Potential Stable Metal Tritide Exposures at the Mound Laboratory

by

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EXECUTIVE SUMMARY

This report presents the bounding and best estimate internal dose associated with the intake of insoluble tritium particulate aerosols in the R/SW Tritium Complex (RSTC) at the Mound Laboratory. Of particular interest are personnel exposures to Type S insoluble stable metal tritides (SMTs) that could deliver more lung dose per unit intake than other more-soluble tritiated compounds. Large numbers of contamination swipe surveys taken on a daily basis from the operating areas during operations were located. The method for estimating the inhalation dose makes use of these contamination swipe data to estimate the SMT concentration resulting from the aerodynamic entrainment and/or mechanical resuspension of surface contamination. The accumulated dose was estimated for a Case Study that can typically be found in the dose reconstruction program. More than 69,000 swipe data entries for Rooms SW-150, SW-13, R-108, and SW-8 collectively were used in the assessment. The bounding and best estimate annual dose equivalents to the lung associated with intakes of the SMT are 0.48 mrem and 0.12 mrem, respectively. The assessment demonstrates that calculated exposures from the inhalation of insoluble metal tritides at Mound were small (in the millirem range), plausible, and bounding.

For the purposes of dose reconstruction, it is not necessary to determine “true” activity of SMT materials, due to beta energy self-absorption. In Section 2 of the *Mound Technical Basis Document for Stable Tritiated Particles and Organically Bound Tritium* (SRDB Ref ID 32921), it was demonstrated that apparent or “observed” activity on swipe samples is a better indicator of dose or dose potential than “true” activity. Moreover, it was demonstrated that knowledge of the specific SMT material and its size distribution are essentially unimportant to radiological protection. A simple radioassay for collected tritium is sufficient. For the purposes of this paper, it is necessary to determine the efficiency of the PC-5 proportional counter for counting SMTs.

For the purpose of EEOICPA dose reconstruction, the observed activity from the PC-5 or LS represents the actual doses.

1.0 INTRODUCTION

Tritium research, development, analytical recovery, enrichment, and surveillance activities occurred in the SW/R Tritium Complex (SRTC) on the Mound Laboratory site. The SW/R Tritium Complex consisted of the Semi-Works (SW) Building and two rows of rooms in the adjacent Research (R) Building that were converted to tritium operations. SRTC tritium operations started in these rooms in the 1960s and continued beyond the 1980s. Workers could have handled and been exposed to special tritium compounds including metal tritides while working in the SRTC. Mound had a comprehensive tritium urinalysis program, and workers with the potential for non-trivial exposure to SMTs participated in this program. In addition, Mound had a comprehensive air monitoring program designed to detect elemental tritium and/or tritiated water. In reality, SMTs are almost always accompanied by these more common forms of tritium, and this mitigates the potential for undetected releases of SMTs. Nonetheless, concern has been expressed regarding the adequacy of conventional tritium urinalysis and air monitoring methods for the detection of releases of insoluble SMTs. In the bounding case, if all tritium is in the form of insoluble (Type S) SMTs, a urinalysis program could fail to detect rather large intakes, which could result in correspondingly large missed doses, particularly to the lung. This study reconstructs the potential exposures to SMTs for workers who had a theoretical potential for exposure to SMTs at Mound using an alternative method of more precisely bounding doses.

The focus of this study is on Mound workers who had worked in the following four rooms in the SRTC:

- SW-150, which housed the Gas Synthesis, High Pressure Gas Loading, Pinch Weld, Gas Tungsten Arc (GTA) Welding, and Component Functional Testing Systems

- SW-13, which housed the Gas Synthesis System, the tritiated water synthesis and sampling system, and the Metallurgical Analysis Processes

- R-108, which housed and tritium recovery operations that included solid tritiated metal compounds, gas recovery, and purification from other tritium-handling processes

- SW-8, which housed the Effluent Removal System and was involved in tritium enrichment, recovery process technology, and the processing and containment of tritium-contaminated scrap from Mound activities as well as scrap generated at other DOE sites

For completeness, this study is expanded to address potential SMT exposures to workers during the decontamination and decommissioning (D&D) phase of the SW/R Tritium Complex.

2.0 METHODOLOGY

Dose estimates are determined via a dose reconstruction Case Study. The case in question specifies a worker who performed tritium operations in one of the SRTC rooms for two years and was first diagnosed with cancer 10 years after his/her last work environmental intake - a total span of 12 years from first intake to first cancer diagnosis. The dose estimates are based on the annual dose equivalents for the lung, which is the critical organ for the inhalation pathway. In order to maximize the estimated SMT exposures, the worker is assumed to have worked during the two years in which the air concentrations were the highest.

The annual dose equivalents are calculated by using contamination surveillance (swipe) data to calculate the airborne concentrations of SMTs in the work areas, followed by using dose conversion factors (DCFs) derived from the Integrated Modules for Bioassay Analysis (IMBA) computer program to calculate annual dose equivalent (DE) to target organs from SMT intakes. The airborne contamination concentration is obtained by applying a resuspension factor defined as the ratio between the airborne concentration of a pollutant per cubic meter directly over a contaminated surface and the areal pollutant surface contamination. The concept of re-suspending surface contamination is conventionally used by the U.S. Department of Energy

(DOE) and the U.S. Nuclear Regulatory Commission to perform safety analyses in the licensing of their facilities and operations. This method of dose estimation or consequence analysis is bounding (the tritium on the swipe samples are assumed SMTs) and inherently conservative. Appendix A presents the detailed tritium swipe analysis, including discussions regarding the swipe data search analysis, parameters, and assumptions that resulted in the annual dose equivalent to various organs.

3.0 CASE STUDY DOSE ANALYSIS

The calculation of the SMT exposures for the Case Study is represented by Equation (1):

$$DE = \sum_{k=1}^{m} \sum_{j=1}^{n-i} AD_{k,j} \tag{1}$$

Where:

DE = Accumulated dose equivalent (mrem)
AD = Annual dose from an intake
m = Number of years of intake
n = Number of years from first intake to the year cancer was diagnosed
j = Number of years of annual doses from a single intake
k = Year of intake
i = Integer series in increments of 1 from 0 to n.

Expanding for the Case Study (n = 12 years, m = 2 years) results in Equation (2):

$$DE = \sum_{j=1}^{12} AD_{1,j} + \sum_{j=1}^{11} AD_{2,j} \tag{2}$$

Substituting the annual dose equivalents to the lung in Appendix A to Equation (2) yields the maximum potential SMT dose to the workers who worked in the SRTC during the period from 1968 through 1989. The maximum potential SMT doses are presented in Table 1.

Table 1: Maximum Potential SMT Doses to the Lung (mrem)

Room	Best Est. (50th percentile) Swipe Values			Bounding (95th percentile) Swipe Values		
	$\sum_{j=1}^{12} AD_{1,j}$	$\sum_{j=1}^{11} AD_{2,j}$	Total	$\sum_{j=1}^{12} AD_{1,j}$	$\sum_{j=1}^{11} AD_{2,j}$	Total
SW-150	0.04	0.04	0.08	0.16	0.15	0.31
SW-13	0.04	0.03	0.07	0.12	0.11	0.23
R-108	0.02	0.01	0.03	0.10	0.07	0.17
SW-8	0.02	0.11	0.12	0.30	0.19	0.48

Note: The respective two years with the highest air concentrations associated with the specified rooms are:

	95th percentile		50th percentile	
	Year 1	Year 2	Year 1	Year 2
SW-150	1968	1977	1968	1977
SW-13	1975	1974	1974	1975
R-108	1985	1984	1985	1989
SW-8	1977	1975	1986	1969

4.0 RESULTS DISCUSSION

Table 1 lists the resulting bounding and the best estimate SMT lung doses for the Case Study scenario for all the SRTC rooms of interest. The highest bounding and best estimate DE values in Table 1 are 0.48 mrem and 0.12 mrem to the lung, respectively. These DE values are those that the Mound tritium workers could potentially have received by working in the SRTC. It can be concluded that the exposures from the inhalation of Type S insoluble metal tritides at Mound are below the plausible mrem levels range.

5.0 DECONTAMINATION AND DECOMMISSIONING PHASE

Interviews from three health physics professionals who worked at Mound have provided insight into the tritium (T_2, HT, HTO and OBT) and SMT monitoring programs that were in effect at Mound during various phases of plant remodeling and D&D activities. A summary of the salient points made in their interviews are presented below. In this overview, the facilities of primary concern are the SW and R buildings where SMTs were developed or used. Interviewees are identified in this document by the initial of their last name.

Work performed on the insoluble SMT compounds was performed inside glove boxes equipped with HEPA filters so the likelihood of these particulates entering the facilities' ductwork was extremely low. Tritiated particulates found inside the ductwork were most likely associated with hydrated iron oxides (rust) that could have formed from a reaction of HTO on the iron/stainless steel in the ductwork. Any tritium in this water of hydration would act as HTO after intake. In addition, upon completion of the insoluble tritide campaign, the laboratory workers who had worked with these materials completely cleaned up the laboratories, hoods, and glove boxes prior the beginning of any facility D&D being performed. As a result of this clean-up, the exposure potential of D&D workers to these compounds was very low.

Insoluble SMTs at Mound were a small fraction of the total tritium handled or processed through the plant, and protective measure implemented for its monitoring were accounted for by the protections for HTO and OBT. Although the insoluble SMT particles contain quantities of tritium, the chemistry and biokinetics of the SMTs did not represent a significant exposure hazard, primarily due to the low energy of the tritium betas and their self-absorption within the particles themselves. These particles, because of their insolubility, would not produce a whole body exposure like HTO or OBT. Insoluble SMT particles could have exposed the lungs, but not to the level predicted by the amount of tritium in the volume of the particles. Only exposures from the beta rays leaving the surface of the particles could expose the lung or other organs.

The workplace monitoring concentrated on personnel protective measures against the most likely tritium compound hazards in the Mound workplaces. Health Physics procedures and practices implemented at the plant were uniform and strictly enforced in assessing the workplace hazards prior to the initiation of either facility modifications or D&D activities.

Interview Summaries:

The first person interviewed, Mr. XX, worked at Mound from 1981 to 2005. In previous interviews with Mr. XX, we interpreted him to say that "all workers that were involved in the ductwork removal between the B, R and SW buildings to the SW stack were bioassayed for tritium." Clarification from Mr. XX indicated that our interpretation was in error. He indicated that D&D workers came from two populations of workers, PP Building workers and SW Building workers. Only SW workers were on a routine tritium bioassay program; PP workers were not. He indicated that this mix of workers applied the normal end-of-job sampling protocols they used. Although they all wore dust respirators, only the PP workers left nose swipes because that was their procedure after wearing a respirator in the plutonium areas; SW workers did not leave nose swipes because the respirators were for dust protection only. The PP workers did not leave bioassay samples for tritium because the "ducts were from the cold side of SW and therefore no need." Although Mr. XX suspected the ducts were clean, he confirmed that the reason he had directed that the ductwork be swiped for alpha was his recent experience in PP Building D&D. He knew that some alpha emitters had been used in SW Building; to confirm that this run of ductwork had not come from those areas he had swipes taken and counted for alpha. No alpha activity was found. These swipes were not counted for tritium. This work preceded by about 10 years concerns about D&D removal of SW building ductwork and the issues of stable metal tritides.

Mr. XX was not at Mound during the D&D phase of the SW Building ductwork project. He suggests that Mr. XY, who was involved with the tritium areas in the R, SW and T buildings, would know the workplace indicators surrounding this project. The plant established a methodology to quantify the radiological hazards associated with insoluble SMT by using scanning electron microscopy (SEM) techniques and stoichiometrically calculating the amount of tritium in the number and size of particles collected on breathing zone (BZ) air samplers worn by workers.

The second person interviewed, Mr. XY, worked at Mound from 1990 to 2003. Mr. XY indicated that full-blown D&D of SW and R buildings, excluding Corridor 5, did not get started until 1998 or 1999. With the implementation of DAC-hr tracking, based on the use of BZ sample results collected from workers, the plant did begin regularly monitoring for insoluble particulate tritides. All of these D&D workers wore BZ samplers and this change occurred around 1999. The assumption used to monitor workers was that the urine samples analyzed for betas represented the soluble tritium from tritium gas and/or HTO, and the particulates collected by the BZ samplers represented the insoluble particles and tritium betas that would not have shown up in the urine samples. The BZ filters would have been counted via liquid scintillation (LS) and/or proportional counters. There was a Technical Basis Document (TBD) developed describing the methods used for this analysis.

The third person interviewed, Mr. XZ, worked at Mound from 1997 through 2003. Mr. XZ was involved in the implementation of the programs and practices, and the development of the Radiation Work Permits (RWPs), that were in place to monitor and protect workers during the D&D of these areas. Some of the specific work controls and work place monitoring indicators included the swiping of all ductwork. Any area with the potential for contamination (tritium, alpha, or beta) was required to be characterized. A Needs Evaluation was required prior to entry or demolition to assess the level of worker protections required, the need to wear breathing zone samplers to collect particulates, and the need for bioassay sampling and analyses for intake determinations.

BZ samples were examined via SEM techniques and LS counted for tritium. Mr. XZ indicated that, based on this sampling and analysis protocol, the insoluble stable metal tritides were not a significant exposure hazard, and they were less of a hazard compared to the soluble forms (HTO and OBT) that would show up in urinalysis. The radiological controls for an area/job were driven by the soluble tritium forms (HTO & OBT), not the insoluble SMT. He mentioned that, generally, high-contamination areas (HCAs) were the only areas likely to exceed 2% of a DAC and require personal monitoring for tritium. Mr. XZ felt that it would be rare to have a situation where a job would run into an unexpected HCA and not already have some form of air monitoring in place to estimate the insoluble SMT exposure. He did not recall any incidents where it was determined after the fact that a worker should have been monitored for insoluble SMTs and was not. It was Mr. XZ's recollection that the D&D of the main tritium areas did not occur until the insoluble SMT monitoring program was in place. The D&D health physics program was aware of the fact that insoluble SMTs were produced during operations and the protective measures and monitoring techniques used at the plant during this phase of Mound's history provided adequate protection and monitoring for these potential hazards. In addition, Mr. XZ felt that the protective measures for HTO used at the plant during the previous phases of Mound's history also provided adequate protection to mitigate exposures from insoluble SMTs.

Conclusion

The worker protection practices and health physics program used at Mound for protection against insoluble tritides, and the processes in which they were encountered, indicates that the SMTs did not present any internal dose to workers, theoretically and physically.

6.0 REFERENCES

Chu, S., *Excel Spreadsheet, R-108 SW-8 in 1980s 3-12* [location to be determined]

Chu, S., *Excel Spreadsheet, R-108 SW-8 pre 1980 3-12* [location to be determined]

Chu, S., *Excel Spreadsheet, SW-13 SW-150 1960s-1990s* [location to be determined]

APPENDIX A: ANNUAL ORGAN DOSE EQUIVALENT CALCULATIONS

A 1.0 Analytical Model

During the SW/R Tritium Complex (SRTC) operational period, routine smear samples were taken in each room and counted to ensure that surface contamination levels were within the limits set by the Radiological Control Program at that time. The routine facility contamination surveillance (swipe) data on record were used to calculate airborne SMT concentration by applying a resuspension factor (RF) that enables estimation of the amount of removable surface contamination that had become airborne due to the aerodynamic entrainment and mechanical actions or disturbances. The RF is defined as the ratio between the airborne concentration of a pollutant per cubic meter directly over a contaminated surface and the areal pollutant surface contamination; the RF has a unit of m^{-1}. In concept, the factor represents the uniform concentration above a contaminated surface at a certain height. The factors are derived from resuspension rate experiments and field studies in which the airborne concentration of a pollutant was measured at a specified height above the surface collected over a specified period versus the level of surface contamination.

Next, dose conversion factors (DCFs) derived from the Integrated Modules for Bioassay Analysis (IMBA) computer program were used to calculate the annual dose equivalent (DE) to target organs from SMT intakes. The DEs are estimated to provide 50 subsequent annual doses from the total intake in the year specified for the Case Study dose reconstruction used in this analysis.

The calculation model is represented by Equation (A-1):

$$DE = \{[(C_{PC-5} \times (Eff_{PC-5})^{-1}) \times CF] \times 100 \times RF\} \times Br \times T \times DCF \tag{A-1}$$

Where:

DE = Internal organ dose (mrem)

C_{PC-5} = Contamination swipe data as counted by a PC-5 proportional counter (cpm/100 cm^2)

Eff_{PC-5} = Counter efficiency (cpm/dpm)

CF = Conversion Factor of 4.505×10^{-7} µCi/dpm

100 = Constant that converts 100 cm^2 to m^2

RF = Resuspension Factor defined as the ratio between the airborne concentration of a pollutant per cubic meter directly over a contaminated surface and the areal pollutant surface contamination (unit = m^{-1})

Br = Worker's breathing rate of 1.2 m^3/hr (ICRP 1994a)

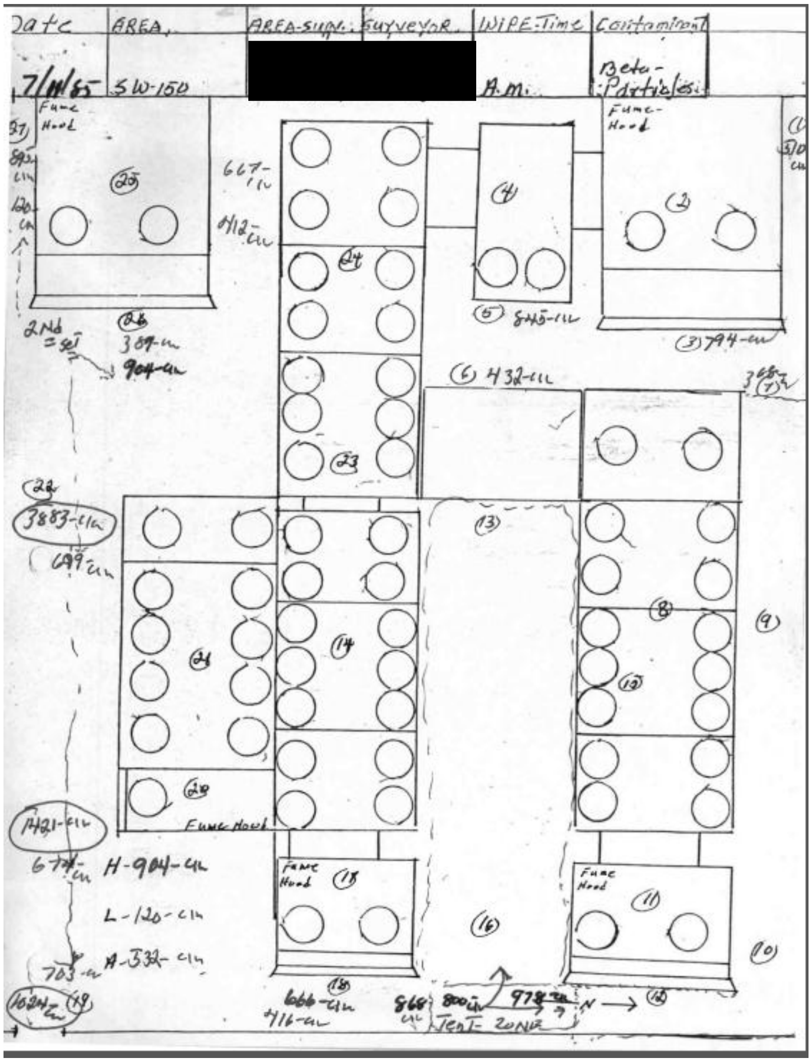
T = Exposure time of 2,000 working hr/yr

DCF = Dose Conversion Factor for Type S, 5-µm activity median aerodynamic diameter (AMAD) SMT for the target organ (mrem/µCi)

Exposures to SMT are estimated on a monthly or annual basis using the 50th and 95th percentile SMT air concentrations derived from the contamination swipe data. The surface contamination represented by the swipe samples is assumed to consist entirely of insoluble SMT particulates. Nine target organs projected to receive the highest total doses over an extended period (50 years) are evaluated for the inhalation of Type S SMT particulates.

A 2.0 Contamination Survey Data and Analysis

The routine contamination swipe data used in this report are obtained from a set of Building Contamination Surveys (Wipe Samples) Reports for the R and SW Buildings. More than 10,900 SRDB documents were reviewed and more than 220,000 pages were read. Twenty-nine (29) of those reports contained swipe data reported on a routine basis for Rooms SW-150, SW-13, R-108, and SW-8 for the period between 1968 and 1989. Typical locations in the rooms where swipe samples were taken are shown in Figures A-1 through A-4. In general, when the swipe data were reported, only the high, low and average values were reported, as shown in Figure A-5. The high values are used to generate the data statistics except for data taken in Rooms R-108 and SW-8 from the 1970s up to 1984. For these rooms and this time period, each high, low and average datum was considered a distinct data point for use to generate the data statistics. Figure A-6 shows the yearly swipe sample populations of the four rooms in the 22-year period. A total of >69,000 swipe data values were used for all four rooms. Although swipe data are available for a varying number of months (e.g., from 5 to 12 per year), typically there is a sufficiently large number of samples to develop the 95th-percentile contamination values on a monthly basis. Data for several months are combined to increase the data population to more than ten, when necessary. The airborne SMT concentrations in the rooms were calculated based on the median and 95th-percentile values.



NOTE: Swipe locations related to the measurements denoted by the uncircled values with units of cm.

Figure A-1: Typical Contamination Swipe Locations Denoted by the Measurements in Room SW-150

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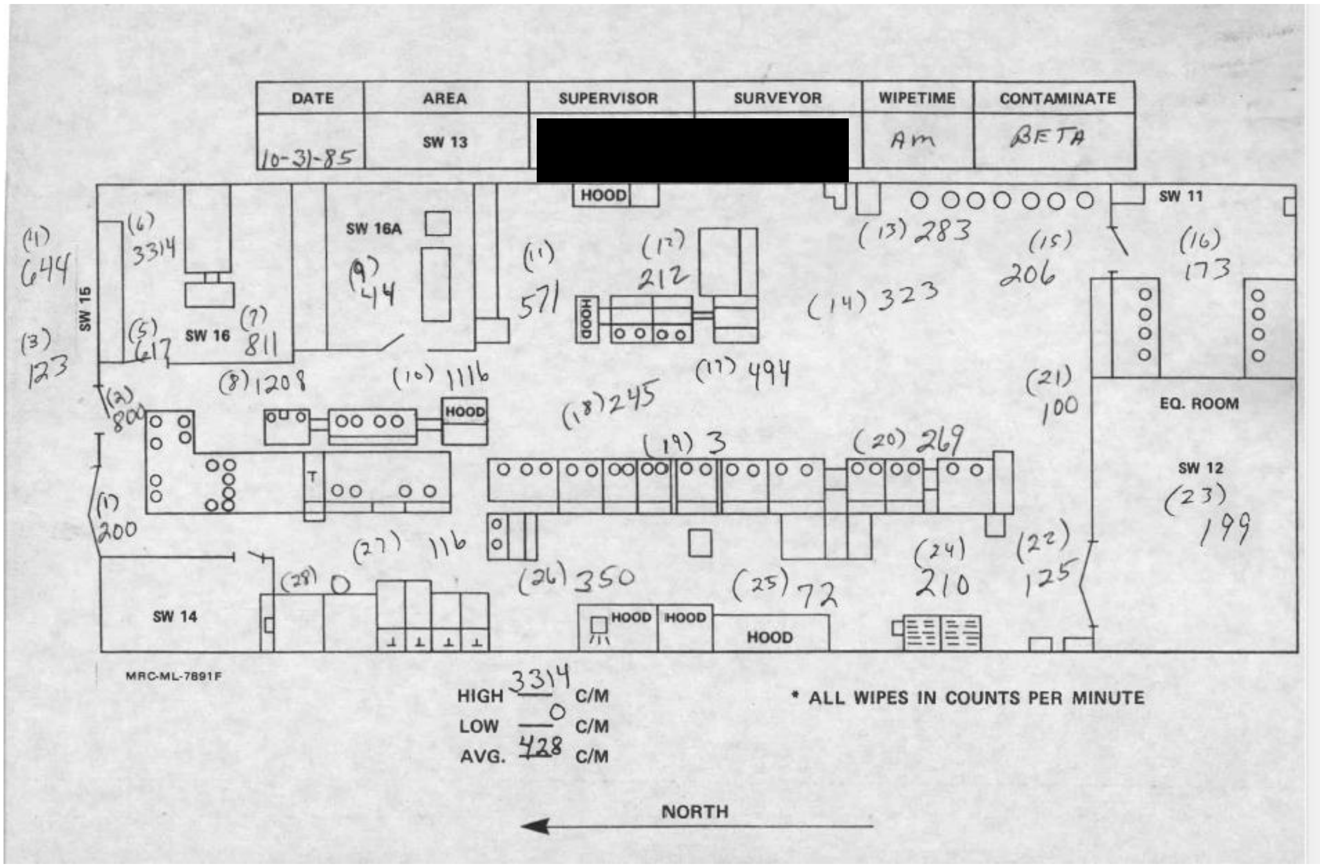


DATE	AREA	SUPERVISOR	SURVEYOR	WIPETIME	CONTAMINATE
10-31-85	SW 13	[redacted]	[redacted]	Am	BETA

HIGH 3314 C/M
LOW 0 C/M
AVG. 428 C/M

* ALL WIPES IN COUNTS PER MINUTE

Figure A-2: Typical Contamination Swipe Locations Denoted by the Measurements in Room SW-13

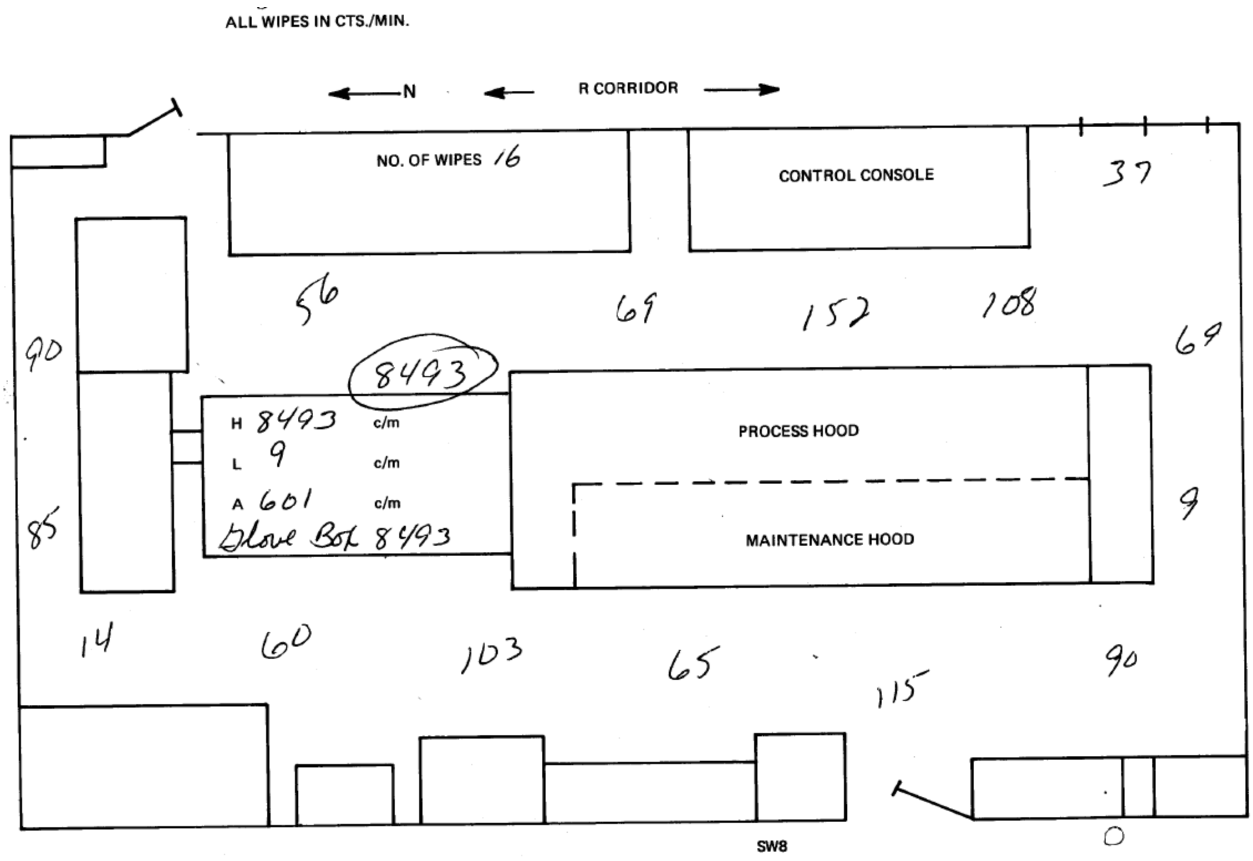


Figure A-3: Typical Contamination Swipe Locations Denoted by the Measurements in Room R-108

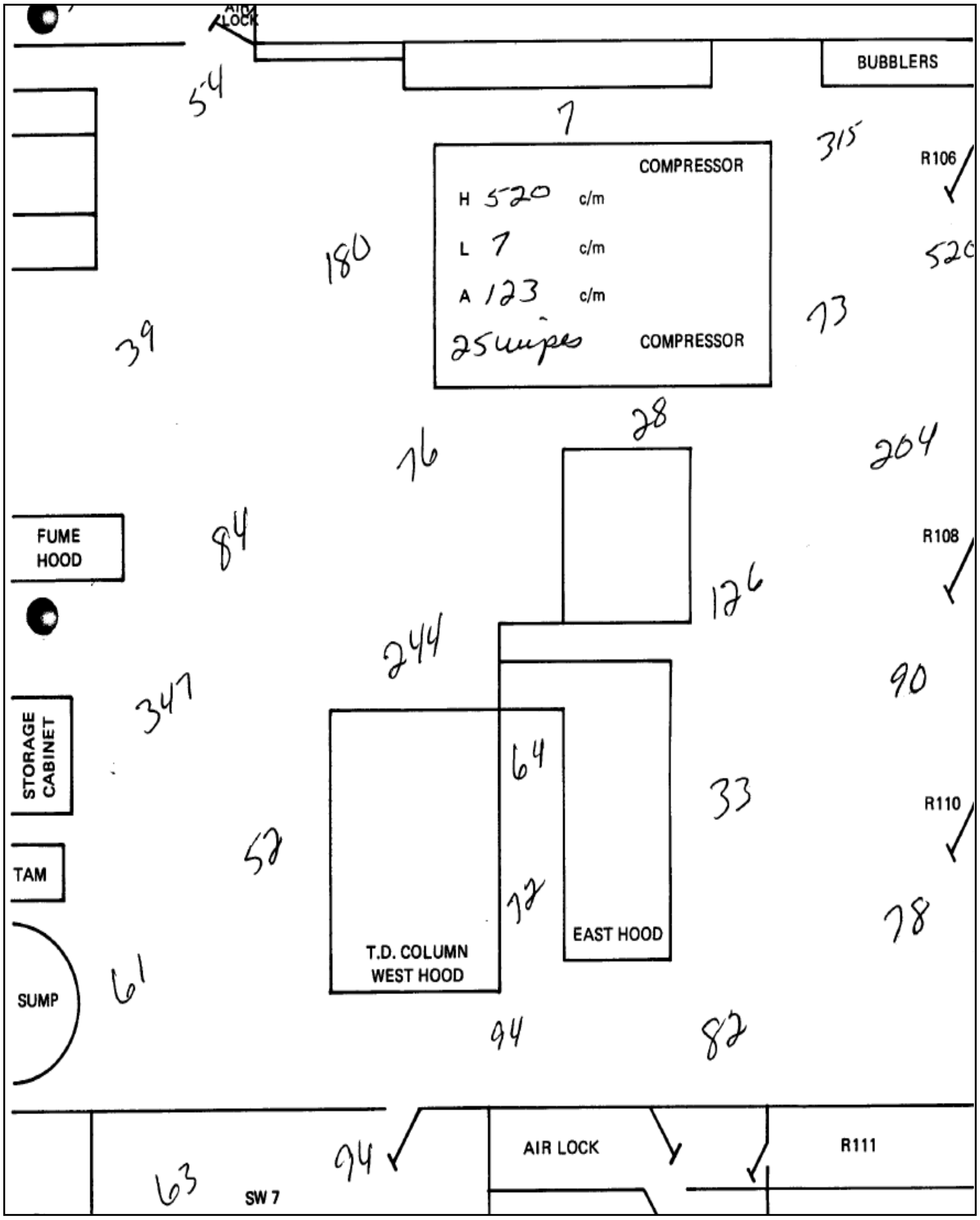
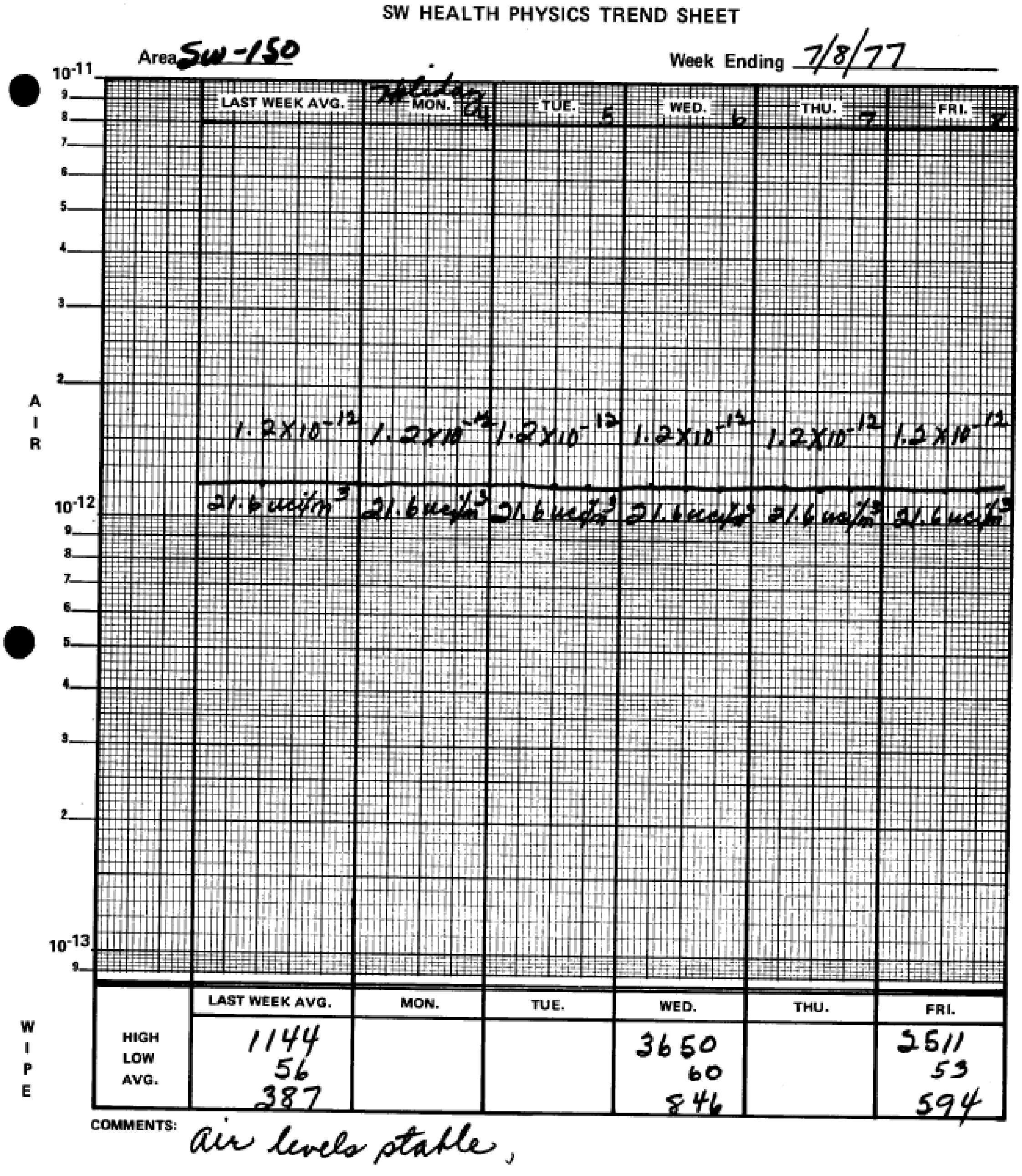


Figure A-4: Typical Contamination Swipe Locations Denoted by the Measurements in Room SW-8



SW HEALTH PHYSICS TREND SHEET

Area SW-150

Week Ending 7/8/77

	LAST WEEK AVG.	Holiday MON. 4	TUE. 5	WED. 6	THU. 7	FRI. 8
AIR	1.2×10^{-12}	1.2×10^{-12}	1.2×10^{-12}	1.2×10^{-12}	1.2×10^{-12}	1.2×10^{-12}
	$21.6\ uci/m^3$	$21.6\ uci/m^3$	$21.6\ uci/m^3$	$21.6\ uci/m^3$	$21.6\ uci/m^3$	$21.6\ uci/m^3$

WIPE		LAST WEEK AVG.	MON.	TUE.	WED.	THU.	FRI.
	HIGH	1144			3650		2511
	LOW	56			60		53
	AVG.	387			846		594

COMMENTS: air levels stable,

Figure A-5: Typical High, Low and Average Swipe Values Reported on the Health Physics Trend Sheets

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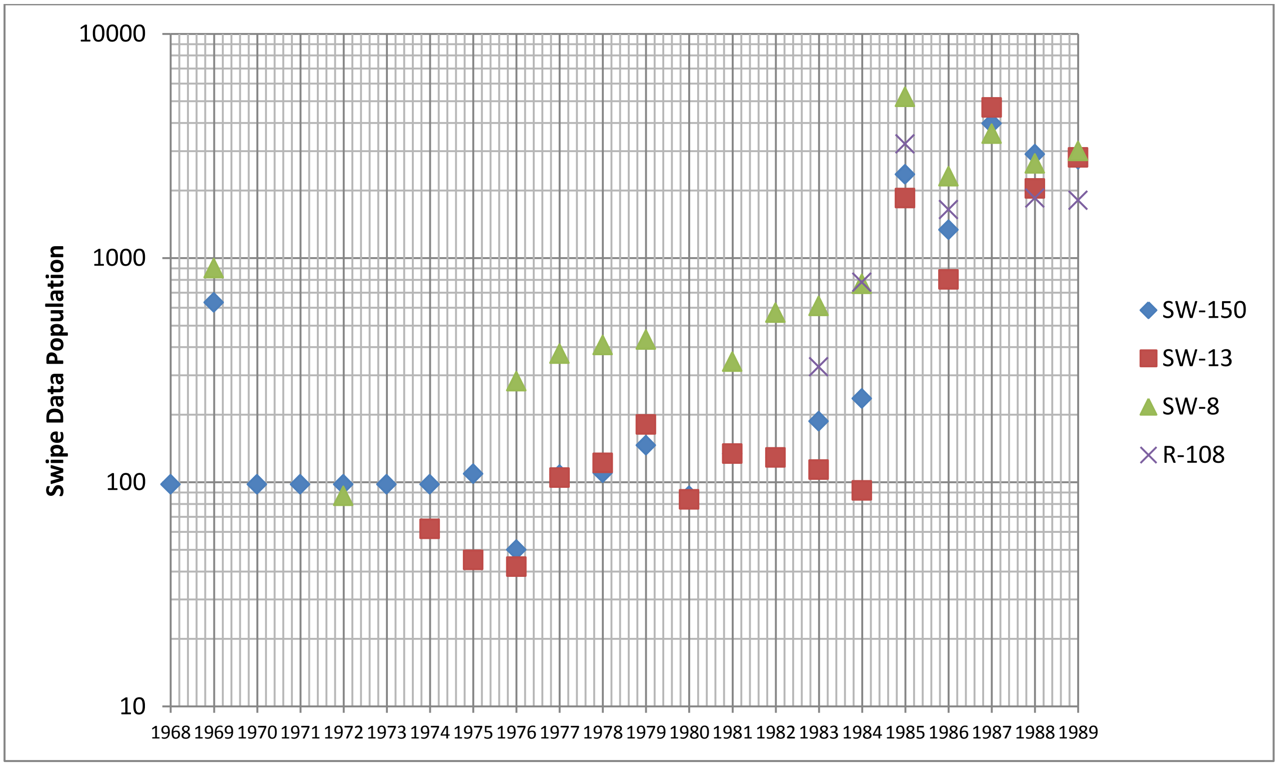

Figure A-6: Available Swipe Sample Populations

The 95th-percentile contamination values are developed by: (1) plotting the “z scores” of the data on the x axis and the natural logs of the data on the y axis; and (2) using the plotted data to determine a linear equation and the associated fit parameter, R^2. The linear equation will be in the form of Equation A-2:

$$y = mx + b \qquad \text{(A-2)}$$

Where:

y = Natural log of the data
m = Slope of the line
x = Z-score
b = Y-intercept

For a true lognormal distribution, the geometric mean (GM), which is also the 50th percentile, is equal to (e^{b}); the geometric standard deviation (GSD) is equal to (e^{m}); and the 95th percentile is equal to [GM × $(GSD)^{1.645}$]. Figures A-7 and A-8 show the resulting 95^{th}- and 50^{th}- percentile swipe values for the rooms that were used to calculate the airborne contamination.

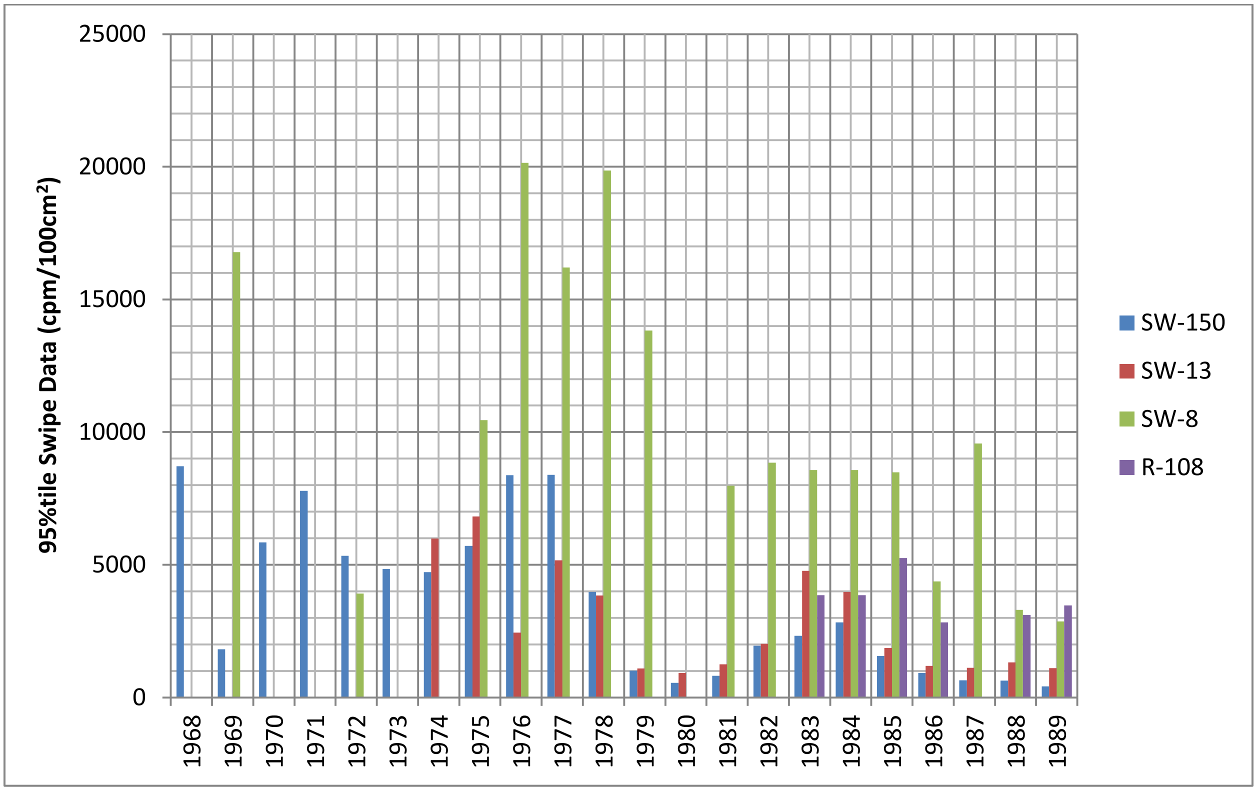

Figure A-7: 95^{th} Percentile Monthly Swipe Sample Counts

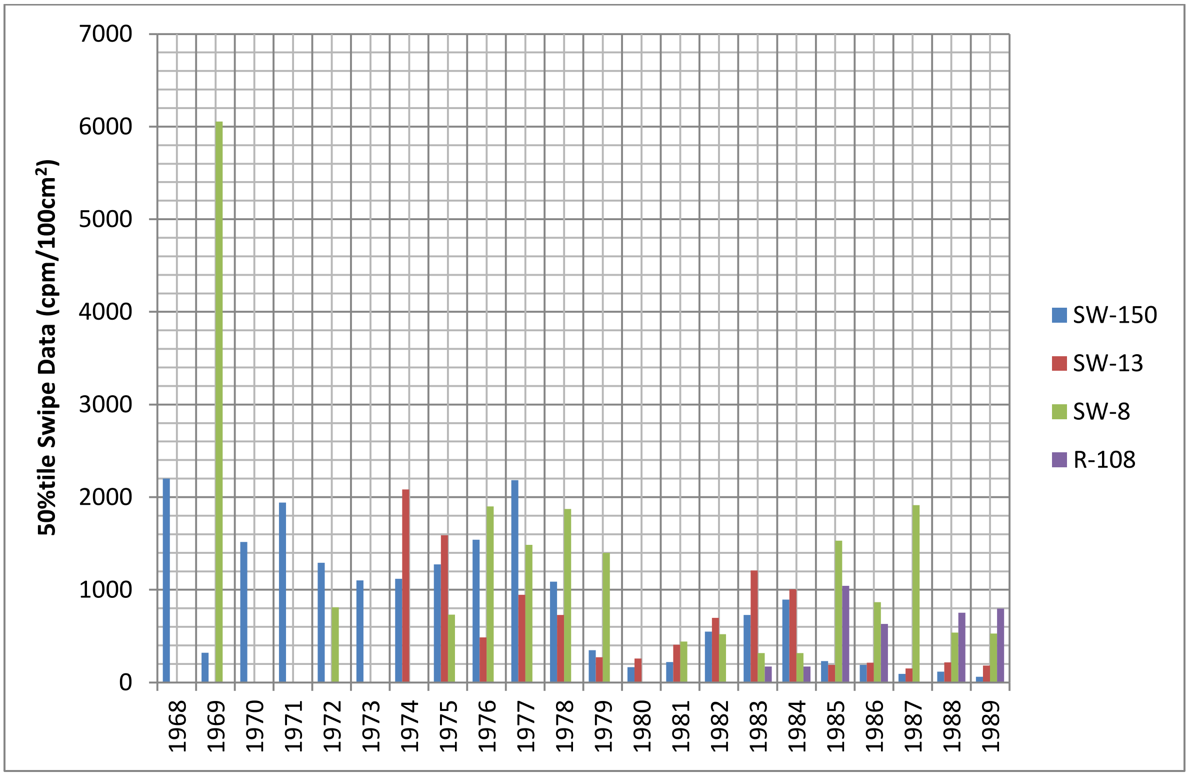

Figure A-8: 50th Percentile Monthly Swipe Sample Counts

Table A-1 identifies the respective two years with the highest swipe sample values for the specified SRTC rooms based on the 95th- and 50th- percentile swipe data values.

Table A-1: Two Years with the Highest Swipe Sample Values by SRTC Room

Room	50th Percentile	95th Percentile
SW-150	1968 1977	1968 1977
SW-13	1974 1975	1974 1975
SW-8	1969 1986	1975 1977
R-108	1985 1989	1985 1984

A 3.0 PC-5 Efficiency (*EFF_{PC-5}*) and Self Absorption Factor (SAF_e)

For dose reconstruction, it is not necessary to determine “true” activity of SMT materials, due to beta energy self-absorption. In Section 2 of the *Mound Technical Basis Document for Stable Tritiated Particles and Organically Bound Tritium* (SRDB Ref ID 32921), it was demonstrated that apparent or “observed” activity on swipe samples is a better indicator of dose or dose potential than “true” activity. Moreover, it was demonstrated that knowledge of the specific SMT material and its size distribution are essentially unimportant to radiological protection. A simple radioassay for collected tritium is sufficient. For the purposes of this paper, it is necessary to determine the efficiency of the PC-5 proportional counter for counting SMTs.

The PC-5 gas proportional counter was generally used to count tritium contamination control swipes at Mound prior to August 1993. The PC-5 is a “gross beta” counter with variable beta ray detection efficiency that is proportional to the energy of the beta emission. Consequently, the PC-5 data are reported in counts per minute (cpm). In order for a PC-5 counter result to be quantitative and be reported in units of disintegrations per minute (dpm), a calibration factor must be determined.

By 1990, the Packard “Tricarb” liquid scintillation (LS) counter was introduced at Mound for quantitative measurement of tritium on contamination control swipes. For tritium compounds, (e.g., tritiated water) that completely dissolve in the counting cocktail, LS systems are able to provide quantitative results because the factors that affect counting efficiency are measured and compensated using the transformed spectral index of the external standard quench parameter called tSIE. An additional self-absorption correction factor is required for compounds that are not soluble in the LS cocktail.

By definition, SMTs are relatively insoluble in lung fluids and LS cocktail so the assumption of complete solubility is not valid. The energy from beta rays originating inside a SMT particle can be absorbed inside the particle before reaching the particle surface where it becomes available for measurement or for delivery of dose to the surrounding tissue. For low energy beta rays (average 5.7 keV) emitted during the decay of tritium, self absorption can approach 100% when the particles are large (> 10 μm) because only the energy from betas emitted from the particle surface are available for measurement. Conversely, self-absorption can approach 0% for extremely small particles on the nanometer scale. The first step in establishing a counting efficiency for the PC-5 is to develop a correction factor for self-absorption applicable in the LS counts. That requires knowledge of the SMT particle size.

The following calculation assumes that the swipe counted in the LS counter detects chemically-pure metal tritide particles, and that all of the released beta emissions (surface activity) are measured as apparent dpm. This dpm measurement is converted to mass (Equation A-3), volume of a spherical particle (Equation A-4) and the diameter of that spherical particle (Equation A-5). The SAF_e is determined through the application of Equation A-8.

The measurements from the LS counter are converted to corrected activity (total beta in dpm) using the SAF_e in Equation A-9. Equation A-10 is then used to calculate the efficiency of the PC-5 proportional counter for tritium betas.

$$m(g) = A(dpm)\frac{Ci}{2.22 \times 10^{12}} \times \frac{g}{SpAct(Ci)} \tag{A-3}$$

$$V(cm^3) = A(dpm)\frac{Ci}{2.22 \times 10^{12}\ dpm} \times \frac{g}{SpAct(Ci)} \times \frac{cm^3}{\rho(g)} \tag{A-4}$$

<u>Where</u>:

A = Uncorrected tritium activity in dpm as measured by the LS counter
SpAct = Specific activity of SMT
ρ = SMT density
2.22×10^{12} = Value for converting dpm to Ci

An examination of the Self Absorption Factors (SAFs) using the *ρ* and *SpAct* data available in published literature indicated that the *SAFs* were fairly insensitive to these data and that the effect of self-absorption was slightly less pronounced for the compounds that had higher *ρ* and *SpAct* values. Therefore, the higher *ρ* and *SpAct* values are used in this study and they are nominally in the range of 11-12 g/cm^3 and 2-3 Ci/g, respectively.

Based on the equation for the volume of a sphere, $V = \frac{4}{3}\pi r^3$, and $d = 2 \times r$, the diameter of the metal tritide particle (*d*) in µm is calculated as shown in Equation A-5.

$$d\ (\mu m) = 2 \times r = 2 \times \sqrt[3]{\frac{3V}{4\pi}} \times \frac{1 \times 10^4\ \mu m}{cm} \qquad \text{(A-5)}$$

Tsoulfanidis (1991) described a method for calculating the self-absorption factor (SAF) in spherical particles. Building on that work, Knopf, Wang et al. (1998) developed a numerical method to evaluate the self absorption factor of tritium beta rays (SAF_β), which is the fraction of beta rays escaping the particle, and for SAF_e, which is the fraction of the beta energy that escapes a spherical particle. The SAF_e is a better quantity for correction of LS counting efficiency because almost any amount of beta energy deposited in the LS cocktail will result in a count being recorded in the tritium "window." The SAF_e is also appropriate for dosimetry calculations because almost any amount of ionization from a beta decay that reaches living tissue can impart dose.

Equations A-6 and A-7 define the SAF_e as a function of tritide particle size (*d*). Figure A-9 illustrates the SAF_β and SAF_e results as function of particle size.

$$SAF_e = \frac{1}{0.856 + 2.88d} \qquad \text{for } d > 0.05\ \mu m \qquad \text{(A-6)}$$

$$SAF_e = 1 \qquad \text{for } d < 0.05\ \mu m \qquad \text{(A-7)}$$

Tritium swipe counting records are available documenting the results of swipes counted on both an LS counter and on a PC-5 system (SRDB Ref IDs: 81787, pdf pp. 8-247; 81788, pdf pp. 2-628; 81907, pdf pp. 425-700; 81908, pdf pp. 58-62; 81909, pdf pp. 2-692). A sample of 356 of these data pairs were transcribed for evaluation in a spreadsheet titled “Mound LSC & PC5 Comparison” (Sources: SRDB Ref IDs: 81787, pdf pp. 28-38, 44, 50, 60, 70, 80, 90, 100, 110; 81788, pdf pp. 2, 20). The PC-5 counting efficiency value for each paired sample (discussed below) is calculated by dividing the PC-5 count rate in cpm by the self-absorption-corrected LS counter activity in dpm. The sample of 356 pairs was reduced to 292 pairs by eliminating the 14 instances in which the PC-5 counting efficiency was 0%, and the 50 instances in which the PC-5 efficiency was judged to be implausibly high based on operating experiences of using a proportional counter for tritium counting (i.e., > 5%). All subsequent calculations are based on the 292 paired samples.

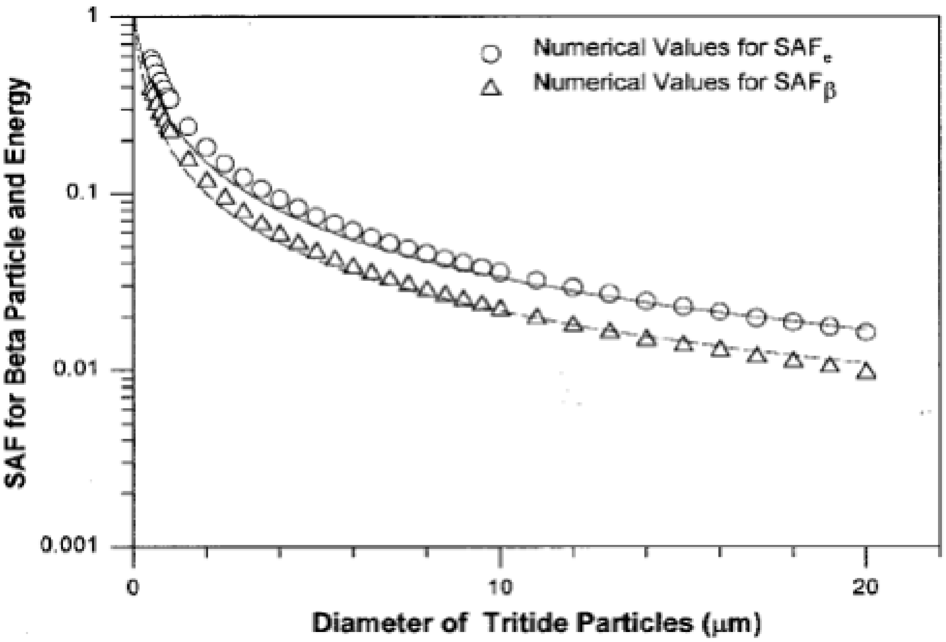

Figure A-9: Self-absorption Factors for Beta Particles and Beta Energy in SMT

The particle diameter distribution derived from the 292 pairs of count data can be fit to a lognormal distribution with a GM = 2.8 μm and GSD = 1.5. Figure A-10 illustrates the data and the fitted distribution. The great majority of particles represented by this distribution would be respirable. The default particle size assumption of 5 μm used in dose reconstruction is reasonably consistent with this distribution. The assumption that all activity is in a single particle is both bounding and favorable to the claimant. If the activity is more finely divided and distributed into more abundant but smaller particles, the SAF_e for each particle would be higher and the total activity would be lower.

The particle diameter calculated in Equation A-5 can be used in Equation A-6 to determine the SAF_e as a function of activity in the particle. Results of these calculations for a few activities of interest are shown in Table A-2. Figure A-11 presents the SAF_e as a function of SMT particle activity.

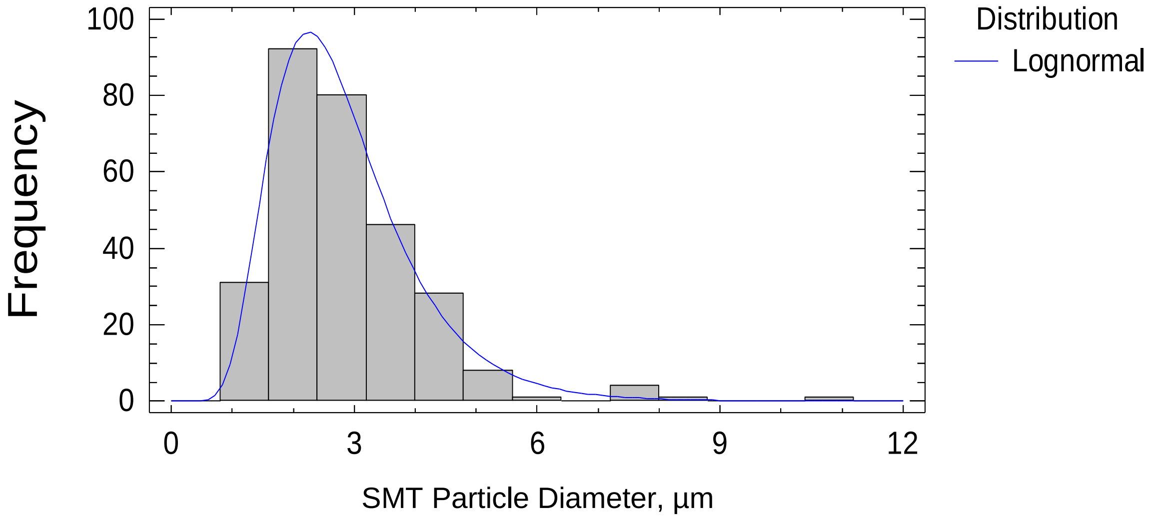

Figure A-10: Metal Tritide Particle Diameter Distribution Calculated from Uncorrected LS Counter Data

Table A-2: SMT Particle Mass, Diameter and Self-absorption Factor for Tritium Beta Rays (SAF_e) as a Function of the Uncorrected Activity of SMT Measured in the LS Counter

Measured Activity (dpm)	Particle mass (ng)	Particle diameter (μm)	SAF_e
1	0.00018	0.31	0.58
10	0.0018	0.66	0.36
100	0.018	1.4	0.20
1000	0.18	3.1	0.10
10000	1.8	6.6	0.050
20000	3.5	8.3	0.040

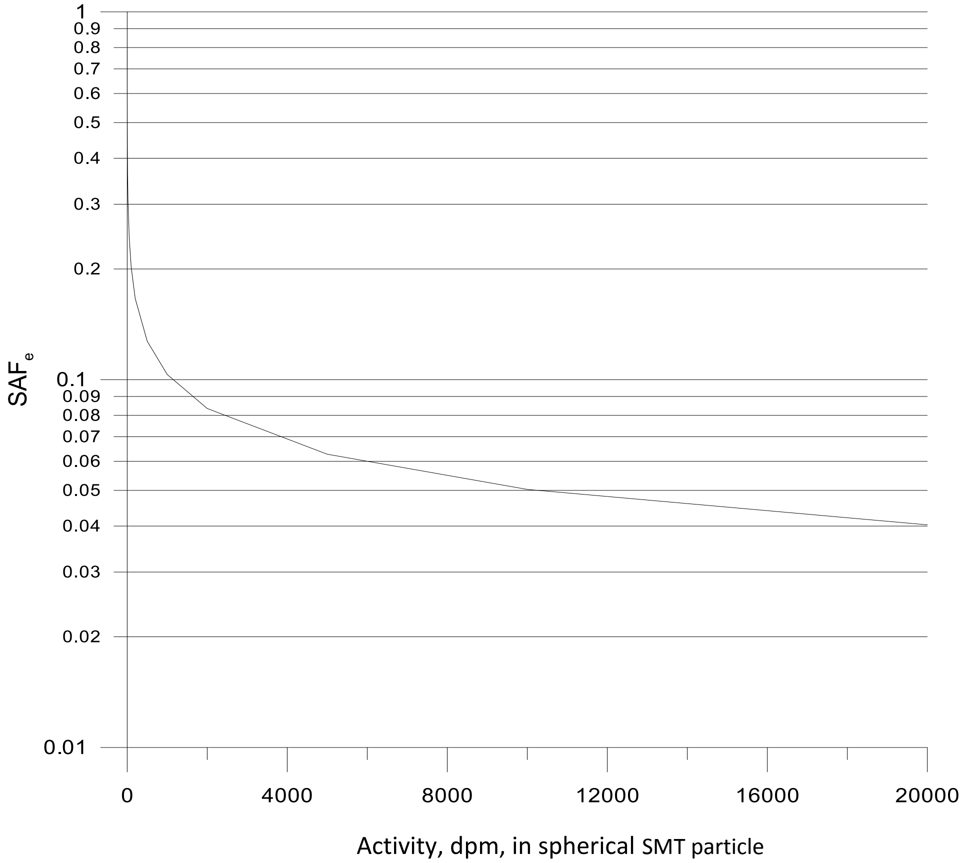

Figure A-11: SAF_e as a Function of SMT Particle Activity

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When the nominal values for specific activity and density are used, Equation A-4, Equation A-5, and Equation A-6 can be combined and simplified, resulting in Equation 8:

$$SAF_e(A) = \frac{1}{0.856 + 0.8825 \times \sqrt[3]{A}} \qquad \text{(A-8)}$$

The 292 SAF_e values can be fit to a lognormal distribution with a GM = 0.118 and GSD = 1.4, as shown in Figure A-12.

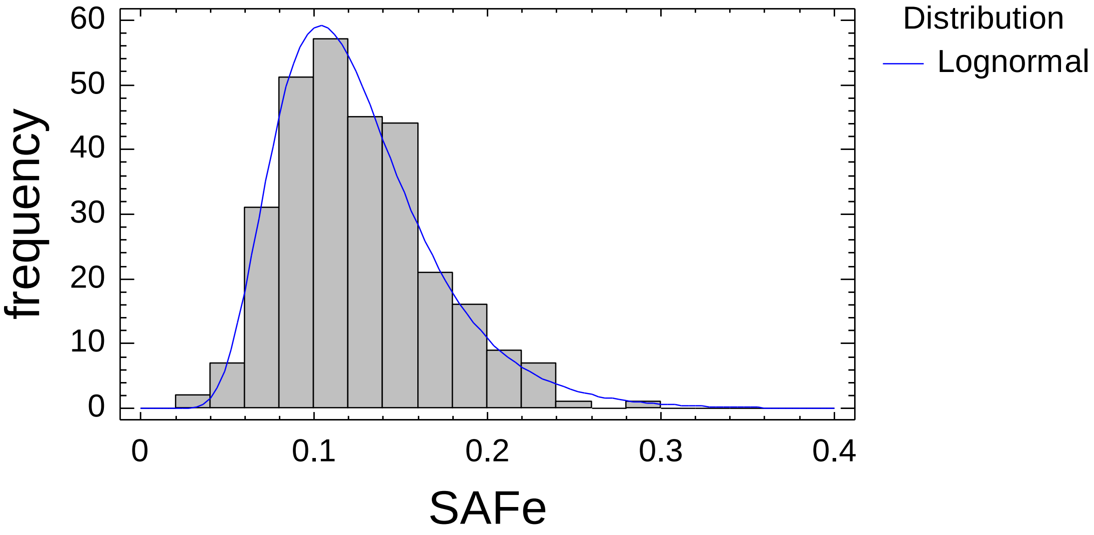

Figure A-12: Calculated SAF_e Values Fitted to a Lognormal Distribution

The self-absorption of beta rays by the SMT particles in swipes can be substantial and should be used to correct the nominal liquid scintillation counting efficiency. This can be accomplished by dividing the reported LS swipe activity (*A*) values by the corresponding $SAF_e(A)$ values, as shown in Equation A-9.

$$LS\ Act_{SAF-corrected} = \frac{A}{SAF_e(A)} \qquad \text{(A-9)}$$

The quotient of the ordered pairs representing the PC-5 count rate in cpm, and self-absorption-corrected LS counter activity in dpm, can be used to estimate the PC-5 counting efficiency, as shown in Equation A-10.

$$PC5Eff = \frac{PC5\ cpm}{LS\ Act_{SAF-corrected}} \quad \text{(A-10)}$$

The counting efficiencies of the 292 values, illustrated in Figure A-13, can be fit to a lognormal distribution with an arithmetic mean = 0.016, a GM = 0.011, and GSD = 2.2. The GM, nominally 1%, is assumed to represent the SMT counting efficiency of the PC-5.

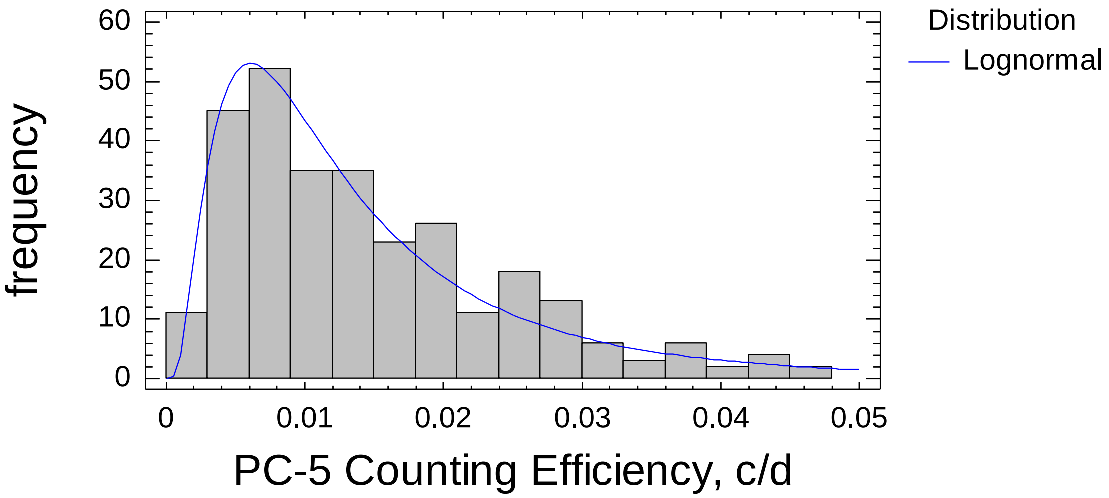

Figure A-13: PC-5 Counting Efficiency for SMT

The SAF_e can also be used as a multiplicative factor to adjust the calculated dose to lung tissue from SMT particles. Energy from beta decay that does not deposit in living tissue does not contribute to dose. In other words, lower tissue doses result when the SAF_e is included in the dose calculation. The dosimetry model for tritium compounds implemented in IMBA does not include the SAF_e (ORAUT 2007); however, a best estimate of dose would require this factor to be included. The SAF_e should be applied to the lung and esophagus because the SMT particle is the dominant chemical form in these organs. Most other tissues are irradiated by tritium in the form of HTO (which dissolves from the SMT), so use of the SAF_e is not appropriate. A few tissues (e.g., stomach wall and colon) could be irradiated by both chemical forms. To ensure a conservative dose calculation, SAF_e would not be applied to organs outside the respiratory tract.

Equation A-11 presents the organ/tissue dose calculation modified by the SAF_e for use in best estimate respiratory tract doses associated with SMT.

$$H_T = D_T \times w_R \times w_T \times SAF_e \quad \text{(A-11)}$$

Where:

H_T = Corrected dose to respiratory tract tissues
D_T = Absorbed dose in tissue T
W_R = Radiation weighting factor
W_T = Tissue weighting factor

Based on the above discussion, it is concluded that a PC-5 counter efficiency of 1% and a median SAF_e value of 0.12 should be incorporated in lung dose calculations.

A 4.0 Resuspension factor (*RF*)

A resuspension factor of 5×10^{-5} m^{-1} was selected for use in this study. This value came from ORAUT-OTIB-0070, *Dose Reconstruction During Residual Radioactivity Periods at Atomic Weapons Employer Facilities,* and is the highest of the four resuspension factors cited in the OTIB. OTIB-00070 compiles the following resuspension factors recommended to be used for dose assessments by DOE and NRC.

Based on their studies, DOE recommended that a value of 10^{-6} m^{-1} be used under quiescent conditions and a factor of 10 higher (10^{-5} m^{-1}) be used under conditions of moderate activity. The NRC initially proposed a resuspension factor of 5×10^{-5} m^{-1} to be used but later revised to

9.6×10^{-7} m^{-1} based on the fact that fresh deposits are not likely to be encountered at decommissioned facilities.

A 5.0 Dose Conversion Factors

The annual DCFs were calculated with IMBA. For calculating intake and dose from SMTs, NIOSH uses the guidance in ORAUT-OTIB-0066 (ORAUT 2007). This publication implements the recommendations for SMT aerosols in ICRP Publication 71. Because intakes were calculated based on air concentrations rather than urine bioassay, the modifications to the urine bioassay model discussed in ORAUT-OTIB-0066 were not necessary. IMBA was used to generate a table of annual dose equivalents per unit intake for Type S, 5-µm activity median aerodynamic diameter (AMAD) SMTs for various organs. DCFs were calculated for the nine organs projected to receive the highest total doses over an extended period (50 years). These organs were all from the respiratory and gastrointestinal tracts. Table A-3 lists the organs for which dose conversion factors were calculated.

Table A-3: Target Organ Designations and Descriptions

Organ	Description
SI	Small Intestine
ULI	Upper large intestine
LLI	Lower large intestine
ET	Extrathoracic
Lung	Lung
Colon	Colon
LN(ET)	Lymphatics and lymph nodes that drain the ET region
AI	Alveolar interstitial
LN(TH)	Lymphatics and lymph nodes that drain the thoracic region

The results of the IMBA calculations appear in Table A-4. DCF for the lung reflects the application of the SAF_e and the CDE is the sum for the 50-year period.

Table A-4: Annual Dose Equivalents Per Unit Intake to Various Organs for 50 Years

Year	Dose Conversion Factors (rem/μCi)								
	SI	ULI	LLI	ET	Lung(1)	Colon	LN(ET)	AI	LN(TH)
1	2.75E-05	1.65E-04	4.82E-04	6.89E-07	1.27E-04	3.02E-04	2.17E-04	3.18E-03	5.61E-04
2	4.23E-07	2.27E-06	6.56E-06	6.16E-07	8.02E-05	4.13E-06	5.16E-04	2.01E-03	7.94E-04
3	2.71E-07	1.45E-06	4.17E-06	7.36E-07	5.48E-05	2.63E-06	6.70E-04	1.37E-03	8.26E-04
4	1.76E-07	9.30E-07	2.68E-06	7.82E-07	3.84E-05	1.69E-06	7.37E-04	9.59E-04	8.41E-04
5	1.16E-07	6.01E-07	1.73E-06	7.83E-07	2.76E-05	1.09E-06	7.52E-04	6.88E-04	8.43E-04
6	7.68E-08	3.92E-07	1.13E-06	7.60E-07	2.04E-05	7.09E-07	7.39E-04	5.07E-04	8.37E-04
7	5.16E-08	2.57E-07	7.34E-07	7.19E-07	1.54E-05	4.64E-07	7.03E-04	3.82E-04	8.19E-04
8	3.54E-08	1.71E-07	4.87E-07	6.73E-07	1.19E-05	3.08E-07	6.61E-04	2.97E-04	7.97E-04
9	2.48E-08	1.16E-07	3.27E-07	6.24E-07	9.51E-06	2.07E-07	6.16E-04	2.36E-04	7.71E-04
10	1.78E-08	8.01E-08	2.24E-07	5.78E-07	7.76E-06	1.42E-07	5.71E-04	1.92E-04	7.43E-04
11	1.31E-08	5.62E-08	1.56E-07	5.29E-07	6.40E-06	9.94E-08	5.24E-04	1.58E-04	7.09E-04
12	9.94E-09	4.06E-08	1.12E-07	4.85E-07	5.38E-06	7.13E-08	4.81E-04	1.33E-04	6.76E-04
13	7.73E-09	3.01E-08	8.18E-08	4.44E-07	4.57E-06	5.24E-08	4.41E-04	1.13E-04	6.42E-04
14	6.18E-09	2.29E-08	6.17E-08	4.07E-07	3.93E-06	3.97E-08	4.04E-04	9.66E-05	6.09E-04
15	5.02E-09	1.78E-08	4.74E-08	3.71E-07	3.39E-06	3.06E-08	3.68E-04	8.31E-05	5.73E-04
16	4.16E-09	1.42E-08	3.75E-08	3.38E-07	2.94E-06	2.43E-08	3.36E-04	7.21E-05	5.39E-04
17	3.50E-09	1.16E-08	3.02E-08	3.09E-07	2.57E-06	1.96E-08	3.07E-04	6.28E-05	5.06E-04
18	2.99E-09	9.58E-09	2.49E-08	2.82E-07	2.25E-06	1.62E-08	2.80E-04	5.50E-05	4.76E-04
19	2.56E-09	8.02E-09	2.07E-08	2.56E-07	1.97E-06	1.35E-08	2.55E-04	4.80E-05	4.44E-04
20	2.22E-09	6.80E-09	1.74E-08	2.34E-07	1.73E-06	1.14E-08	2.33E-04	4.21E-05	4.14E-04
21	1.93E-09	5.81E-09	1.48E-08	2.13E-07	1.52E-06	9.70E-09	2.12E-04	3.69E-05	3.86E-04
22	1.69E-09	5.02E-09	1.27E-08	1.95E-07	1.34E-06	8.35E-09	1.94E-04	3.26E-05	3.61E-04
23	1.48E-09	4.32E-09	1.09E-08	1.77E-07	1.18E-06	7.18E-09	1.76E-04	2.86E-05	3.34E-04
24	1.30E-09	3.75E-09	9.44E-09	1.61E-07	1.04E-06	6.21E-09	1.61E-04	2.52E-05	3.10E-04
25	1.14E-09	3.27E-09	8.19E-09	1.47E-07	9.20E-07	5.39E-09	1.46E-04	2.22E-05	2.88E-04
26	1.01E-09	2.86E-09	7.13E-09	1.34E-07	8.15E-07	4.71E-09	1.34E-04	1.96E-05	2.68E-04
27	8.90E-10	2.49E-09	6.19E-09	1.22E-07	7.18E-07	4.09E-09	1.22E-04	1.72E-05	2.47E-04
28	7.86E-10	2.18E-09	5.40E-09	1.11E-07	6.35E-07	3.57E-09	1.11E-04	1.52E-05	2.28E-04
29	6.95E-10	1.90E-09	4.71E-09	1.02E-07	5.62E-07	3.12E-09	1.01E-04	1.34E-05	2.11E-04

Table A-4: Annual Dose Equivalents Per Unit Intake to Various Organs for 50 Years

Year	Dose Conversion Factors (rem/μCi)								
	SI	**ULI**	**LLI**	**ET**	**Lung(1)**	**Colon**	**LN(ET)**	**AI**	**LN(TH)**
30	6.16E-10	1.67E-09	4.12E-09	9.27E-08	4.98E-07	2.73E-09	9.23E-05	1.19E-05	1.95E-04
31	5.44E-10	1.46E-09	3.59E-09	8.43E-08	4.40E-07	2.38E-09	8.39E-05	1.05E-05	1.80E-04
32	4.82E-10	1.28E-09	3.14E-09	7.68E-08	3.90E-07	2.08E-09	7.65E-05	9.26E-06	1.66E-04
33	4.27E-10	1.12E-09	2.74E-09	7.00E-08	3.46E-07	1.82E-09	6.97E-05	8.19E-06	1.53E-04
34	3.80E-10	9.89E-10	2.40E-09	6.40E-08	3.07E-07	1.60E-09	6.37E-05	7.26E-06	1.41E-04
35	3.36E-10	8.66E-10	2.10E-09	5.82E-08	2.72E-07	1.40E-09	5.79E-05	6.41E-06	1.30E-04
36	2.98E-10	7.60E-10	1.83E-09	5.30E-08	2.41E-07	1.22E-09	5.28E-05	5.68E-06	1.19E-04
37	2.65E-10	6.68E-10	1.60E-09	4.83E-08	2.14E-07	1.07E-09	4.81E-05	5.03E-06	1.10E-04
38	2.36E-10	5.89E-10	1.41E-09	4.42E-08	1.91E-07	9.42E-10	4.40E-05	4.47E-06	1.01E-04
39	2.09E-10	5.16E-10	1.23E-09	4.01E-08	1.69E-07	8.23E-10	4.00E-05	3.95E-06	9.26E-05
40	1.86E-10	4.54E-10	1.07E-09	3.66E-08	1.50E-07	7.22E-10	3.65E-05	3.51E-06	8.50E-05
41	1.65E-10	3.99E-10	9.40E-10	3.33E-08	1.34E-07	6.33E-10	3.32E-05	3.11E-06	7.81E-05
42	1.48E-10	3.52E-10	8.25E-10	3.05E-08	1.19E-07	5.57E-10	3.04E-05	2.77E-06	7.18E-05
43	1.31E-10	3.09E-10	7.21E-10	2.77E-08	1.06E-07	4.87E-10	2.76E-05	2.45E-06	6.57E-05
44	1.17E-10	2.72E-10	6.31E-10	2.52E-08	9.44E-08	4.27E-10	2.52E-05	2.18E-06	6.03E-05
45	1.04E-10	2.39E-10	5.53E-10	2.30E-08	8.41E-08	3.75E-10	2.29E-05	1.94E-06	5.53E-05
46	9.30E-11	2.11E-10	4.86E-10	2.10E-08	7.52E-08	3.30E-10	2.10E-05	1.73E-06	5.08E-05
47	8.27E-11	1.86E-10	4.24E-10	1.91E-08	6.69E-08	2.89E-10	1.91E-05	1.54E-06	4.64E-05
48	7.39E-11	1.64E-10	3.72E-10	1.74E-08	5.97E-08	2.54E-10	1.74E-05	1.37E-06	4.25E-05
49	6.60E-11	1.44E-10	3.26E-10	1.59E-08	5.34E-08	2.23E-10	1.58E-05	1.22E-06	3.90E-05
50	5.90E-11	1.27E-10	2.86E-10	1.45E-08	4.77E-08	1.96E-10	1.44E-05	1.09E-06	3.57E-05
CDE	2.88E-05	1.71E-04	5.01E-04	1.29E-05	4.41E-04	3.14E-04	1.21E-02	1.10E-02	1.81E-02

(1) = SAF$_e$ of 0.12 applied

A 6.0 Results

Substituting the parameters given in the above sections into Equation (A-1) yields the following results:

- The resulting representative SMT concentrations derived from the median and 95th-percentile swipe sample results for the years from 1968 to 1989 for all four rooms (Figures A-14 and A-15).

- The resulting 50 annual DEs to the critical organ (lung) from a total intake of SMT in a single year for the two highest swipe count years (Table A-1) for the period from 1968 to 1989 (Tables A-5 and A-6). Dose Equivalent values in Tables A-5 and A-6 are used for the Dose Reconstruction Case Study.

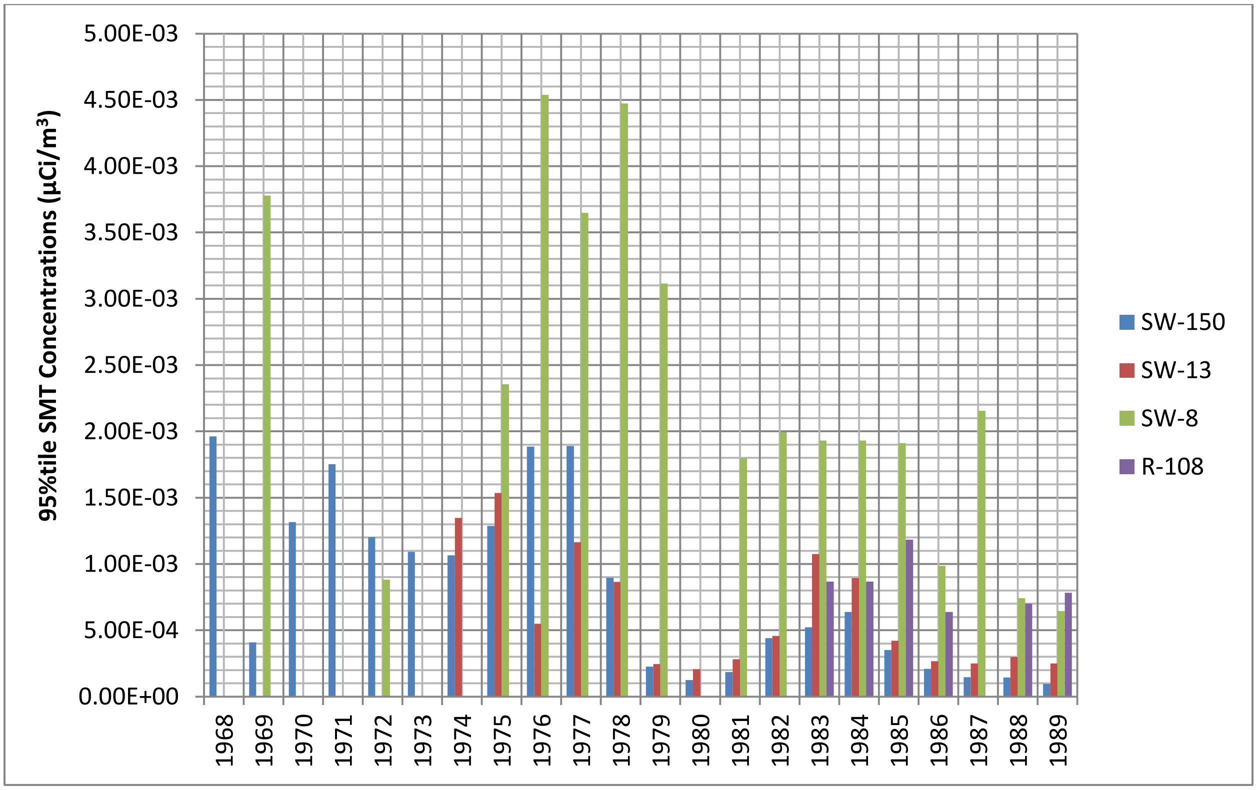

Figure A-14: Representative SMT Bounding (95th Percentile) Concentrations from 1968 to 1989

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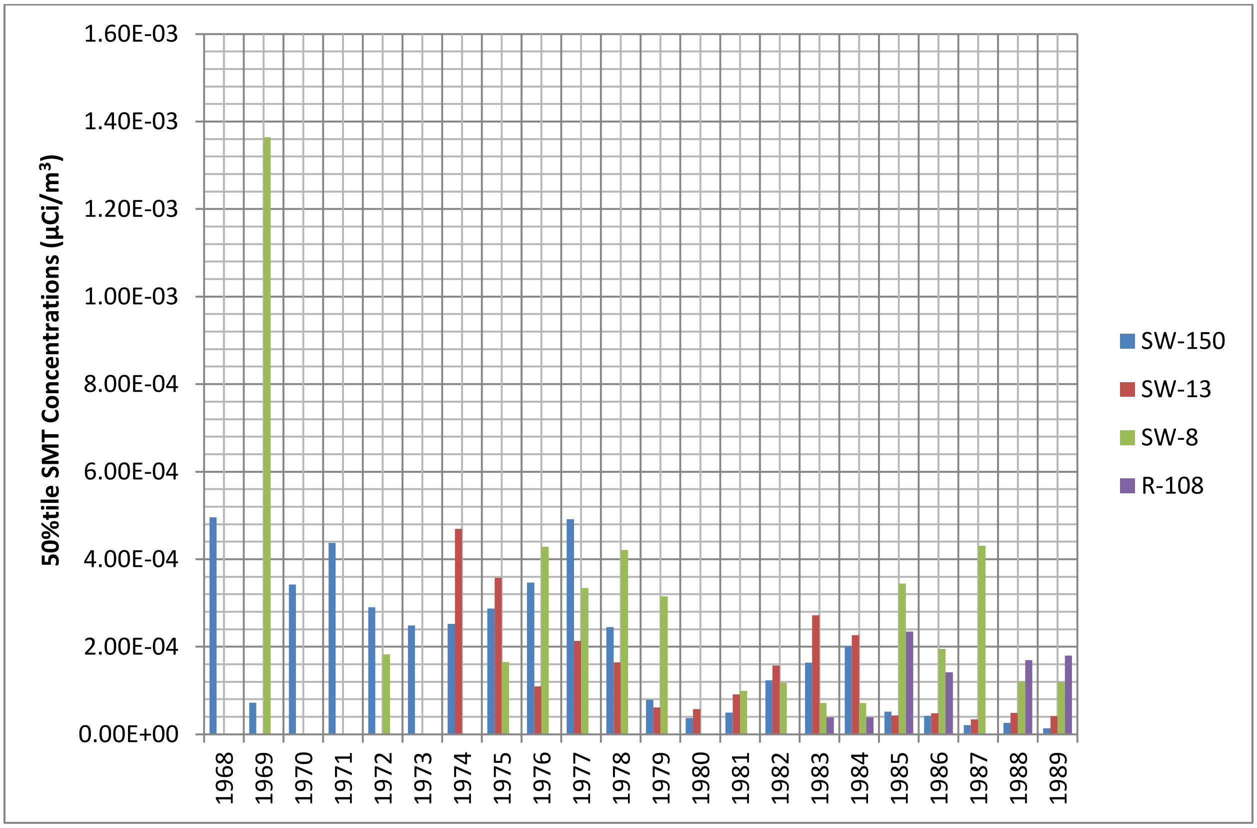

Figure A-15: Representative SMT Best Estimate (Median) Concentrations from 1968 to 1989

Table A-5: Annual Lung Dose Equivalent (mrem) for the Two Highest Swipe Count Years (Table A-1) in Rooms SW-150 and SW-13 for the Period 1968 to 1989

Year	SW-150				SW-13			
	Bounding (95%tile)		Best Estimate (50%tile)		Bounding (95%tile)		Best Estimate (50%tile)	
	1968	1977	1968	1977	1974	1975	1974	1975
1	4.99E-02	4.81E-02	1.26E-02	1.25E-02	3.43E-02	3.91E-02	1.19E-02	9.10E-03
2	3.15E-02	3.03E-02	7.95E-03	7.89E-03	2.16E-02	2.46E-02	7.53E-03	5.74E-03
3	2.15E-02	2.07E-02	5.44E-03	5.39E-03	1.48E-02	1.68E-02	5.15E-03	3.92E-03
4	1.51E-02	1.45E-02	3.81E-03	3.78E-03	1.04E-02	1.18E-02	3.61E-03	2.75E-03
5	1.08E-02	1.04E-02	2.74E-03	2.71E-03	7.44E-03	8.47E-03	2.59E-03	1.97E-03
6	8.00E-03	7.70E-03	2.02E-03	2.00E-03	5.49E-03	6.26E-03	1.91E-03	1.46E-03
7	6.03E-03	5.81E-03	1.52E-03	1.51E-03	4.14E-03	4.72E-03	1.44E-03	1.10E-03
8	4.69E-03	4.52E-03	1.18E-03	1.18E-03	3.22E-03	3.67E-03	1.12E-03	8.54E-04
9	3.73E-03	3.60E-03	9.43E-04	9.35E-04	2.56E-03	2.92E-03	8.93E-04	6.80E-04
10	3.04E-03	2.93E-03	7.69E-04	7.63E-04	2.09E-03	2.38E-03	7.28E-04	5.55E-04
11	2.51E-03	2.42E-03	6.35E-04	6.30E-04	1.73E-03	1.97E-03	6.01E-04	4.58E-04
12	2.11E-03	2.03E-03	5.33E-04	5.29E-04	1.45E-03	1.65E-03	5.05E-04	3.85E-04
13	1.80E-03	1.73E-03	4.54E-04	4.50E-04	1.23E-03	1.40E-03	4.29E-04	3.27E-04
14	1.54E-03	1.49E-03	3.90E-04	3.87E-04	1.06E-03	1.21E-03	3.69E-04	2.81E-04
15	1.33E-03	1.28E-03	3.36E-04	3.33E-04	9.14E-04	1.04E-03	3.18E-04	2.42E-04
16	1.16E-03	1.11E-03	2.92E-04	2.90E-04	7.94E-04	9.04E-04	2.76E-04	2.11E-04
17	1.01E-03	9.71E-04	2.55E-04	2.53E-04	6.92E-04	7.89E-04	2.41E-04	1.84E-04
18	8.84E-04	8.52E-04	2.23E-04	2.21E-04	6.07E-04	6.92E-04	2.11E-04	1.61E-04
19	7.74E-04	7.45E-04	1.95E-04	1.94E-04	5.31E-04	6.05E-04	1.85E-04	1.41E-04
20	6.79E-04	6.54E-04	1.72E-04	1.70E-04	4.67E-04	5.31E-04	1.62E-04	1.24E-04
21	5.98E-04	5.76E-04	1.51E-04	1.50E-04	4.11E-04	4.68E-04	1.43E-04	1.09E-04
22	5.28E-04	5.08E-04	1.33E-04	1.32E-04	3.62E-04	4.13E-04	1.26E-04	9.61E-05
23	4.64E-04	4.47E-04	1.17E-04	1.16E-04	3.19E-04	3.63E-04	1.11E-04	8.45E-05
24	4.09E-04	3.94E-04	1.03E-04	1.02E-04	2.81E-04	3.20E-04	9.78E-05	7.45E-05
25	3.61E-04	3.48E-04	9.12E-05	9.05E-05	2.48E-04	2.83E-04	8.63E-05	6.58E-05
26	3.20E-04	3.08E-04	8.08E-05	8.01E-05	2.20E-04	2.50E-04	7.65E-05	5.83E-05
27	2.82E-04	2.71E-04	7.12E-05	7.06E-05	1.94E-04	2.20E-04	6.74E-05	5.13E-05

Table A-5: Annual Lung Dose Equivalent (mrem) for the Two Highest Swipe Count Years (Table A-1) in Rooms SW-150 and SW-13 for the Period 1968 to 1989

Year	SW-150				SW-13			
	Bounding (95%tile)		Best Estimate (50%tile)		Bounding (95%tile)		Best Estimate (50%tile)	
	1968	1977	1968	1977	1974	1975	1974	1975
28	2.49E-04	2.40E-04	6.30E-05	6.24E-05	1.71E-04	1.95E-04	5.96E-05	4.54E-05
29	2.21E-04	2.12E-04	5.57E-05	5.52E-05	1.51E-04	1.72E-04	5.27E-05	4.02E-05
30	1.96E-04	1.88E-04	4.94E-05	4.90E-05	1.34E-04	1.53E-04	4.68E-05	3.56E-05
31	1.73E-04	1.66E-04	4.36E-05	4.33E-05	1.19E-04	1.35E-04	4.13E-05	3.15E-05
32	1.53E-04	1.47E-04	3.87E-05	3.83E-05	1.05E-04	1.20E-04	3.66E-05	2.79E-05
33	1.36E-04	1.31E-04	3.43E-05	3.40E-05	9.32E-05	1.06E-04	3.24E-05	2.47E-05
34	1.21E-04	1.16E-04	3.05E-05	3.02E-05	8.28E-05	9.43E-05	2.88E-05	2.20E-05
35	1.07E-04	1.03E-04	2.69E-05	2.67E-05	7.33E-05	8.35E-05	2.55E-05	1.94E-05
36	9.47E-05	9.12E-05	2.39E-05	2.37E-05	6.50E-05	7.41E-05	2.26E-05	1.72E-05
37	8.41E-05	8.10E-05	2.12E-05	2.11E-05	5.77E-05	6.58E-05	2.01E-05	1.53E-05
38	7.49E-05	7.21E-05	1.89E-05	1.88E-05	5.14E-05	5.86E-05	1.79E-05	1.36E-05
39	6.64E-05	6.39E-05	1.68E-05	1.66E-05	4.56E-05	5.19E-05	1.59E-05	1.21E-05
40	5.90E-05	5.69E-05	1.49E-05	1.48E-05	4.05E-05	4.62E-05	1.41E-05	1.08E-05
41	5.25E-05	5.06E-05	1.33E-05	1.32E-05	3.61E-05	4.11E-05	1.26E-05	9.57E-06
42	4.68E-05	4.51E-05	1.18E-05	1.17E-05	3.22E-05	3.66E-05	1.12E-05	8.53E-06
43	4.16E-05	4.01E-05	1.05E-05	1.04E-05	2.86E-05	3.25E-05	9.94E-06	7.58E-06
44	3.71E-05	3.57E-05	9.36E-06	9.28E-06	2.55E-05	2.90E-05	8.86E-06	6.75E-06
45	3.30E-05	3.18E-05	8.34E-06	8.27E-06	2.27E-05	2.58E-05	7.90E-06	6.02E-06
46	2.95E-05	2.84E-05	7.46E-06	7.40E-06	2.03E-05	2.31E-05	7.06E-06	5.38E-06
47	2.63E-05	2.53E-05	6.64E-06	6.58E-06	1.80E-05	2.06E-05	6.28E-06	4.79E-06
48	2.35E-05	2.26E-05	5.92E-06	5.88E-06	1.61E-05	1.83E-05	5.61E-06	4.27E-06
49	2.09E-05	2.02E-05	5.29E-06	5.25E-06	1.44E-05	1.64E-05	5.01E-06	3.82E-06
50	1.87E-05	1.80E-05	4.73E-06	4.69E-06	1.29E-05	1.46E-05	4.47E-06	3.41E-06

Table A-6: Annual Lung Dose Equivalent (mrem) for the Two Highest Swipe Count Years (Table A-1) in Rooms R-108 and SW-8 for the Period 1968 to 1989

Year	R-108				SW-8			
	Bounding (95%tile)		Best Estimate (50%tile)		Bounding (95%tile)		Best Estimate (50%tile)	
	1984	1985	1985	1989	1975	1977	1969	1986
1	2.21E-02	3.01E-02	5.97E-03	4.70E-03	5.99E-02	9.28E-02	3.47E-02	4.96E-03
2	1.39E-02	1.90E-02	3.77E-03	2.96E-03	3.78E-02	5.85E-02	2.19E-02	3.13E-03
3	9.52E-03	1.30E-02	2.57E-03	2.03E-03	2.58E-02	4.00E-02	1.50E-02	2.14E-03
4	6.67E-03	9.09E-03	1.80E-03	1.42E-03	1.81E-02	2.80E-02	1.05E-02	1.50E-03
5	4.79E-03	6.53E-03	1.30E-03	1.02E-03	1.30E-02	2.01E-02	7.53E-03	1.08E-03
6	3.54E-03	4.82E-03	9.57E-04	7.53E-04	9.60E-03	1.49E-02	5.56E-03	7.95E-04
7	2.67E-03	3.64E-03	7.22E-04	5.68E-04	7.24E-03	1.12E-02	4.19E-03	6.00E-04
8	2.07E-03	2.83E-03	5.61E-04	4.41E-04	5.63E-03	8.72E-03	3.26E-03	4.66E-04
9	1.65E-03	2.25E-03	4.47E-04	3.51E-04	4.48E-03	6.94E-03	2.60E-03	3.71E-04
10	1.35E-03	1.83E-03	3.64E-04	2.86E-04	3.65E-03	5.66E-03	2.12E-03	3.03E-04
11	1.11E-03	1.51E-03	3.01E-04	2.36E-04	3.02E-03	4.67E-03	1.75E-03	2.50E-04
12	9.34E-04	1.27E-03	2.53E-04	1.99E-04	2.53E-03	3.93E-03	1.47E-03	2.10E-04
13	7.94E-04	1.08E-03	2.15E-04	1.69E-04	2.15E-03	3.34E-03	1.25E-03	1.78E-04
14	6.83E-04	9.31E-04	1.85E-04	1.45E-04	1.85E-03	2.87E-03	1.07E-03	1.53E-04
15	5.88E-04	8.02E-04	1.59E-04	1.25E-04	1.60E-03	2.47E-03	9.25E-04	1.32E-04
16	5.11E-04	6.97E-04	1.38E-04	1.09E-04	1.39E-03	2.15E-03	8.03E-04	1.15E-04
17	4.46E-04	6.07E-04	1.21E-04	9.48E-05	1.21E-03	1.87E-03	7.01E-04	1.00E-04
18	3.91E-04	5.33E-04	1.06E-04	8.32E-05	1.06E-03	1.64E-03	6.14E-04	8.79E-05
19	3.42E-04	4.66E-04	9.25E-05	7.28E-05	9.28E-04	1.44E-03	5.38E-04	7.69E-05
20	3.00E-04	4.09E-04	8.12E-05	6.39E-05	8.15E-04	1.26E-03	4.72E-04	6.75E-05
21	2.64E-04	3.60E-04	7.15E-05	5.62E-05	7.17E-04	1.11E-03	4.15E-04	5.94E-05
22	2.33E-04	3.18E-04	6.31E-05	4.96E-05	6.33E-04	9.81E-04	3.67E-04	5.24E-05
23	2.05E-04	2.79E-04	5.55E-05	4.36E-05	5.56E-04	8.62E-04	3.22E-04	4.61E-05
24	1.81E-04	2.47E-04	4.89E-05	3.85E-05	4.91E-04	7.60E-04	2.84E-04	4.07E-05
25	1.60E-04	2.18E-04	4.32E-05	3.40E-05	4.33E-04	6.71E-04	2.51E-04	3.59E-05
26	1.41E-04	1.93E-04	3.83E-05	3.01E-05	3.84E-04	5.95E-04	2.22E-04	3.18E-05
27	1.25E-04	1.70E-04	3.37E-05	2.65E-05	3.38E-04	5.24E-04	1.96E-04	2.80E-05

Table A-6: Annual Lung Dose Equivalent (mrem) for the Two Highest Swipe Count Years (Table A-1) in Rooms R-108 and SW-8 for the Period 1968 to 1989								
Year	**R-108**				**SW-8**			
	Bounding (95%tile)		**Best Estimate (50%tile)**		**Bounding (95%tile)**		**Best Estimate (50%tile)**	
	1984	**1985**	**1985**	**1989**	**1975**	**1977**	**1969**	**1986**
28	1.10E-04	1.50E-04	2.98E-05	2.34E-05	2.99E-04	4.63E-04	1.73E-04	2.48E-05
29	9.75E-05	1.33E-04	2.64E-05	2.07E-05	2.65E-04	4.10E-04	1.53E-04	2.19E-05
30	8.65E-05	1.18E-04	2.34E-05	1.84E-05	2.35E-04	3.64E-04	1.36E-04	1.94E-05
31	7.64E-05	1.04E-04	2.07E-05	1.63E-05	2.07E-04	3.21E-04	1.20E-04	1.72E-05
32	6.77E-05	9.22E-05	1.83E-05	1.44E-05	1.84E-04	2.84E-04	1.06E-04	1.52E-05
33	6.00E-05	8.18E-05	1.62E-05	1.28E-05	1.63E-04	2.52E-04	9.43E-05	1.35E-05
34	5.33E-05	7.27E-05	1.44E-05	1.13E-05	1.45E-04	2.24E-04	8.38E-05	1.20E-05
35	4.72E-05	6.43E-05	1.28E-05	1.00E-05	1.28E-04	1.98E-04	7.41E-05	1.06E-05
36	4.19E-05	5.71E-05	1.13E-05	8.91E-06	1.14E-04	1.76E-04	6.58E-05	9.41E-06
37	3.72E-05	5.07E-05	1.01E-05	7.91E-06	1.01E-04	1.56E-04	5.84E-05	8.36E-06
38	3.31E-05	4.51E-05	8.96E-06	7.05E-06	8.99E-05	1.39E-04	5.21E-05	7.44E-06
39	2.94E-05	4.00E-05	7.94E-06	6.24E-06	7.96E-05	1.23E-04	4.61E-05	6.60E-06
40	2.61E-05	3.56E-05	7.06E-06	5.55E-06	7.08E-05	1.10E-04	4.10E-05	5.87E-06
41	2.32E-05	3.17E-05	6.28E-06	4.94E-06	6.30E-05	9.76E-05	3.65E-05	5.22E-06
42	2.07E-05	2.82E-05	5.60E-06	4.41E-06	5.62E-05	8.71E-05	3.26E-05	4.66E-06
43	1.84E-05	2.51E-05	4.98E-06	3.91E-06	4.99E-05	7.73E-05	2.89E-05	4.13E-06
44	1.64E-05	2.23E-05	4.43E-06	3.49E-06	4.45E-05	6.89E-05	2.58E-05	3.68E-06
45	1.46E-05	1.99E-05	3.95E-06	3.11E-06	3.96E-05	6.14E-05	2.30E-05	3.28E-06
46	1.31E-05	1.78E-05	3.53E-06	2.78E-06	3.54E-05	5.49E-05	2.05E-05	2.93E-06
47	1.16E-05	1.58E-05	3.14E-06	2.47E-06	3.15E-05	4.88E-05	1.83E-05	2.61E-06
48	1.04E-05	1.41E-05	2.81E-06	2.21E-06	2.81E-05	4.36E-05	1.63E-05	2.33E-06
49	9.26E-06	1.26E-05	2.51E-06	1.97E-06	2.51E-05	3.89E-05	1.46E-05	2.08E-06
50	8.28E-06	1.13E-05	2.24E-06	1.76E-06	2.25E-05	3.48E-05	1.30E-05	1.86E-06

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