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Predicting Worker Exposure from a Glovebox Leak

by

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Abstract

It is difficult to predict immediate worker radiological consequences from a hypothetical accident. This is recognized in DOE safety analysis guidance and the reason such guidance does not call for quantitative determinations of such consequences. However, it would be useful to at least have a means of systematically and formally quantifying worker dose to be able to identify the relative risks of various processes and to provide an order-of-magnitude impression of absolute consequences.

In this report, we present such a means in the form of a simple calculation model that is easily applied and generates reasonable, qualitative dose predictions. The model contains a scaling parameter whose value was deduced from extensive laboratory ventilation flow rate measurements performed at Los Alamos National Laboratory (LANL) over the last several years and from recent indoor radioactive contamination dispersion measurements, also at LANL. Application of the model is illustrated with the aid of two example calculations.

Introduction

Overview

Predicting immediate worker radiological consequences from a hypothetical airborne leak from a glovebox is difficult. This difficulty is recognized in DOE safety analysis guidance in general and the reason that such guidance does not call for quantitative determinations of immediate worker consequences from postulated accidents. In contradistinction, however, DOE safety analysis guidance provides specific approaches to evaluating consequences to an offsite individual.

The reason that worker consequences from such events are difficult to predict is that their phenomenology is impossible to define (predict) to the precision required. This situation arises from the fact that both the distance from source to the receptor and the duration of exposure are short. Uncertainties in the location of the worker (relative to the source) and the duration of exposure are therefore large fractions of their respective absolute values.

Additional complications arise from local obstructions to flow, such as the leaking glovebox itself, and from the fact that immediate worker exposure times are on the order of the characteristic periods of the turbulent fluctuations of the airflow that is dispersing the leaked material.

Exposure values are therefore intrinsically uncertain. That uncertainty is integrated out in calculations of consequences to the Maximally Exposed Offsite Individual (MOI) for whom the exposure period is taken as 2 hours by convention. Two hours is a reasonably realistic exposure period for an offsite individual, but not for an immediate worker.

Modeling

While these intrinsic limitations on estimating immediate worker exposures from glovebox leaks exist, sophisticated computational fluid dynamics modeling approaches have nevertheless been used to model radioactive aerosol and gas dispersion in laboratory rooms. Such approaches are useful for determining exposures at fixed locations-such as radiation monitors-and as tools for developing ventilation strategies and emergency egress procedures. They can also be used to help define generic worker consequence models as is done here. They are, however, also time consuming and specific to the detailed characteristics of the room being modeled and cannot, of course, overcome the intrinsic limitations of worker consequence modeling discussed above.

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Formal Model

In view of this situation, it is natural to reach for a *formal* model that is easily applied and generates reasonable, qualitative dose predictions-ones that might be expected to hold approximately for many similar accidents. Keep in mind, however, that circumstances are conceivable in which the immediate worker would receive a much higher dose.

It is useful to remember here that predictions of offsite consequence are treated similarly. The consequence from an airborne release is conventionally calculated as a consequence to the MOI-also a formal construct. Consequence to the MOI serves as a relative measure of consequence rather than as a realistic estimate of public exposure.

There are two immediate candidates for estimating worker consequences, an instantaneous mixing model and a gradual mixing model.

Instantaneous Mixing Model

The simplest model, the instantaneous mixing (IM) model, assumes that the release from the glovebox is instantaneous and that the released material spreads instantaneously and homogeneously throughout the room that houses the glovebox. In that case, the worker breathes the average concentration of the released hazardous material for the time it takes the worker to leave the room—the egress time—and the consequence to the worker is just the dose inhaled over that period.

Gradual Mixing Model

A more sophisticated model, the gradual mixing (GM) model, considers the hazardous material leak to be instantaneous and the leaked material to disperse at a constant velocity in all directions of a hemisphere whose plane coincides with the floor of the room and whose center is the leak site. Such a model was proposed by Drivas et al., 1996, and has been used at other DOE sites (WIPP, 1999).

The model assumes a larger and larger volume, uniformly occupied by the material released by the source, at lower and lower concentration as the cloud disperses. The immediate worker is initially at a radius equal to the extent of the structure releasing the source—the glovebox in this case—and is assumed to leave the room after a time that is longer than it takes the cloud to disperse. The worker is thus immersed in the cloud from the moment the cloud reaches the worker to the time the worker leaves the room.

Description of the Worker Dose Models

Instantaneous Mixing Model

According to the assumptions of the IM model, the released, airborne material instantly and uniformly occupies the room. Its concentration is therefore simply $C = Q/V$, where Q is the amount of hazardous material released from glovebox (source term) and V is the volume of the room.[1] The dose to the worker is therefore

$$Dose = C \times Br \times \boldsymbol{t} \times DCF \,, \tag{1}$$

with

Br = breathing rate of receptor
DCF = dose conversion factor: dose from one gram of inhaled material
ô = worker exposure time

[1] Ventilation losses over a period equal to the worker's egress time can be shown to be negligible relative to the approximations of the model. This is true if the residence time of the air in the room is appreciably longer than the worker egress time, which is generally the case at LANL.

Gradual Mixing Model

The GM model uses the more realistic assumption of gradual dispersion of the released material. The released cloud is assumed to expand such that its radius, *r*, is proportional to the time, *t*, since release, or $r = at$, where *a* = the constant speed of expansion.

This assumption matches the physically intuitive picture in which the source term is diluted as the surrounding clean air mixes with it through the turbulent convection flow that is always present. Intuitively, the volume of clean air that enters the source cloud is proportional to the area of the interface between source cloud and clean air, or the hemisphere of radius *r*. Mathematically, this proportionality can be expressed by

$$\frac{dV}{dt} = \frac{d}{dt}\frac{2}{3}\pi r^{3} = \alpha 2\pi r^{2}, \tag{2}$$

where α is the proportionality constant between the influx flow rate and the interface area.

The solution of this equation is

$\frac{dr}{dt} = \alpha$, so that the *a* of the WIPP model is just the α of our approach.

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Description of the Worker Dose Models, Continued

Ventilation Flow

The WIPP Safety Analysis Report (WIPP, 1999) assumes a = 0.25 m/s based on estimates of ventilation flow for the location of interest at WIPP. In view of our interpretation of a, the order-of-magnitude of this value seems reasonable for turbulent mixing in essentially still, room air. For one, it corresponds roughly to what one observes as the migration rate of cigarette smoke—on the order of a meter or less in a second.

LANL Estimates

For LANL, a value for a can be estimated from recent studies of turbulent convection flow velocities and aerosol transport rates in two laboratory rooms and in a scaled-down mockup facility of such a room (Whicker, 1997, Whicker, 2001, Wasiolek, 1999). The relevant findings from these studies are summarized in Appendix A. In addition, a re-examination of some of the raw data for one of those studies was undertaken by Whicker and is presented in Appendix B. A value for á can also be estimated from the continuous air monitor (CAM) alarm times that were recorded by one of us (Wannigman; see Appendix C) for the accidental release of plutonium-238 at LANL in March 2000. That estimate is illustrated in Appendix C.

The LANL studies by Whicker et al. (1997) and the measurements of plutonium-238 dispersal by Wannigman lead to the following observations that are relevant here:

- Mean air speeds (average over dispersed measurement locations) in a room are directly proportional to the air exchange rate for the room. That is, turbulent mixing in the room is dominated by ventilation flow, not natural convection.
- Mean air speed depends on the size of the room, but less so on the furniture in the room. Table 1 shows the measurements that were taken.

Table 1. Average Air Speeds by Room and Air Exchange Rate

	V (m^3)	EX (1/h)	<u> (cm/s)
Room 420	1,350	7-10	20
Mockup	70.3	6	3–5
Mockup	70.3	12	7-12

V = volume of room; EX = air exchange rate; <u> = average room air speed.
Where a range of values is given, it refers to stratified sample averages by elevation of aerosol samplers

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LANL Estimates (continued)

- Lag times[2] are inversely proportional to the air exchange rate and generally decrease as furniture is removed from the room. A set of 20 lag-time measurements in Room 420 between specific, but dispersed source-sampler couples, repeated three times, gave an average cloud-front speed of 7.3 cm/s for a range of speeds between 5 cm/s and 12 cm/s. This speed is less than half the 20 cm/s average air speed measured for Room 420. The *discrepancy* can be understood from the fact that local air velocity measurements capture the randomly directed flow velocities of the turbulent motion—not the directed flow of the cloud-front—the á implied by our model. One would expect the cloud-front speed to be lower.
- Lag times inferred for Room 206, from CAM alarm times for the accidental plutonium-238 release of March 2000 can be inferred as is done in Appendix C. Those values range between 17 cm/s and 20 cm/s—reminiscent of the average air speeds that were measured for Room 420, but not the corresponding cloud-front speeds. This discrepancy is not understood, although an explanation may lie in the possibility that the flow was channeled, as appears to be the case from inspection of the concentration isopleths drawn by Wannigman from sampler measurements during the event.

These observations indicate that one can expect a range for á that reflects room air exchange rate, room size, and obstructions to flow in the room. These will vary somewhat from situation to situation, while a generic worker dose model must predict reasonably conservative upper bounds for all situations. It will be shown below that worker dose is sensitively dependent on á, with higher doses for smaller values of á. For this reason, and observing the measured range of 7 cm/s to 20 cm/s, it seems reasonable to chose á = 10 cm/s for the model.

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[2] Lag time is approximately the time between the release of a puff of aerosol and the arrival of the puff's leading edge at a particular aerosol sampler.

LANL Estimates (continued)

If we assume that the expanding cloud reaches the receptor (worker) at time t_1 and the receptor leaves the room at time t_2 after the leak occurs, one can integrate over the breathed, time-dependent hazardous material concentration to arrive at the dose to the worker, assuming that the worker is unable to escape the uniformly dispersed cloud. Thus, by Equ. 1,

$$Dose = \int_{t_1}^{t_2} (C \times Br \times DCF)\,dt$$

$$= \int_{t_1}^{t_2} (Q/V \times Br \times DCF)dt$$

$$= Q \times Br \times DCF \int_{t_1}^{t_2} dt \,/ (\frac{2p}{3} r^3)$$

$$= \frac{Q \times Br \times DCF}{\frac{2p}{3} a^3} \int_{t_1}^{t_2} \frac{dt}{t^3},$$

(3)

and this expression integrates to

$$Dose = \frac{Q \cdot Br \cdot DCF}{\frac{4}{3} p a^3} \left(\frac{1}{t_1^2} - \frac{1}{t_2^2} \right). \qquad (4)$$

Here, the as yet undefined variables are:

t_1 = time when the cloud reaches the receptor

t_2 = time when the receptor leaves the room.

Note that the cloud expansion velocity, *á*, is to the third power.

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LANL Estimates (continued)

For both these models, the release is assumed to be instantaneous. This is approximately true for spills, but not for fires that may last longer than it takes the worker to leave the room. In the latter case, it is appropriate to allow for this discrepancy by reducing the total source term, Q, by the fraction of the release time the worker is exposed to the source: t_2/t_s. Here t_s is the duration of the source.

Generic Evaluation of Worker Dose Models

The IM and GM models have been evaluated and compared for a normalized release of 1 milligram of respirable plutonium-239 aerosol. For plutonium-239 as oxide (lung clearance class Y), the dose conversion factor is DCF = 1.92×10^7 rem CEDE/g (for example, see Rao, 2000).

Gradual Mixing Model Assumptions

For the gradual mixing model, we assume that the dispersing cloud has to traverse a distance on the order of a glovebox dimension before reaching the worker. We assume this dimension to be 1 meter. This means that with a dispersion velocity of 0.1 m/s, t_1 = 10 s. This value, the time for the worker to leave the room (t_2) and the volume of the room is parameterized. Examples of the calculations are shown in the Appendix D and in figures 1, 2, and 3.

Model Comparison

It is clear from the figures, that the IM model is probably not realistic enough to satisfy the requirement that a generic worker dose model be somewhat realistic and conservative (see Figure 2). It also suffers from a strong, unrealistic dependence on room volume (Figure 1), essentially because it is not a mechanistic model.

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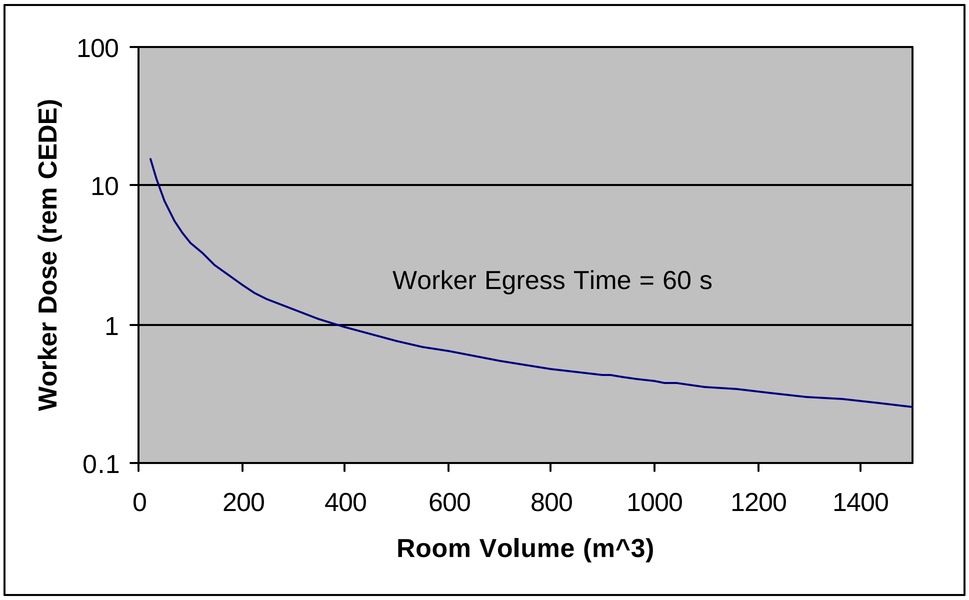

Figure 1. Worker Dose from Release of 1 mg Respirable Plutonium-239 Oxide: IM Mixing Model Dependence on Room Volume

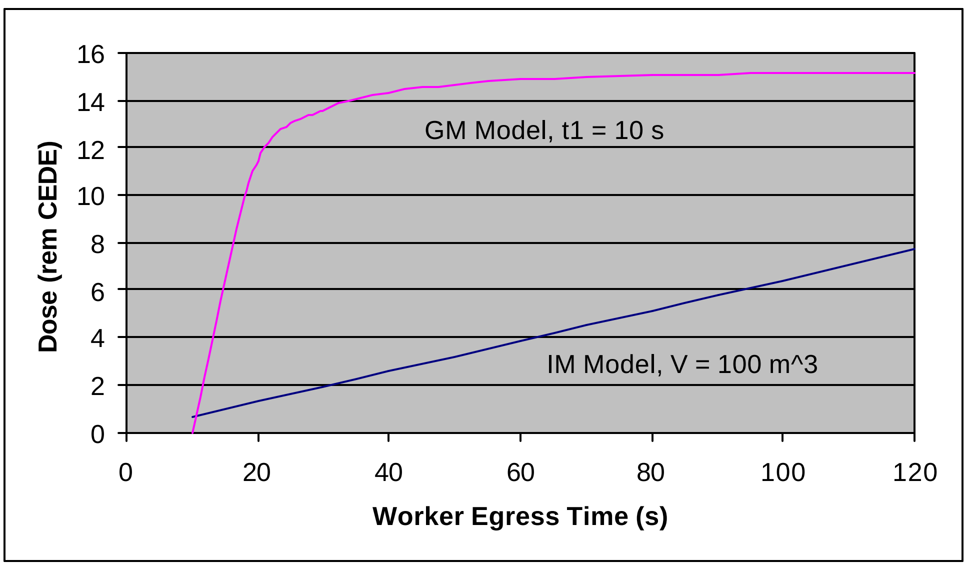

Figure 2. Worker Dose from Release of 1 mg Respirable Plutonium-239 Oxide: IM Model and GM Model Dependence on Worker Egress Time

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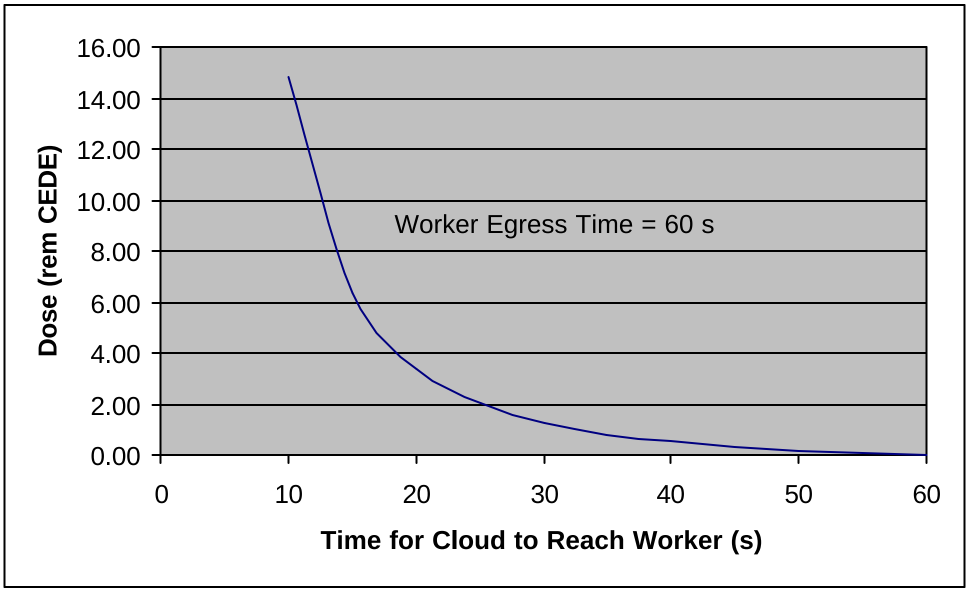

Figure 3. Worker Dose from Release of 1 mg Respirable Plutonium-239 Oxide: GM Model Dependence on t_1

Gradual Mixing Model Parameter Values

The GM model suffers from the uncertainty in the assumption of isotropic dispersion and in choice of the cloud-worker interception time, t_1 and egress time, t_2. For this report, the parameter values of the model are chosen based on the best available data from actual events and sampling studies. The GM model, using the formally chosen intercept time t_1 = 10 s, is recommended for systematic worker dose assessments. In the absence of measured egress times, the formal, generic value used here—60 seconds—is also recommended.

Gradual Mixing Model Applied to Isotopes Other than Plutonium-239

The above, normalized results can be adapted to the releases of other materials using the following conversion factors:

- If x grams are assumed to be released, multiply the results of the figures by 10^3x.
- If an isotope (or standard isotopic mixture) other than plutonium-239 is released, use the following factors (Jordan, 2000) to multiply the results depicted in figures 1, 2, and 3.
- If the source is a long-term release with estimated release time $t_s > t_2$, then multiply the total release, Q, by t_2/t_s.

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Table 2. Selected Conversion Factors

Isotope or Isotopic Mixture	If W Class, Multiply Graphed Values by	If Y Class, Multiply Graphed Values by
Plutonium-238	349	257
Weapons-Grade Plutonium	1.92	1.37
Heat Source Plutonium	319	235
EU	2.91×10^{-5}	4.89×10^{-4}

Example Calculations

Example 1

For the first example, we assume a glovebox contains weapons-grade plutonium fines that are contaminated with cutting oil. The fines spontaneously ignite, burn until extinguished, and ignite some of the gloves that are attached to the glove box, providing a leak path to the laboratory room. We assume the leak path factor (*LPF*) for material that is leaking from the glovebox to the room to be 1. The quantity of fines that are involved in the fire, or the material-at-risk (*MAR*) is assumed to correspond to the criticality limit for the glovebox—4.5 kg weapons-grade plutonium. It takes half an hour for the plutonium fire to extinguish, and the release is assumed uniform over that period. It takes 60 seconds for the worker to recognize that there is a fire and to leave the room.

From the DOE handbook on release fractions (DOE, 1994), the source term is

$$Q = MAR \times ARF \times RF \times LPF \tag{5}$$

where

ARF = Airborne Release Fraction

RF = Respirable Fraction.

For plutonium fires, the DOE handbook gives the bounding values

$ARF = 5 \times 10^{-4}$, $RF = 0.5$.

The source term for this problem is therefore

$Q = 4{,}500 \times 5 \times 10^{-4} \times 0.5 = 1.125$ g.

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Example 1 (continued)

From Figure 2 (or Appendix D), the worker dose from the release of 1 milligram of respirable plutonium-239 is 14.85 rem CEDE, given a worker egress time of 60 s. From Table 2, the conversion factor for weapons-grade plutonium (oxide aerosol is in lung clearance class Y) is 1.37. Since the fire is assumed to last 30 minutes, while the worker leaves in 1 minute, the dose to the worker is reduced by 1/30.

The dose to the immediate worker from the burning plutonium is therefore $1.125 \times 10^3 \times 1.37 \times 14.85 \times 1/30 = 763$ rem CEDE. If the worker is assumed to be 2 m instead of 1 m from the source, this value would be reduced by a factor of about 4.4 (to 173 rem CEDE); see Figure 3 (or Appendix D).

Example 2

In the second example, we assume a fine heat source oxide powder spill in a glovebox that is experiencing slight overpressurization, causing airborne powder to leak from the glovebox. Because the glovebox is designed to be airtight (less than10^{-6} cm^3/s for a 1 atmosphere pressure difference), the leak will be small and we conservatively assume that just 10^{-6} of the airborne powder leaks out[3]—that is, the leak path factor is 10^{-6}. The glovebox has a limit of 500 g on dispersible plutonium-238 and we assume this amount for the MAR.

From the DOE handbook (DOE, 1994), the bounding ARF for spills is 2×10^{-3}. The RF for heat source powder is close to 1. The source term is therefore $500 \times 2 \times 10^{-3} \times 1 \times 10^{-6} = 10^{-6}$ g. The release from the glovebox may persist for hours, but with exponential decay. For the sake of this example, we assume it instantaneous.

The dose to the immediate worker from 1 mg of respirable plutonium-239 is again 14.38 rem CEDE, again assuming an egress time of 60 s. From Table 2, the conversion factor for heat source plutonium is 235. The dose to the immediate worker from the leaked heat source plutonium is therefore $10^{-6} \times 10^3 \times 235 \times 14.85 = 3.5$ rem CEDE.

[3] A 10^{-6} cm^3/s leak from a 1 m^3 glovebox over a period of an hour implies a fractional release, over that hour, of $10^{-6}/10^6 \times 3{,}600 = 3.6 \times 10^{-9}$. Our 10^{-6} conservatively assumes some degradation of the glovebox leak-tightness since testing.

Conclusion

It is difficult to accurately predict the consequence to immediate workers from the inadvertent release of radioactive material from a glovebox. In contrast to calculated doses to the MOI, the dose to the immediate worker is sensitively dependent on the precise conditions of the accident, including the location of the worker relative to the source, how quickly the accident is detected, and how long it takes the worker to leave the room. Because of these sensitivities, even an order-of-magnitude prediction is difficult. The generic approach adopted in the report must be seen as formal and an average over an ensemble of possible results.

It is nevertheless instructive to estimate worker dose in this generic way, and this is done in this report. While the dose numbers are uncertain, particularly as applied to a specific event, the method provides a systematic approach for comparing worker doses from various postulated accidents.

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Whicker, 1997	J. J. Whicker, et al., *Evaluation of Continuous Air Monitor Placement in a Plutonium Facility*, Health Physics, Vol. 72, No. 5, pp.734-743, May 1997.
Whicker, 1999	J. J. Whicker, G. D. Baker, and P. T. Wasiolek, *Quantitative Measurements of Airflow inside a Nuclear Laboratory*, Health Physics, Vol. 79(6), pp.712-721, 2000.
Whicker, 2001	J. J. Whicker, P. T. Wasiolek, and R. A. Tavani, *Influence of Room Geometry and Ventilation Rate on Airflow and Aerosol Dispersion: Implication for Worker Protection*, Los Alamos Laboratory Report, LA-UR-00-5898.
WIPP, 1999	WIPP Safety Analysis Report, DOE/WIPP-95-2065 REV.3 Chapter 5, pp.5.2-16, October 25, 1999.

Appendix A
Selective Summary
of LANL Room Dispersion Measurements

J. J. Whicker, G. D. Baker, and P. T. Wasiolek, *Quantitative Measurements of Airflow inside a Nuclear Laboratory*, Health Physics, Vol. 79(6), pp.712-721, 2000.

- Room 420. Air velocity measurements.
- Dimensions: 18 m × 15 m × 5 m = 1,350 m^3.
- Air exchange rate: 7/h to 10/h.
- Mean air speed for all 69 sample locations was 19.9 cm/s with standard deviation 7.4 cm/s.
- Mean turbulence intensity was 35% with a standard deviation of 8.7%.

P. T. Wasiolek, et al., *Room Airflow Studies Using Sonic Anemometry*, Indoor Air, Vol. 9, pp.125-133, 1999.

- Room 420 and Mockup Facility. Air velocity measurements.
- Dimensions of Room 420: 18 m × 15 m × 5 m = 1,350 m^3.
- Mockup Facility: 6.1 m × 4.8 m × 2.4 m = 70.3 m^3.
- Air exchange rate for mockup facility was 6/h. For Room 420, it was nominally 10/h.
- Mean air speed for all 19 sampling locations in the mockup facility was 3.8 cm/s with standard deviation of 1.9 cm/s.
- Mean air speed for all 17 sampling locations in Room 420 was 20.0 cm/s with standard deviation 7.4 cm/s.

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J. J. Whicker, P. T. Wasiolek, and R. A. Tavani, *Influence of Room Geometry and Ventilation Rate on Airflow and Aerosol Dispersion: Implication for Worker Protection*, Los Alamos Laboratory Report, LA-UR-00-5898, 2000.

- Mockup facility. Air velocity and aerosol puff release measurements.
- Dimensions of mockup facility: 6.1 m × 4.8 m × 2.4 m = 70.3 m^3.
- Air exchange rates of 6/h and 12/h.
- Mean air speeds at 6/h ranged from 3 to 5 cm/s and 7 to 12 cm/s at 12/h, depending on room configuration and elevation of sample. That is, the mean air speed is proportional to the air exchange rate.
- Mean turbulence intensity does not change significantly with room air exchange rate.

  (Turbulence Intensity, K, is defined as $K = \frac{u_{r.m.s.}}{\bar{u}}$*, where* $u_{r.m.s}$ *is the root mean square air speed and û is the mean air speed. The observation that the turbulent intensity does not change significantly with room air exchange rate, while the mean air speed is proportional to it, therefore implies that the fluctuating speed, or turbulent eddy motion, increases in proportion to the air exchange rate of the room. This implies better mixing with increased air exchange, which may be intuitive, although one could imagine a decoupling between mixing rate and air exchange rate if mixing were dominated by thermal convection currents. This appears not to be the case for PF-4 laboratory rooms with air exchanges of nominally 6/h to10/h.)*

- Aerosol measurements: 16 samplers (laser particle counters, or LPCs). Lag times are inversely proportional to the air exchange rate. Lag times generally decrease as furniture is removed from room.
- At air exchange rate of 6/h, lag time was 152 s averaged over all sampler and release locations. It was 75 s for the air exchange rate of 12/h.

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J. J. Whicker, et al., *Evaluation of Continuous Air Monitor Placement in a Plutonium Facility,* Health Physics, Vol. 72, No. 5, pp.734-743, May 1997.

- Rooms 209 and 420. Aerosol puff release measurements
- Dimensions of Room 209: 18 m × 12 m × 5 m = 1,080 m^3;
- Room 420: 18 m × 15 m × 5 m = 1,350 m^3.
- Air exchange rates were 6/h for Room 209 and 10/h for Room 420.
- Airflow from ceiling inlet diffusers along ceiling down walls, inward along floor and upward along glovebox faces.
- Lag times were resolved by release group in this paper and thus cannot yield statistics on cloud-front speeds. Range: less than 0.5 minutes to 5 minutes. However, unpublished calculations by the authors of this paper provide cloud-front speeds for selected release point and sampler couples. These are presented in Appendix B.

Appendix B
Selected Lag Time Measurements, Room 420

The following table was developed by Jeff Whicker, ESH-4, from unpublished data gathered as part of the test series of reference (Whicker, 1997).

Table B-1. Aerosol Lag Times

(averages over three releases)

	Lag Time (s)	Distance (cm)	Speed (cm/s)	
Release Location R3				
LPC 7	20	160	8.00	
LPC 8	30	267	8.90	
LPC 9	80	292	3.65	
LPC 10	33.33	231	6.93	
LPC 12	56.67	460	8.12	7.12
Release Location R4				
LPC 7	47.5	234	4.93	
LPC 8	37.5	353	9.41	
LPC 9	45	277	6.16	
LPC 10	57.5	300	5.22	
LPC 12	62.5	406	6.50	6.44
Release Location R6				
LPC 7	50	300	6.00	
LPC 8	23.33	231	9.90	
LPC 9	20	127	6.35	
LPC 10	46.67	290	6.21	
LPC 12	43.33	376	8.68	7.43
Release Location R9				
LPC 7	30	277	9.23	
LPC 8	20	234	11.70	
LPC 9	40	198	4.95	
LPC 10	50	323	6.46	
LPC 12	30	287	9.57	8.38
Average Cloud-Front Speed			**7.34**	cm/s

Appendix C
Continuous Air Monitor Alarm Lag Times from LANL Plutonium-238 Release March 2000

The March 2000 airborne release of a small amount of plutonium-238 into a laboratory room at LANL was recorded by four continuous air monitors (CAMs) that automatically record alarm times (and other data). These times were provided by David Wannigman, ESH-1. They can be used to estimate the speed at which the cloud front of the release progressed through the laboratory, as follows.

There were four CAMS in the room, one at each corner, near floor level. They alarmed as follows.

CAM	**Absolute Time**	**Time Delay*** sec
A	13.57.27	
B	13.57.46	19
C	13.58.04	37
D	13.57.58	31

* Time delays of each CAM relative to CAM A, which gave the first alarm.

The time of the accidental release is unknown. However, one can use the delay times to estimate the desired cloud-front speeds if the radial distances from the point of release to each CAM are known. These were taken from a floor plan of the facility.

CAM	**Distance** m	**Extra Distance*** m
A	5.8	
B	9.5	3.7
C	11.9	6.1
D	11.2	5.4

* The extra distance traveled relative to that for CAM A, the closest CAM to the source. Note that it alarmed first, as expected.

The apparent cloud-front speed on the last legs to CAMs A, B, and C are therefore 0.19 m/s, 0.16 m/s and 0.17 m/s, respectively.

Appendix D
Example Calculations for a 1-mg Release of Plutonium-239

Table D-1. Instantaneous Mixing (IM) Model

Dose (rem)	Q (g)	V (m^3)	Br (m^3/s)	tau (s)	DCF (rem/g)
3.83999616	**0.001**	**100**	**3.33E-04**	**60**	**1.92E+07**

	Q = 0.001 g tau = 60s
	IM Model
V (m^3)	Dose (rem)
25	15.36
50	7.68
100	3.84
200	1.92
300	1.28
400	0.96
500	0.77
600	0.64
700	0.55
800	0.48
900	0.43
1000	0.38
1500	0.26

	V = 100 m^3 Q=0.001 g	**t1 = 10 s**
	IM Model	**GM Model**
tau (s)	Dose (rem)	Dose (rem)
10	0.64	0.0
20	1.28	11.5
30	1.92	13.6
40	2.56	14.3
50	3.20	14.7
60	3.84	14.9
70	4.48	15.0
80	5.12	15.0
90	5.76	15.1
100	6.40	15.1
110	7.04	15.2
120	7.68	15.2

Table D-2. Gradual Mixing (GM) Model

Dose (rem)	Q (g)	Br (m^3/s)	a (m/s)	DCF (rem/g)	t1 (s)	t2 (s)
14.8544472	**0.001**	**3.33E-04**	**0.1**	**1.92E+07**	**10**	**60**

Dose1 (rem)	15.27886
Dose2 (rem)	0.42441278
	14.8544472

	t2 = 60 s
	GM Model
t1 (s)	Dose (rem)
10	14.85
15	6.37
20	3.40
25	2.02
30	1.27
35	0.82
40	0.53
45	0.33
50	0.19
55	0.08
60	0.00