumed to be equivalent to the mass airborne concentration of fog. Fog is a naturally-occurring stable liquid aerosol generated by condensation of moisture in air and probably creates a larger proportion of fine droplets than the dispersal mechanisms in these instances.
 5. All the liquid spilled from the IX FEED wall storage tanks is assumed to be available while in fact much of the liquid will be buried under debris. The calculated value can be up to an order of magnitude high.
- Source term for nominal windspeed of 130 mph (58 m/sec), probability of occurrence 2×10^{-5} per year.

The level of damage postulated at this nominal windspeed is not substantially different than that for a nominal windspeed of 110 mph--both areas (FAB-1 and -6) holding substantial quantities of Pu were essentially demolished. Additional damage incurred by the facility due to the increase in windspeed is to other portions of the facility not holding Pu. The Nuclear Material vault may lose portions of a wall but "no damage of any consequence is likely to occur."⁽⁵⁾ Thus, no significant increase in source term is postulated.

Source Terms from Earthquakes

- Source term for peak ground acceleration levels of 0.015 g to 0.04 g, probability of occurrence 1.8×10^{-2} per year at 0.025 g.

The principal damage to the facility postulated for the ground acceleration levels are horizontal cracks through the mortar in the block walls. Although some of the cracks may extend completely through the walls, compression due to the weight of materials on the crack will prevent them from being noticeable gaps. Furthermore, all primary barriers remain intact and therefore no significant airborne release of Pu is postulated under these conditions.

- Source term for ground acceleration levels of 0.08 g to 0.16 g, probability of occurrence 3.4×10^{-4} per year at 0.13 g.

FAB-1: The damage scenario reported in reference (6) for the FAB-1 area and the equipment in the area is reproduced below:

The top of the NMV and WES/DW west walls above their respective roof decks acts to resist seismically-induced forces from the FAB-1 area for east-west shaking. Forces are distributed through the corridor roof immediately adjacent to the FAB-1 east wall. Cracking occurs due to the easterly component of shaking after the approximately 3/8" gap in the corridor roof is closed with this roof slipping on its angle seat at the FAB-1 east wall. Major horizontal cracking just above the roof deck will occur at levels of ground shaking of approximately 0.08 g to 0.09 g.

Most gloveboxes will slide on their stands. Some primary filters will be knocked off glovebox tops. Some of the ducting from primary filters to secondary filters will be ruptured, most likely at the taped joints at one end or the other of the vertical pipe sections just above the filters. Some of the gloveboxes may fall off their stands if shaking is of sufficient duration. Such an occurrence would also insure damage to the primary filters and ducting. Gloveboxes which slide off stands may be damaged with some tearing of gloves, cracking of windows and partial impairment of containment. The above described events will occur at ground shaking levels of approximately 0.13 g. These events, coupled with wall cracking, may allow a small quantity of chemical release. This event may be precluded by mechanically connecting gloveboxes to their supporting stands. Similar damage at somewhat higher acceleration levels due to sliding of the box and stand on the floor (0.21 g) also may be precluded by anchoring the stands to the floors. If properly anchored, the seismic capacities of gloveboxes and stands will be much higher than the acceleration level at roof collapse in FAB-1 and FAB-6.

The type and range of the response of the enclosures in FAB-1 to this level of ground acceleration is illustrated in Figure 12. No structural damage which would result in a significant unfiltered pathway to the ambient atmosphere around the facility is postulated.

Based upon the above damage scenario, it is assumed that all airborne material released from the enclosures is processed through a functional exhaust system. Normally most of the flow passing through the FAB-1 area (58%) is processed through two banks of HEPA before release with the remainder passing through one bank. Most of the flow processed through two banks is via

FIGURE 12. Range and Type of Responses in FAB-1 Area to 0.08-0.16 g Ground Acceleration Levels, 3×10^{-4} per Year Probability of Occurrence

the enclosures. The intake and outlets of most enclosures are sealed with HEPA filters and the enclosures constitute a significant pressure drop in the system. Disconnecting the enclosures from the duct allows the airflow to bypass the enclosures, reducing the pressure in that component and increasing the flow. All the exhaust from the Chemical Laboratory passes through two banks of HEPA filters prior to release and represents 56% of the flow passing through FAB-1. Thus, approximately 75% of the particulate material exhausted from these areas would be attenuated by a factor of 4×10^6 and 25% by a factor of 2000.

Inasmuch as the roof remains intact, crush is not a potential damage mode, and the maximum damage level is assumed to be puncture or penetrate. A damage ratio similar to that used in the 110 mph wind hazard scenario was applied--"high," one-half enclosures punctured or penetrated; "best estimate," one-fourth enclosures punctured or penetrated, and "low," one-eighth enclosures punctured or penetrated. The remaining enclosures are assumed to lose only one external HEPA filter or to remain functional.

FFTF Line

The pertinent information on the 32 enclosures that constitute the FFTF Line is shown in Table 3a. The "upper limit" source term was estimated by applying the "high" damage ratio to the total time dependent release listed in Table 3a and multiplying by the attenuation resulting from the passage of airborne particulate material through the filtration system. The "best estimate" source term was calculated under the assumption that glovebox #176A and #177 held dispersible material at risk and the mass airborne concentration in all the remaining enclosures is a result of surface contamination only. The "lower limit" source term is for a non-operational facility--no dispersible material inventory at risk. A linear atmosphere exchange rate of 20 hr duration was used. The estimated source terms for the area are shown in Table 6.

Conversion Facility

The pertinent information on the seven enclosures that make up the Conversion Facility are listed in Table 3b. The "upper limit" source term was

TABLE 6. Estimated Source Term for Earthquake, 0.08 to 0.16 g Peak Ground Acceleration Levels

Airborne Release of Plutonium, mg, $\leq 10 \mu\text{m AED}$					
	Building	FFTF Line	Conversion Facility	Scrap Recovery	Analytical Laboratory
• Upper Limit					
Instantaneous	-	-	-	-	-
Additional mass in next 2 hr	5×10^{-3}	2×10^{-3}	2×10^{-3}	2×10^{-4}	9×10^{-4}
Additional mass in next 6 hr	1×10^{-2}	5×10^{-3}	5×10^{-3}	6×10^{-4}	3×10^{-3}
Additional mass in next 16 hr	2×10^{-2}	9×10^{-3}	9×10^{-3}	1×10^{-3}	6×10^{-3}
Additional mass in next 3 days	-	-	-	-	-
• Best Estimate					
Instantaneous	-	-	-	-	-
Additional mass in next 2 hr	1×10^{-3}	4×10^{-4}	2×10^{-4}	1×10^{-4}	5×10^{-4}
Additional mass in next 6 hr	3×10^{-3}	1×10^{-3}	7×10^{-4}	3×10^{-4}	1×10^{-3}
Additional mass in next 16 hr	8×10^{-3}	3×10^{-3}	1×10^{-3}	6×10^{-4}	3×10^{-3}
Additional mass in next 3 days	-	-	-	-	-
• Lower Limit					
Instantaneous	-	-	-	-	-
Additional mass in next 2 hr	6×10^{-4}	2×10^{-4}	1×10^{-4}	5×10^{-5}	3×10^{-4}
Additional mass in next 6 hr	2×10^{-3}	6×10^{-4}	4×10^{-4}	2×10^{-4}	7×10^{-4}
Additional mass in next 16 hr	3×10^{-3}	1×10^{-3}	9×10^{-4}	3×10^{-4}	1×10^{-3}
Additional mass in next 3 days	-	-	-	-	-

calculated as outlined in the discussion of the FFTF Line calculations. Only four of the seven enclosures routinely have any dispersible material inventory at risk. All the material processed in this area are plutonium compounds, and the overall effect of the area on the source term is greater than another area of comparable size processing MO. The "on-the-average" dispersible inventory at risk is so low that the "best estimate" and "lower limit" source terms are for a "standby" facility. The estimated values are shown in Table 6.

Analytical Laboratory

The pertinent information on the 26 enclosures in this area are shown in Table 3c. The "upper limit," "best estimate," and "lower limit" source terms were calculated by applying the damage ratio to the surface contamination inventories. Use of the liquid airborne release factors in this situation generated lesser source terms since the vast majority of the mass airborne was non-radioactive (primarily water). The values are listed in Table 6.

FAB-6: The damage scenario reported in reference (6) for the FAB-6 area and equipment is reproduced below:

Major horizontal cracking will occur at a level of 0.16 g in the west wall of FAB-6 at the FAB-6 roof line due to westerly motion resisted by the very stiff FAB's -3, -4, and -5 roof diaphragms.

Most gloveboxes will slide on their stands. Some primary filters will be knocked off glovebox tops. Some of the ducting from primary filters to secondary filters will be ruptured, most likely at the taped joints at one end or the other of the vertical pipe sections just above the filters. Some of the gloveboxes may fall off their stands if shaking is of sufficient duration. Such an occurrence would also insure damage to the primary filters and ducting. Gloveboxes which slide off stands may be damaged with some tearing of gloves, cracking of windows and partial impairment of containment. The above described events will occur at ground shaking levels of approximately 0.13 g. These events coupled with wall cracking may allow a small quantity of chemical release. This event may be precluded by mechanically connecting gloveboxes to their supporting stands. Similar damage at somewhat higher acceleration levels due to sliding of the box and stand on the floor (0.21 g) also may be precluded by anchoring the stands to the floors. If properly anchored, the seismic capacities of gloveboxes and stands will be much higher than the acceleration level at roof collapse in FAB-1 and FAB-6.

The types and ranges of responses of the enclosures in the FAB-6 area to this level of ground acceleration are shown in Figure 13. As in FAB-1, no structural damage which results in a significant unfiltered pathway to the ambient atmosphere is postulated.

The exhaust system remains functional and all particulate material must pass through two banks of HEPA filters prior to release to the ambient atmosphere around the facility.

The wall storage tanks remain intact and any airborne burden would result from the loss of integrity by the enclosures.

Scrap Recovery

The pertinent information on the eight enclosures and other equipment that make up the area are shown in Table 3d. The calculational methodology used to estimate the "upper limit," "best estimate," and "lower limit" source terms is covered in an earlier section. The estimated contributions from this area to the overall building source term from this scenario is shown in Table 6.

Overall Building Source Terms

The estimated airborne releases of plutonium from the building as a consequence of this damage scenario are listed in Table 6 and are considerably smaller than estimated for the wind hazard scenarios. The damage inflicted upon the structure and contained equipment is not as severe as in the wind hazard scenario resulting in the airborne release of materials; and, therefore, the airborne mass release is smaller and greatly attenuated by the filtration system. The FFTF Line and Conversion Facility are the principal contributors to the upper limit source term while the FFTF Line and Analytical Laboratory are the major sources for the best estimate and lower limit source terms.

- Source terms for ground acceleration levels of 0.20 g to 0.29 g, 7.1×10^{-5} per year probability of occurrence.

FAB-1: The damage scenario reported in reference (6) is reproduced below:

FIGURE 13. Range and Type of Responses in FAB-6 to 0.08-0.16 g Ground Acceleration Level, 3×10^{-4} per Year Probability of Occurrence

Collapse of the FAB-1 roof system is expected at the peak ground acceleration level of 0.21 g. The corridor roof just east of FAB-1 will become unseated at this acceleration level. This will occur as the NMV and WES/DW areas are rigid systems moving essentially with the ground motion, while the FAB-1 system is relatively flexible in east-west rigid body motions. The corridor roof will slip on its angle seat and come off at a relative displacement of about 4 inches, with the roof of the FAB-1 area moving towards the west. The FAB-1 wall/roof system for east-west shaking is a combined rigid body system which includes the FAB-1 main area east and west bearing walls and roof with the Chem Lab west bearing wall and lower roof. This system, with the corridor roof off, will fail in the rigid body instability mode for east-west shaking at essentially the same level at which the corridor roof falls off (0.21 g). Rigid body instability of this system occurs at roof displacements of about 10 inches followed by collapse of the three major bearing walls. Concurrent with this collapse, the Upper Hot Cell walls and roof system above the FAB-1 roof and Hot Cell second-story slab will collapse (0.21 g) in a rigid body response mode to north-south shaking. The Hot Cell walls and roof may collapse just prior to the main FAB-1 roof system, in which case the main system collapse will be abetted at the north end of FAB-1 by pieces of the falling upper roof/wall components.

Gloveboxes in the FAB-1 area will be impacted by falling roof joists with some concrete roof plank attached. Glovebox failure is concurrent with the FAB-1 wall/roof collapse at 0.21 g. Boxes will be crushed and rupture. Side walls will buckle and homalite windows will pop out. Primary filter boxes on top of gloveboxes will be destroyed. Destruction is expected to be more complete in the FAB-1 area than in the FAB-6 area because of the heavier roof structure. However, some protective containment of the glovebox contents may be provided by the cover of roof plank rubble. The planks are expected to break into relatively large pieces upon impact with the floor and equipment, and the piping system may act to cushion the impact during roof system collapse.

Figure 14 is a pictorial representation of the type and range of structure and equipment damage that may result from the impact of ground accelerations of this severity.

The damage ratios and dispersible materials inventories are the same as in the 110 mph wind hazard scenario; and, therefore, the estimated mass airborne releases of plutonium are the same. Releases are shown in Table 5.

FAB-6: The damage scenario for this area in this ground acceleration range is reproduced below:

FIGURE 14. Range and Type of Responses in FAB-1 to 0.20 g - 0.29 g Ground Acceleration Level, 7.1×10^{-5} per Year Probability of Occurrence

The east and west walls and the roof system of FAB-6 collapsed at a peak ground acceleration level of 0.22 g. This occurs when rigid body displacement at the top of the east wall becomes so large (about 9 inches) that instability results from easterly motion. The top of the wall will continue to rotate, the roof joists unseat; and the east wall will break into small pieces (of one or a few blocks) under the bending action of gravity as displacements at the top grow large. The major parts of the west wall will collapse similarly and the roof joists will unseat. A portion of this wall will remain standing where held at the top by the roof anchors and beams of FAB's -3, -4, and -5. The south end wall of FAB-6 will likely remain standing unless ground shaking becomes yet stronger (0.27 g to 0.28 g), at which time it also collapses. Nonbearing cantilever walls in the rigid body failure mode generally have higher capacities than the bearing walls as inertia forces which cause rigid body rotations to act at lower points on the nonbearing walls.

At a level of 0.29 g, diaphragm shear transfer failure is expected at the north and south walls of FAB-3; and failure of the FAB's -3, -4, and -5 Areas in a rigid body mode is expected almost immediately thereafter. Concurrent with roof and wall collapse of the FAB-6 Area (0.22 g) the closely spaced roof joists (3 feet spacing) will likely strike the critical gloveboxes, causing rupture of these boxes and destruction or heavy damage to the primary filter. The joists, in impacting a box, will cause the box side walls to buckle with some rupture; and the homalite windows will crack, with some popping out of their stud holders. Prior to roof collapse, small missiles (as may be hypothesized at higher shaking levels) will not puncture the gloveboxes. The vertical waste storage tanks mounted on the east wall of FAB-6 are also expected to rupture as a result of roof collapse.

Figure 15 is an illustration of the types and range of damage anticipated. The illustration is based upon some of the piers in the west wall remaining functional, preventing the complete collapse of the roof.

As in the case of the FAB-1 area, all the contributing factors are essentially the same as in the 110 mph scenario, and the source terms listed in Table 5 apply.

- Overall Building Source Terms

See Table 5.

FIGURE 15. Range and Type of Responses in FAB-6 to 0.20 g - 0.29 g Ground Acceleration Level, 7.1×10^{-5} per Year Probability of Occurrence.

REFERENCES

1. Structural Condition Documentation and Structural Capacity Evaluation of the Babcock and Wilcox Facility, Leechburg, PA, for Earthquake and Flood, Task I Structural Condition, Engineering Decision Analysis Company, Inc. (EDAC) for Lawrence Livermore Laboratory, Livermore, CA, July 1977.
2. J. Mishima, L. C. Schwendiman and J. E. Ayer, Identification of Features Within Plutonium Fabrication Facilities Whose Failure May Have a Significant Effect on the Source Term, Battelle-Northwest, Richland, WA, August 11, 1977.
3. T. T. Fujita, Review of Severe Weather Meteorology at Babcock and Wilcox Company, Leechburg, PA, a report submitted to Argonne National Laboratory under Contract No. 31-109-3731, January 31, 1977.
4. Seismic Risk Analysis for the Babcock and Wilcox Facility, Leechburg, PA, TERA Corporation, for Lawrence Livermore Laboratory, Livermore, CA, October 1977.
5. K. C. Metha, J. R. McDonald and D. A. Smith, Response of Structures to Wind Hazard at the Babcock and Wilcox Plant, Leechburg, PA, Volume I, Institute for Disaster Research, Texas Tech University, Lubbock, TX, December 1977.
6. Structural Condition Documentation and Structural Capacity Evaluation of Babcock and Wilcox Facility at Leechburg, PA, Vol. II -- Structural Capacity Evaluation, Engineering Decision Analysis Company, Inc., for Lawrence Livermore Laboratory, Livermore, CA, July 1977.
7. T. T. Mercer, "Matching Sampler Penetration Curves to Definitions of Respirable Fraction," Health Physics, 33, No. 3, pp. 259-264, (Figure 2, p. 260), September 1977.
8. R. B. McPherson and E. C. Watson. Environmental Consequences of Postulated Plutonium Releases From the Babcock and Wilcox Plant, Leechburg, Pennsylvania, as a Result of Severe Natural Phenomena (Draft), Battelle, Pacific Northwest Laboratories, Richland, WA, September, 1978.
9. W. F. Heer, Letter to Mr. J. B. Martin (NRC) dated 6-23-77, "Initial Response to Mr. J. B. Martin's Letter of March 24, 1977," Babcock and Wilcox - Nuclear Materials Division, Apollo, PA.
10. J. S. Dziewisz. Letter to Mr. J. B. Martin (NRC) dated 8-15-77, "Second Response to Mr. J. B. Martin's Letter of March 24, 1977," Babcock and Wilcox - Nuclear Materials Division, Lynchburg, VA.

11. J. E. Ayer. Letter to J. Mishima (Battelle Pacific Northwest Laboratory) dated 10-27-78, "Structural and Duty-Cycle Bases for Calculating Releases," U.S. Nuclear Regulatory Commission-Fuel Reprocessing and Recycle Branch, Washington, D.C.
12. J. Mishima, "Data Useful in the Evaluation of Airborne Plutonium from Postulated Accident Situations," Appendix C in Considerations in the Assessment of the Consequences of Effluents from Mixed Oxide Fabrication Plants, BNWL-1697, Battelle, Pacific Northwest Laboratories, Richland, WA, June 1973, p. C.12.
13. L. C. Schwendiman, Supporting Information for the Estimation of Plutonium Oxide Leak Rates Through Very Small Apertures, BNWL-2198, Battelle, Pacific Northwest Laboratories, Richland, WA, January 1977.
14. J. H. Perry, Ed., Chemical Engineers' Handbook, 2nd Edition, McGraw-Hill Book Company, Inc., New York (1941).
15. R. P. Allen, H. W. Arrowsmith, L. A. Charlot and J. L. Hooper, Electro-polishing as a Decontamination Process: Progress and Applications, PNL-SA-6858, Battelle, Pacific Northwest Laboratories, Richland, WA, April 1978, p. 13.1.
16. K. Stewart. "The Resuspension of Particulate Material From Surface" in Surface Contamination (B. R. Fish, Ed.), Pergamon Press, New York, 1967, p. 63.
17. H. Glauberman, W. R. Bootman and A. J. Breslin, "Studies of the Significance of Surface Contamination" in Surface Contamination (B. R. Fish, Ed.), Pergamon Press, New York, 1967.
18. G. W. Monk, "Viscous Energy Dissipated During the Atonization of a Liquid," Journal of Applied Physics, 23, No. 2, p. 288 (1959).
19. G. A. Sehmel and F. A. Lloyd, "Particle Resuspension Rates," Atmosphere Surface Exchange of Particulate and Gaseous Pollutants, (R. J. Englemann and G. A. Sehmel, Eds.), ERDA-Technical Information Center, 1974.
20. J. Mishima and L. C. Schwendiman, Some Experimental Measurements of Airborne Uranium (Representing Plutonium) in Transportation Accidents, BNWL-1732, Battelle, Pacific Northwest Laboratories, Richland, WA, August 1973.