



ORAU TEAM Dose Reconstruction Project for NIOSH

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New
 Total Rewrite
 Revision
 Page Change

FOR DOCUMENTS MARKED AS A TOTAL REWRITE, REVISION, OR PAGE CHANGE, REPLACE THE PRIOR REVISION AND DISCARD / DESTROY ALL COPIES OF THE PRIOR REVISION.

PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
05/31/2005	00	New Technical Basis Document: Basis for the Development of an Exposure Matrix for Linde Air Products, Tonawanda, New York and Buffalo, New York. First approved issue. Initiated by Cindy Bloom.
01/19/2006	00 PC-1	<p>Modified to incorporate comments from OCAS, a Worker Outreach meeting comment and minor editing. The Introduction on page 10 was updated. Dates were changed in Section 3.0 to incorporate the decision to designate Linde Ceramics workers, who received internal exposures prior to 11/01/1947, as a Special Exposure Cohort. Moved Table 12, an internal exposure table out of Section 4.0. Changes were made to page 23 in Section 3, page 34 in Table 7, page 35 in Table 8, page 38 in Table 11, and Table 12 on page 39. Approved page change revision. No sections were deleted. Training required: As determined by the Task Manager. Initiated by Cindy W. Bloom.</p> <p style="text-align: right;"><u>Signature on File</u> 01/18/2006 Cindy W. Bloom, TBD Team Leader</p> <p style="text-align: right;"><u>Signature on File</u> 01/18/2006 Judson L. Kenoyer, Task 3 Manager</p> <p style="text-align: right;"><u>Signature on File</u> 01/18/2006 Kate Kimpan, Project Director</p> <p style="text-align: right;"><u>Signature on File</u> 01/19/2006 James W. Neton, Associate Director for Science</p>
11/04/2008	01	Approved revision to change from a page change revision (Rev 00 PC-2-B) to a total rewrite (Rev 01-A) as a result of formal NIOSH review. Revised to incorporate: (1) change in facility designation, (2) DOL interpretation of applicability of residual period to Ceramics Plant, (3) and resolution of Advisory Board Working Group comments, (4) clarified the implementation instructions for SEC00044 for the period October 1, 1942 through October 31, 1947. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Task Manager. Initiated by Joseph S. Guido.
11/10/2009	01 PC-1	Approved page change revision to incorporate additional guidance on the use of Attachment E of the document. This change constitutes the resolution of Advisory Board Working Group concern and clarifies how to proceed in the event of credible indication of potential exposure to contaminated burlap bags that were used for transport of ore at Linde Ceramics. Changes were made to page 37 in Section 4.0. No sections were deleted. No changes occurred as a result of formal internal review. Incorporates formal NIOSH review comments. Training required: As determined by the Objective Manager. Initiated by Mutty Sharfi.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
CFR	Code of Federal Regulations
cm	centimeter
d	day
D&D	decontamination and decommissioning
DOE	U.S. Department of Energy
dpm	disintegrations per minute
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ft	foot
FUSRAP	Formerly Utilized Sites Remedial Action Program
GM	geometric mean
GSD	geometric standard deviation
hr	hour
ICRP	International Commission on Radiological Protection
keV	kiloelectron-volt, 1,000 electron-volts
L	liter
lb	pound
LAPC	Linde Air Products Company
LOD	limit of detection
LOOW	Lake Ontario Ordnance Works
MAC	maximum allowable concentration
m	meter
MED	Manhattan Engineer District
MeV	megaelectron-volt, 1 million electron-volts
mg	milligram
mm	millimeter
mr	radiation exposure unit used by MED in the 1940s; interpreted here as millirad for photons and millirem for beta radiation
mR	milliroentgen
mrad	millirad
mrem	millirem
mrep	millirep
MT	metric ton (1,000 kg)
NIOSH	National Institute for Occupational Safety and Health
NYOO	New York Operations Office
OCAS	Office of Compensation Analysis and Support
ORNL	Oak Ridge National Laboratory
ORAU	Oak Ridge Associated Universities

PAEC	potential alpha energy concentration (a measure of concentration of radon progeny)
PAEE	potential alpha energy exposure (a measure of exposure to radon progeny)
pCi	picocuries
PL	preferred level
POC	probability of causation
R	roentgen
R&D	research and development
s	second
SC&A	S. Cohen & Associates
SEC	Special Exposure Cohort
SRDB Ref ID	Site Research Database Reference Identification (number)
t	ton (2,000 lb)
U.S.C.	United States Code
USACE	U.S. Army Corps of Engineers
USBM	U.S. Bureau of Mines
wd	workday
wk	week
WL	working level
WLM	working level-month
yr	year
α	alpha particle
μg	microgram
μm	micrometer
μR	microroentgen
$^{\circ}\text{C}$	degrees Celsius
$^{\circ}\text{F}$	degrees Fahrenheit
§	section or sections

1.0 INTRODUCTION

Technical basis documents (TBDs) and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH staff in the completion of the individual work required for each dose reconstruction.

In this document the word “facility” is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an “atomic weapons employer facility” or a “Department of Energy [DOE] facility” as defined in the Energy Employees Occupational Illness Compensation Program Act [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility as “any building, structure, or premise, including the grounds on which such building, structure, or premise is located ... in which operations are, or have been, conducted by, or on behalf of, the Department of Energy (except for buildings, structures, premises, grounds, or operations ... pertaining to the Naval Nuclear Propulsion Program)” [42 U.S.C. § 7384l(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled “Exposure in the Performance of Duty.” That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer “shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer ... was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation¹] guidelines established under subsection (c) ...” [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation, 42 C.F.R. Pt. 82) define “performance of duty” for DOE employees with a covered cancer or restrict the “duty” to nuclear weapons work (NIOSH 2007a).

The statute also includes a definition of a DOE facility that excludes “buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program” [42 U.S.C. § 7384l(12)]. While this definition excludes Naval Nuclear Propulsion Facilities from being covered under the Act, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled “Exposure in the Performance of Duty”] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally-derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external occupational radiation exposures are considered valid for inclusion in a dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived (NIOSH 2007a):

- Background radiation, including radiation from naturally occurring radon present in conventional structures
- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons

¹ The U.S. Department of Labor (DOL) is ultimately responsible under the EEOICPA for determining the POC.

Under EEOICPA, employment at an AWE facility is categorized as either (1) during the DOE contract period (i.e., when the AWE was processing or producing material that emitted radiation and was used in the production of an atomic weapon), or (2) during the residual contamination period (i.e., periods that NIOSH has determined there is the potential for significant residual contamination after the period in which weapons-related production occurred). For contract period employment, all occupationally derived radiation exposures at covered facilities must be included in dose reconstructions. This includes radiation exposure related to the Naval Nuclear Propulsion Program and any radiation exposure received from the production of commercial radioactive products that were concurrently manufactured by the AWE facility during the covered period. NIOSH does not consider the following exposures to be occupationally derived (NIOSH 2007a):

- Background radiation, including radiation from naturally occurring radon present in conventional structures
- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons

For employment during the residual contamination period, only the radiation exposures defined in 42 U.S.C. § 7384n(c)(4) [i.e., radiation doses received from DOE-related work] must be included in dose reconstructions. Doses from medical X-rays are not reconstructed during the residual contamination period (NIOSH 2007a). It should be noted that under subparagraph A of 42 U.S.C. § 7384n(c)(4), radiation associated with the Naval Nuclear Propulsion Program is specifically excluded from the employee's radiation dose. This exclusion only applies to those AWE employees who worked during the residual contamination period. Also, under subparagraph B of 42 U.S.C. § 7384n(c)(4), radiation from a source not covered by subparagraph A that is not distinguishable through reliable documentation from radiation that is covered by subparagraph A is considered part of the employee's radiation dose. This site profile covers only exposures resulting from nuclear weapons-related work. Exposures resulting from non-weapons-related work, if applicable, will be covered elsewhere.

1.1 PURPOSE

This site profile document provides an exposure matrix for workers at the Tonawanda Laboratory and Linde Ceramics Plant facilities of the Linde Air Products Company (LAPC) in Tonawanda, New York.

NIOSH has determined, and the Secretary, Health and Human Services has concurred, that it is not feasible to reconstruct internal radiation dose for: *“Atomic weapons employees who worked at the Linde Ceramics Plant from October 1, 1942, through October 31, 1947, and who were employed for a number of work days aggregating at least 250 work days either solely under this employment or in combination with work days occurring within the parameters (excluding aggregate work day requirements) established for other classes of employees included in the SEC” (HHS 2005).* Subsequent correspondence (Elliott 2006) confirms that the Tonawanda Laboratory (as well as all other buildings on the Linde Site) are included in this class designation (cohort). Reconstruction of external exposure (including medical X-ray examinations) has been determined to be feasible (HHS 2005).

For any claim referred to NIOSH regarding an employee,

- who was employed during the Cohort period but because of limited employment during this period is not a member of the Cohort, or
- who is a member of the Cohort and whose cancer is not defined as a specified cancer under EEOICPA (and so is not eligible for compensation under EEOICPA without a dose reconstruction),

NIOSH will continue to attempt to complete a dose reconstruction for the exposure period based solely on external and medical X-ray radiation sources. However, because of the SEC determination (HHS 2005) that it is infeasible to adequately reconstruct internal dose during the period October 1, 1942 through October 31, 1947, dose estimates for this period are considered partial dose estimates.

1.2 SCOPE

DOL has designated the Linde Ceramics Plant a DOE facility and the Tonawanda Laboratory an AWE facility (Turcic 2007). This document covers both facilities. The information in this site profile supports the assumed operational and residual contamination periods listed below. DOL has determined that the residual contamination period for the Tonawanda Laboratory is also applicable to the Ceramics Plant (Turcic 2008). Although cleanup activities at the Ceramics Plant continued into July of 1954, the designated covered period for this facility ends in 1953. Post-1953 exposures are also covered under the EEOICPA, but this period is termed the residual exposure period. Because the activities and exposure potential at the Ceramics plant during the first part of 1954 (January 1 through July 7) are the same as in the immediately previous period (1950 to 1953), information on reconstruction of dose for the period from January 1 through July 7 is included in the operational period section of this document. The instructions in this document for reconstruction of dose at the Ceramics plant during the residual period (as defined by DOL as starting on January 1, 1954) pertain to exposures starting after July 7, 1954. July 7, 1954 is used as the definitive end of the decontamination period at the Ceramics plant based on the date of the final survey of the facility, which is documented in a memorandum from the New York Operations Office (NYOO) to Union Carbide that asserts that the decontamination requirements of the contract were fulfilled (Eisenbud 1954).

Facility	Operational period	Residual contamination period ^a
Linde Ceramics Plant and Tonawanda Laboratory	10/01/1942–10/31/1953 1988–1992; 1996 (remediation)	January 1, 1954 to July 2006 ^b

a. Also called the postcleanup period in this document.

b. Excluding 1988 to 1992 and 1996.

Section 2.0 describes the site and its operational history. Sections 3.0 and 4.0 describe estimation of internal and external exposure from 1942 to July 7, 1954, respectively. Section 5.0 describes occupational medical exposure. Section 6.0 provides information on exposures during the residual contamination period after 1953. Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 7.0.

Attachment A contains data that was used in analyzing exposures of workers to beta radiation. Attachment B lists codes and special terminology in the LAPC records. Attachment C shows data sources on uranium progeny concentrations, and Attachment D provides a uranium coworker assessment for November 1947 to January 1950. Attachment E provides an assessment of dose consequences from uranium ore bag that were stored on the site during the postoperations period.

2.0 SITE DESCRIPTION AND OPERATIONAL HISTORY

When the U.S. government and its contractors first became interested in uranium, LAPC, then a division of Union Carbide and Carbon Corporation, operated Tonawanda Laboratory, which had been producing U_3O_8 that was sold as a coloring agent for ceramics. Because of the great interest in obtaining uranium that could be used to create experimental uranium piles, Linde was contracted to develop uranium chemical processes and build a facility that could process large amounts of uranium ore. This commissioned facility was called the Linde Ceramics Plant. The plant worked with two types of radioactive material:

- Refined uranium materials and preprocessed (partially refined) domestic ores, and
- Unprocessed African ores.

Processing of the African ores involved exposures to significantly higher levels of ^{230}Th , ^{226}Ra , and ^{222}Rn . In the other materials, the initial refining process probably removed most nonuranium radionuclides. Due to the long half-lives of ^{230}Th and ^{231}Pa , significant ingrowth of these nuclides and their progeny in the ^{238}U and ^{235}U decay chains did not occur in the interval between the refining of the materials and their processing at Linde.

LAPC performed work for the Manhattan Engineer District (MED) and its successor the U.S. Atomic Energy Commission (AEC) between 1942 and 1949. Tonawanda Laboratory performed research and development (R&D) on uranium processing for the MED beginning in late 1942 and probably ending in 1946. In the early years, it operated pilot plants to develop procedures for the Ceramics Plant. The Ceramics Plant produced uranium materials for the MED and AEC from 1943 to 1946 and from 1947 to 1949. From 1947 to 1949 (and perhaps earlier), Linde received UO_2 for processing from Mallinckrodt Chemical Works (AEC 1949a). The plant also produced nickel material for the K-25 diffusion barrier. The Ceramics Plant was in standby from mid-1946 to late 1947. The end of production in 1949 was followed by cleanup and decontamination and then turnover of the production facilities back to Linde. This turnover probably occurred in 1954.

Uranium processing at the Ceramics Plant involved three steps:

- Step I, conversion of ore to U_3O_8 (black oxide);
- Step II, conversion of U_3O_8 to UO_3 (orange oxide) as an intermediary product and then to UO_2 (brown oxide);
- Step III, conversion of UO_2 to UF_4 (green salt).

The following sections provide more detailed histories of Linde facilities, radiation sources, and processes that related to MED/AEC radiation exposures. Key dates are noted in Table 2-1.

2.1 FACILITIES

The Linde Ceramics Plant and Tonawanda Laboratory were on land that was owned by Union Carbide at East Park Drive and Woodward Avenue in Tonawanda, New York (ORNL 1978, Fig. 3). The site is near the intersection of Riverview Boulevard and Woodward Avenue. It is north of Woodward Avenue, east of East Park Drive, and west of the Conrail railroad tracks.

Table 2-1. Key dates.

Assumed date or period ^a	Event or activity
Ceramics Plant	
06/01/1943–07/31/1946 ^b	Step I production (U ₃ O ₈ from ore or sludge)
06/01/1943–11/30/1943	Preprocessed ores (domestic and scrap)
12/01/1943–11/12/1944	African ores
11/13/1944–01/31/1946	Preprocessed domestic ores
02/01/1946–02/28/1946	African ores (48%) and preprocessed domestic ores (52%)
03/01/1946–06/30/1946	African ores
07/01/1946–07/31/1946	African ores and preprocessed ash
04/27/1943–03/08/1944 ^c	Step II production (UO ₂ from U ₃ O ₈)
07/25/1943–06/26/1946 ^d	Step III production (UF ₄ from UO ₂)
08/01/1946–09/14/1947	Standby
09/15/1947–10/31/1947 ^e	Step III rehabilitation
11/01/1947–06/30/1949 ^f	Step III production
10/01/1944–02/28/1946 ^g	Production of nickel material for K-25 diffusion barrier
07/01/1949–03/31/1950 ^h	Cleanup of Building 30
07/01/1949–12/31/1954 ⁱ	Cleanup of Linde Ceramics Buildings
Before 1978	Demolition of Buildings A and B (office buildings on Figure 2-1)
After 1954	Postcleanup period
08/31/1981 ^j	Demolition of Building 37 began
08/31/1996 ^k	Demolition of Building 38 began
09/05/1998 ^k	Demolition of Building 30 began
09/30/2000 ^l	Soil remediation began (scheduled for completion in 2007) ^l
Tonawanda Laboratory	
10/01/1942–07/31/1946 ^l	MED-related R&D operations
08/01/1946–12/31/1946 ^m	Cleanup period
After 1947	Postcleanup period
04/30/2004 ^l	Demolition of Building 14 began

- Unless more precise information was available, activities were assumed to begin on the first day of the start month and to end on the last day of the completion month in the data source, and demolition activities were assumed to begin on the last day of the start month in the data source.
- All Step I dates and data are based on Table B-1 of Aerospace Corporation (1981) except for the November 1944 transition date from African to domestic ore. The date was determined from analysis of Step I film badge data (see Section 4.1.3.2).
- LAPC (1946a, p. 40).
- LAPC (1946b, p. 42).
- Start date based on Kent (1947, p. 1).
- Start date based on Rennich (1947). End date based on Heatherton, 1948f.
- Hickey, Crawford-Brown, and Tankersley (1988, Figure 13, p. 2).
- Start date assumed to be day after end of Step III production; end date estimated based on Eisenbud (1950).
- Start date assumed to be day after end of Step III production; end date estimated based on Harris (1954).
- Pilon (2004).
- USACE (1998).
- Start date based on Jenness and Ewing (1943). End date assumed to be the end date of 1943 to 1946 production at the Ceramics Plant.
- Start date based on estimated end date of R&D period; end date estimated.

Tonawanda site buildings that were involved in MED/AEC work are shown in Figure 2-1. The Tonawanda Laboratory occupied Building 14, and the Ceramics Plant used Buildings 30, 31, 37, 38, and A. Building B contained MED offices. Ownership of the Ceramics Plant buildings was transferred to LAPC after the site cleanup that began with the shutdown of production in 1949. The transfer probably was completed in 1954. In the 1990s, the site was acquired by Praxair (USACE 2003).

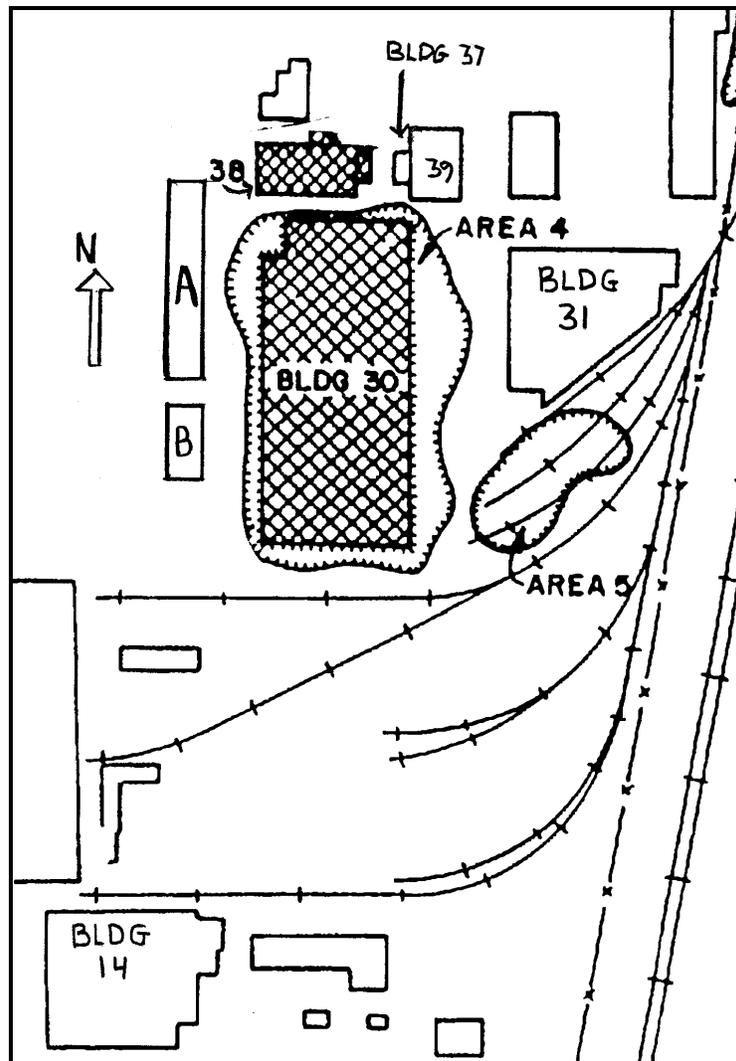


Figure 2-1. Linde Ceramics Plant and Tonawanda Laboratory buildings on LAPC Tonawanda site.

2.1.1 Buildings A and B

Building A was the Linde Ceramics Plant office building for administrative and support personnel. During the MED years, Building B housed the Tonawanda Area Engineer office of the MED (Dupree 1983a) and probably was later used by AEC personnel. The designations A and B were adopted for this document and might be different from the official Linde or MED designations. Buildings A and B were no longer standing in 1978, when the results of a 1976 radiological survey were issued by Oak Ridge National Laboratory (ORNL 1978).

Figure 2-1 is based on Figures 3-1 and B-11 of BNI (1982), Figure 3 of Frame et al. (1981), and LAPC (1945a).

A shelter in which workers were allowed to smoke was at the south end of Building B (Dupree 1983a). This was probably for use only by office workers. A separate smoking shelter was provided for production workers (Klevin 1949a, data sheets 543 and 546).

2.1.2 Building 14 (Tonawanda Laboratory)

Building 14 housed Tonawanda Laboratory. The U.S. Army Corps of Engineers (USACE) has described its use as follows (ACE Buffalo, 2003):

Building 14 was used for laboratory and pilot plant studies for uranium separation in the early part of MED operations. Historical drawings indicate that the MED laboratory and pilot plant studies were initially confined to the south part of the building. It is unclear how extensively the remainder of the building was used for MED operations. However, documents indicate that laboratory and pilot plant operations were continued for the purpose of experimenting and developing more efficient processing methods, and operations appear to have been expanded into most of the building, possibly to support larger pilot studies. The available records do not indicate whether or not the use of Building 14 ceased before the MED/Atomic Energy Commission (AEC) operations were discontinued at Linde.

A 1942 Tonawanda Laboratory directory listed approximately 200 employees (LAPC 1942). The locations of most were designated by room numbers. Some employees were said to be in the Eng. Lab and others in the Proving Lab. A 1944 employee list reported some to be in the Pilot Plant (LAPC 1944a). The terms Proving Lab and Pilot Plant appear to refer to the same facility.

Tonawanda Laboratory is also referred to by other names such as Linde Research Laboratory (Dupree 1983a) and The Laboratory of The Linde Air Products Company (Jenness and Ewing 1943).

Contamination in Building 14 was found in a 1976 radiological survey (ORNL 1978). At the time, Building 14 housed fabrication facilities, research facilities, and offices generally used by 20 to 30 employees. Demolition of Building 14 began in April 2004 (Pilon 2004).

2.1.3 Building 30 (Ceramics Plant)

Building 30—also called the uranium refinery—was used for Steps I and II. Figures 2-2 and 2-3 show the layout. It had two floors. Large pieces of equipment such as digestion tanks were on the ground floor. Process workers operated equipment from the second floor (Dupree 1983a,b). The 1949 to 1950 decontamination work by LAPC and the results are described in Heatherton (1950). As of 1976, the building was used as a shipping and receiving warehouse and occupied by about 20 to 30 employees. Radioactive contamination was found during a 1976 survey (ORNL 1978). Building 30 was demolished during the period from September 5 to 19, 1998 (USACE 1998).

2.1.4 Building 31 (Ceramics Plant)

Building 31 is described as "used in uranium separation process during MED operations" (BNI 1993, p. 1-65). A partially readable 1945 plant drawing indicates that it contained shipping and storage areas, maintenance facilities (including a welding shop, a machine shop, a gauge test room, and a carpentry area), and a small number of associated offices (LAPC 1945a). Building 31 might have been the final location of the Linde Tonawanda nickel processing operations.

As of 1976, the building was described as housing fabrication facilities, offices, and storage areas, and it was occupied by about 12 to 15 employees. Radioactive contamination was found during a 1976 survey (ORNL 1978). Building 31 was decontaminated in 1997 (USACE 2002). As of 2004, it was still standing and in use (Pilon 2004).

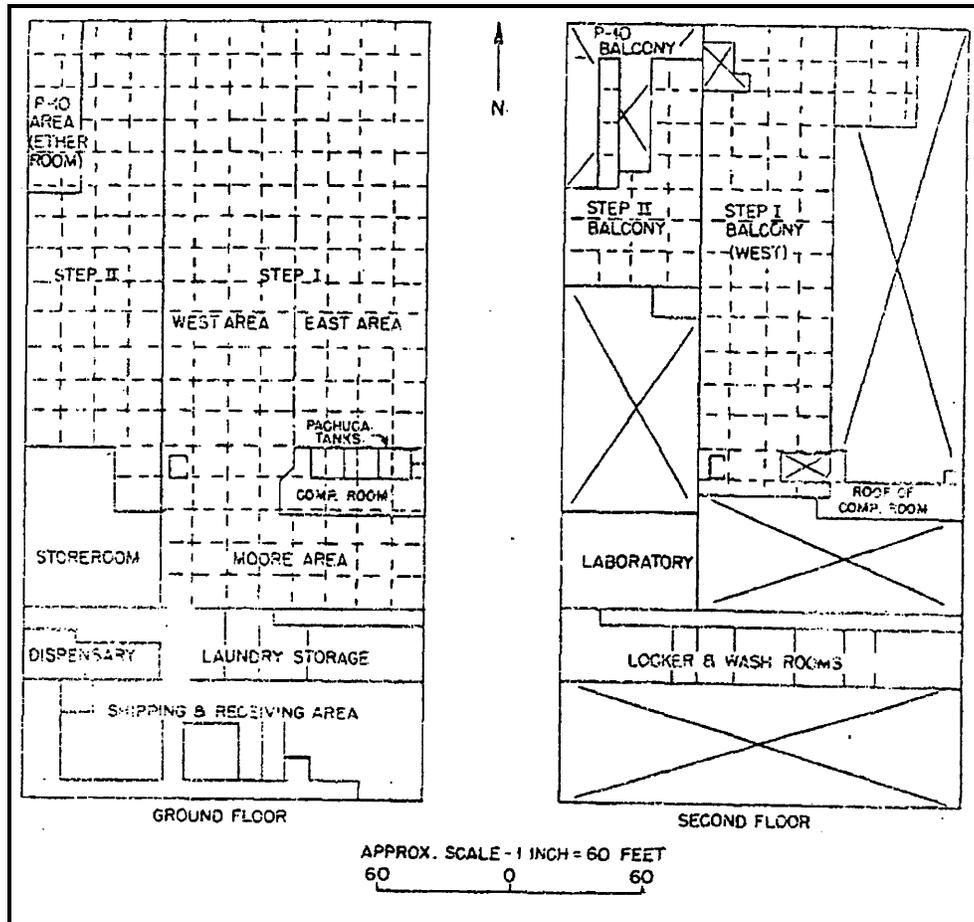


Figure 2-2. Building 30 layout (Heatherton 1950).

2.1.5 **Building 37 (Ceramics Plant)**

Building 37 was a small appendage to Building 39, which was east of Building 38 (Figure 2-1). According to BNI 1993 (p. 1-65), Building 37 was used for Step III. However, no details of this use have been found and its small size, approximately 16 by 36 ft (BNI 1982 Figure B-11), indicates at most a minor role. The 1945 plant drawing labeled it Test Bldg (LAPC 1945a). Radioactive contamination was found in 1976 (ORNL 1978). Linde demolished Building 37 in 1981 (Pilon 2004).

2.1.6 **Building 38 (Ceramics Plant)**

Building 38 was used for Step III. Figure 2-4 shows its layout. Radioactive contamination was found in 1976 (ORNL 1978). Building 38 was demolished in 1996 (Pilon 2004).

2.2 **SOURCE TERMS FOR AFRICAN AND DOMESTIC URANIUM ORES**

Linde used two types of starting materials for Step I (ore to U_3O_8) processing. These are generally referred to as African ore and domestic ore in Linde-related literature. Most of the African ore was pitchblende; some was torbernite (Aerospace Corporation 1981, p. 1). Neither African ore underwent chemical preprocessing before being shipped to Linde. Therefore, they contained not only uranium but also all members of the uranium decay series including radium and its progeny.

The domestic ore category included preprocessed domestic ores and byproducts of other uranium conversion processes. The preprocessed domestic ores derived from tailings from vanadium processing. The preprocessing concentrated the uranium and had the effect of removing "the major

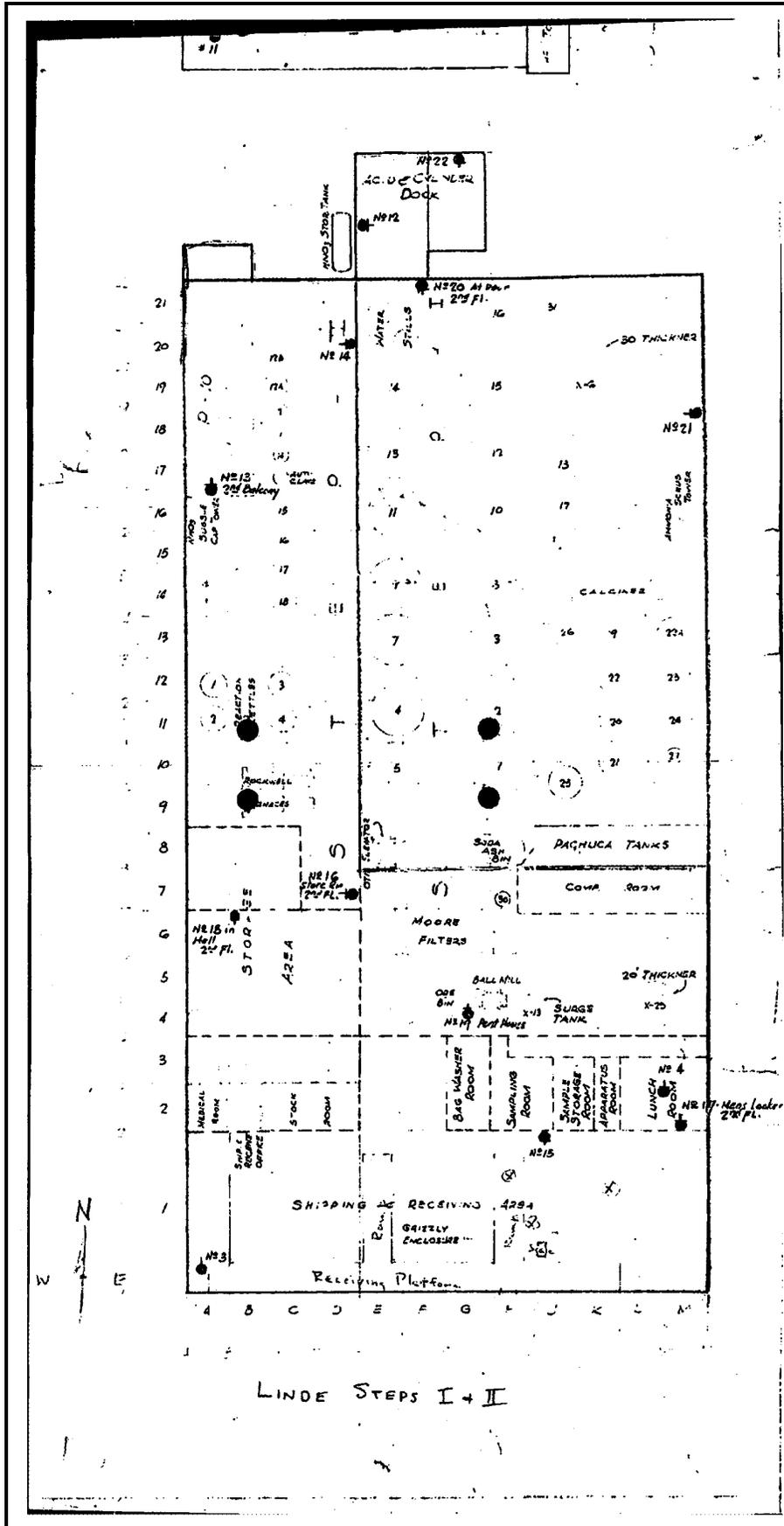


Figure 2-3. Building 30 layout (LAPC undated a).

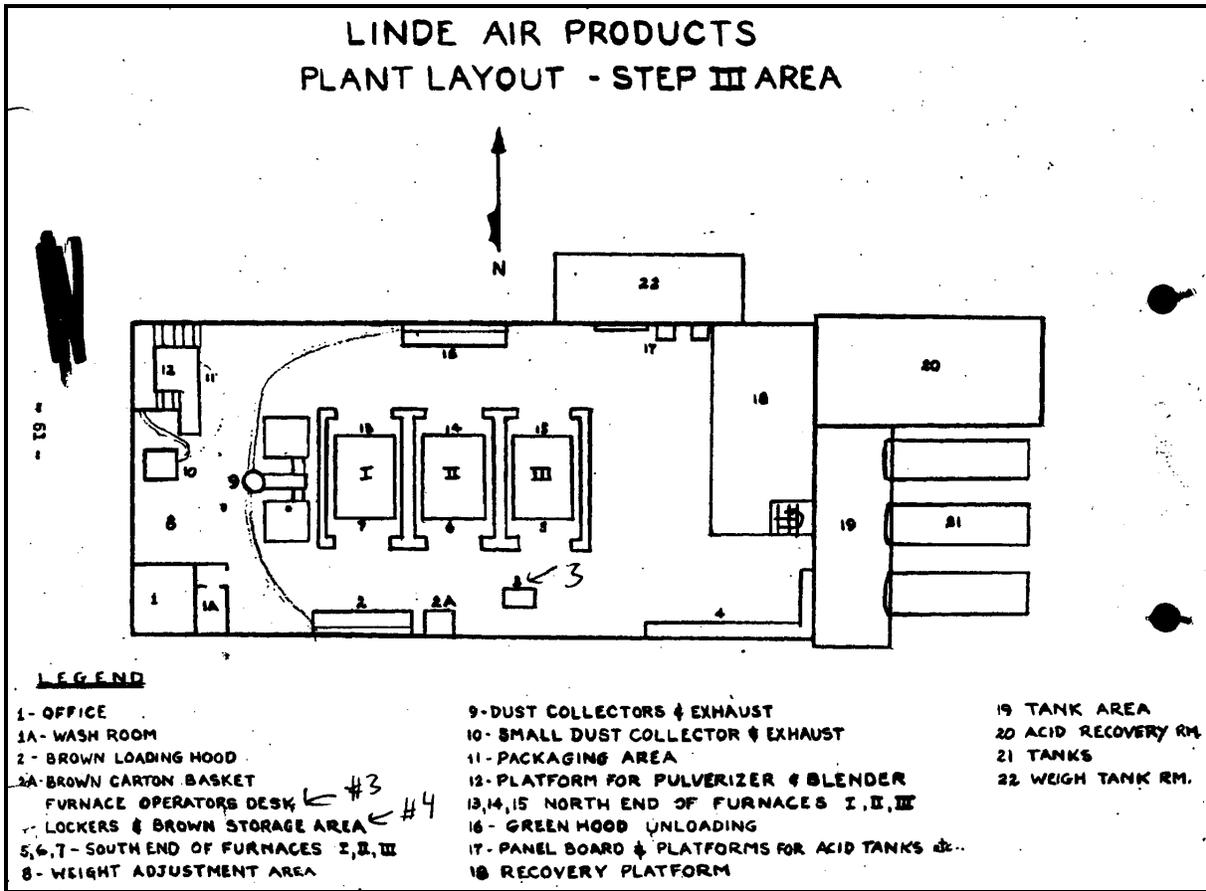


Figure 2-4. Building 38 layout (Klevin 1949a).

portion of the radium" in the original ore (Aerospace Corporation 1981, p. 5). The preprocessing might have also separated uranium from other radionuclides in the ore. If the separation of uranium had been complete, then the radioactivity in the preprocessed ore delivered to Linde would have consisted primarily of ^{234}U , ^{235}U , and ^{238}U (in their natural abundances) and their short-lived progeny that had grown in after the extraction process. The completeness of the separation of uranium from other radioactivity in the vanadium tailings Linde used is not known. A review of the chemical processing concluded only that "the radium in the domestic ore was significantly less than that in the African ores" (Aerospace Corporation 1981, p. B-1).

The distinction between the two types of ore is important. The primary radiological hazards from an ore that contained only uranium and its short-lived progeny would be due to alpha and beta emissions. In contrast, radium and other progeny in the African ores would produce, in addition to the alpha and beta emissions, significant gamma emissions and elevated levels of radon. In this document, the term "domestic ore" always means *preprocessed* domestic ore, and is sometimes referred to as "refined ore." "African ore" always means ore that has not undergone preprocessing.

Enriched uranium (up to 35% or less by mass) might have been used on a limited basis for K-25 barrier testing and R&D at Tonawanda Laboratory. Because of the very limited quantities in comparison to the ore, only natural-abundance uranium is explicitly considered for this site.

2.3 ACTIVITIES

LAPC is reported to have begun research into the processing of uranium ore in the late 1930s before it had a contractual relationship with the MED. At the time, uranium was used to make colored glazes

for ceramic dinnerware. A former MED employee interviewed in 1983 (Dupree 1983a) said that Linde Research Laboratory in Tonawanda, New York, developed a process to obtain purified U_3O_8 from carnotite ore and produced 80 t of U_3O_8 . Linde's capability to provide commercial quantities of U_3O_8 as of 1941 was confirmed in a letter to atomic weapons physicist Leo Szilard (Dana 1941).

On November 16, 1942, LAPC entered into contract W-7401 eng-14 with the MED to design and construct facilities at the Ceramics Plant for processing uranium ores and to produce U_3O_8 , UO_2 , and UF_4 (Cornell 1942; Marshall 1943). The contract also called for R&D into processes that would be used in the Ceramics Plant facilities.

2.3.1 Uranium Research and Development

Available reports indicated two main areas of Tonawanda Laboratory MED uranium work. The first was development of methodologies for Ceramics Plant operations. A report on the first year of work covered the period from October 1942 to November 1943 (Jeness and Ewing 1943). Most of the work was devoted to study of the problems in the design, operation, and improvement of the Ceramics Plant.

Three different large-scale pilot plant programs were described. As of November 20, 1942, one was producing 2 to 3 t of U_3O_8 per week (Bonsib 1942). The third program, which involved African ore, had begun in October 1943 and was expected to conclude in December 1943.

Available documentation from the Laboratory includes three research reports (Brimm 1943a; Skinner 1944; Wiesendanger 1944) and a final report (LAPC 1946c). The final report discussed work on R-10, a low-grade African ore, and Q-20, a natural (i.e., not preprocessed) torbernite ore. No dates for this work were provided, but because R-10 and Q-20 processing did not begin at the Ceramics Plant until February 1946, the R-10 and Q-20 studies at Tonawanda Laboratory probably were performed in late 1945.

The second area of Tonawanda Laboratory work related to conversion of UF_6 process gas to UO_3 . Two research reports (Brimm and Schubert 1945a,b) and a final report (LAPC 1946d) indicated that the associated pilot plant operations used pounds rather than tons of material.

A later Linde research report on uranium processing from September 29, 1948 was prepared by Ceramics Plant rather than Tonawanda Laboratory personnel (Chapman et al 1948). The absence of MED or AEC reports after May 1946 suggests that MED work by Tonawanda Laboratory ended then and that there was no later AEC work. For dose reconstruction, it is assumed that there was no Tonawanda Laboratory work for the MED or AEC after July 31, 1946, the end date of the initial production period at the Ceramics Plant.

2.3.2 Uranium Production

The Linde Ceramics Plant engaged in three different uranium production activities — Steps I, II, and III. Step I (production of U_3O_8) typically involved ores that contained 3% to 20% U_3O_8 by weight. Approximately 70% of the ore was African and 30% domestic by weight. About 26,000 MT of ore were processed, and about 2,300 MT of U_3O_8 were produced (Aerospace Corporation 1981, Table B-1).

Step I (production of U_3O_8) took place in Building 30 from June 1943 through July 1946. Step II (production of UO_2) took place in Building 30 from April 1943 through March 1944. Step III (production of UF_4) took place in Building 38 from July 1943 to June 1946. Linde sent the U_3O_8 from Step I to DuPont and Mallinckrodt after Step II production ceased (Gates 1946). Linde received UO_2 from other companies for Step III processing (AEC 1949a). Tonawanda Laboratory might have

investigated all of these processing steps in its pilot plant. Uranium production was in standby after July 1946. Preparations for Step III resumption began in September 1945. Step III operations were resumed under contract AT-30-1-GEN-165 in November 1947 (Rennich 1947). Linde ended uranium production for the AEC in June 1949.

A MED record-of-negotiations memorandum (Dreveskracht 1945) noted that Linde had offered for sale 36,000 lb of uranium ore concentrates from Colorado and 8,900 lb of residue, which were the "property of Contractor as a result of operations before his present CPFF [cost plus fixed-fee] work for the MED (Contract No. W-7401 eng-14)." The transfer was made under contract W-17-028 eng-29 on May 4, 1945 (USEO 1945). Correspondence indicates that Linde transferred ownership of the uranium concentrates and residues to the government on August 1, 1945 (Martin 1945), and the material was subsequently processed in the Ceramics Plant for MED (Dupree 1983a, Robinson 1945).

Detailed descriptions of the typical Ceramics Plant uranium processing methods are presented below. These include descriptions of chemical and operational processes.

2.3.2.1 Step I (Uranium Ore to U_3O_8)

Step I extracted purified U_3O_8 (black oxide) from uranium ore. The Step I process varied with time as the nature of the ore changed and as Linde gained experience with the procedure.

Domestic ore was ground and mixed with water to form a slurry. Sulfuric acid and other chemicals were added, and the mixture was digested at 90°C for 2 to 3 hours and then cooled to 60°C. This left the uranium in solution as uranyl sulfate along with some of the impurities. Soda ash and sodium bicarbonate were added to make the solution basic. This precipitated most of the remaining impurities and left the uranium in solution as sodium uranyl tricarbonate. The slurry was filtered in Moore filters (described in the next section). The liquors contained the uranium and some objectionable impurities. Vanadium and phosphorous impurities were precipitated by the addition of ferrous and ferric sulfates and then removed in a second filtering in plate and frame presses, which produced "iron cake." The liquors were treated with caustic soda to precipitate the uranium as sodium diuranate, which was removed as cake in a third filtering process. The sodium diuranate cake was treated with sulfuric acid and ammonium sulfate to convert it to an ammonium uranyl sulfate complex. This was removed in a fourth filtering process. The resulting "acid leach cake" was fed to a calciner to drive out the ammonia, sulfur dioxide and trioxide, and water to leave the black oxide (U_3O_8).

A modification of the above procedure was used to treat African ore. The filter cake from the Moore filters (first precipitation step) contained the radium in the ore. In the second step, instead of iron sulfates, sodium sulfide was added to remove lead. Some of the other chemical additives that were used at various points were different (LAPC 1946e; Aerospace 1981, p. A-1).

Step I Operations

Ore was delivered by rail in boxcars. African L-30 pitchblende arrived in burlap bags inside paper bags. Each ore bag weighed 50 to 80 lb. For African ores, the car doors were left open for 12 to 24 hours before unloading to reduce radon concentrations in the car. Either ore bags or bulk ore (the practice varied) were manually loaded onto wheeled carts (buggies) by workers called loaders or movemen and transported to a storage or processing area (Olevitch 1944; LAPC 1946e; Cranch 1944a).

For dry ore, processing began in the dumping room on the receiving platform. Ore was dumped through a grate onto a conveyer belt that carried it to the ore storage bin. The storage bin held about 75 t of ore. Ore from the bin was fed to a ball mill by a Feedoweight (a belt conveyor that weighed the ore). After milling, the ore was fed to the digestion process.

Wet ore was transported to the second floor using the freight elevator and either dumped into the scoop box of the ball mill or directly into digest tanks (skipping the ball mill step). Loaders did not ride on the elevator with the ore.

After the dumping, about a 0.5 lb of ore remained in each bag. To recover it, the bags were shaken in a bag shaker over a conveyor belt onto which freed ore dropped. The bags were then washed, centrifuged, and burned in an incinerator. The washed bags contained about 10% to 30% of the remnant ore. At times, washed bags that were awaiting incineration were stored outdoors on the site. A July 1944 report noted that 19,000 bags were currently being stored (Olevitch 1944, Appendix A).

For digestion, chemicals appropriate to the ore type were added to the digest tanks, and the mixture was heated and cooled to precipitate components. Precipitates were separated from solutions using various filter assemblies. The first filtration in the Step I processing used the Moore filters. A Moore filter consisted of a large basket that contained 24 rectangular leaves with each leaf approximately 35 ft² in area. Each leaf was formed by a rectangular perforated pipe frame over which a bag was stretched. The filter basket was placed by crane into a neutralized digest tank and held there while suction was applied to the pipe. Gelatinous cakes about 1-in. thick formed on the leaves. The basket was removed from the digest tank, placed in a wash tank, washed, and then moved to a hopper. The suction was then reversed to inflate the bags and cause the cake to fall into the hopper. From there the cake was transferred to an open-top truck below the hopper for transport to a storage location. After sampling, the filter cake was hauled away by truck. Radium-containing filter cake from the African ores was shipped to the Lake Ontario Ordnance Works (LOOW) in Lewiston, New York, for storage. Filter cake from the domestic ores went to a tailings pile. From some filter presses, the filter cake was manually dumped by the operators into buggies for transport to the next step. From other presses, the cake could be fed automatically to the next step (MED undated, page 3; Olevitch 1944; LAPC 1946e; Aerospace 1981, p. A-1).

The tanks used in the process were large: 18 to 31 ft in diameter and one story high (Dupree 1983a,b).

2.3.2.2 Step II (U_3O_8 to UO_2)

Step II converted U_3O_8 to UO_2 (brown oxide) with UO_3 (orange oxide) as an intermediary product.

Black oxide (U_3O_8) was dissolved in nitric acid. Some insoluble impurities were filtered off, and the solution was evaporated to molten uranyl nitrate hexahydrate. The next step was based on ether extraction of the uranium. The extraction took advantage of the fact that metallic salts are more soluble in water than in ether, but the uranyl nitrate is nearly equally soluble in either and can be shifted from one medium to the other by changes in volume and concentration ratios. The uranyl nitrate hexahydrate was added to cold ether, and the solution was washed with water. The impurities went to the water layer and the uranyl nitrate to the ether layer. The purified uranyl nitrate was denitrated to powdered uranium trioxide (UO_3) by heating in a stainless-steel pot furnace. The trioxide powder was collected mechanically and flowed by gravity through a micropulverizer into a rotary tube reduction furnace. There the powder was reduced to the desired uranium dioxide (UO_2) using gaseous hydrogen as a reducing agent. The finished UO_2 product was packaged, sampled, sealed, and stored (LAPC 1946a; Aerospace 1981, p. A-1).

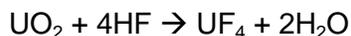
Step II Operations

U_3O_8 in buggies from Step I was weighed and hoisted to the second floor. It was then fed into nitric acid in digest tanks with scoops. The digest tanks were heated to 90°C. After digestion, insoluble impurities were filtered out using a filter press. Liquids were piped from one vessel to another. Frequent chemical analyses of samples were required in this process to determine the progress of

chemical reactions. The processing produced various liquors and some associated cakes that were designated "OK" or "NG" (LAPC 1946a).

2.3.2.3 Step III (UO₂ to UF₄)

Step III converted UO₂ to UF₄ (green salt) using the chemical reaction



The reaction was carried out at 1,000°F. Gaseous anhydrous HF gas was flowed over the UO₂, which was placed on magnesium trays stacked on spacer bars inside 9-in.-square tubes 10 ft long that were inside a furnace (LAPC 1946b; Hickey, Crawford-Brown, and Tankersley 1988, p. 8).

Step III Operations

UO₂ was weighed and hand-troweled into shallow trays inside a hood with a dust collector operating. Twelve pounds of UO₂ were placed on each tray. The oxide was furrowed when loaded to maximize surface area. The trays were transported on buggies and inserted into the furnace.

After loading, the furnace was sealed, purged of air, and heated to the starting temperature. Then the flow of HF gas was started. After the required number of hours, the heat and gas flow were stopped, and the furnace was purged of HF gas, cooled, and opened.

The trays were removed from the furnace and hand-placed onto buggies for transport to and placement inside an unloading hood with a dust collector. Good material (light green) was loaded into hoppers. Bad material (dark green) was placed in fiber-pack drums for later retreatment. Good material was pulverized, blended, sampled, packaged, weighed, and shipped (LAPC 1946b; Hickey, Crawford-Brown, and Tankersley 1988, p. 8).

2.3.3 Nickel Production

After the shutdown of Step II in 1944, the Step II equipment was converted for use in production of nickel powder, a nonradioactive process, which occurred from October 1944 through February 1946 (Hickey, Crawford-Brown and Tankersley 1988, pp. 9 and 13). The nickel was for use in the K-25 diffusion barrier (Hunter 1949; Dupree 1983b, p. 3).

There is discrepant evidence on the location of the nickel processing work. A contractual record (USA 1945) states that Linde was contracted on April 7, 1944, via letter contract W-7418 eng-51 to construct and equip a plant to produce 80 t of special nickel oxide per month and that the plant was to be constructed in Tonawanda on the same premises and adjacent to the buildings that were used in connection with contract W-7401 eng-14 (the contract for the uranium refining work). A drawing that was attached to a former Tonawanda Area Engineer Office employee interview record (Dupree 1983a) shows the location of the nickel processing to be in a building east of Building 30. Therefore, nickel processing might have occurred in Building 31 (see Figure 2-1). However, another record of interview (Dupree 1983b) states that when Step II operations in Building 30 ended, the Step II area was used to refine nickel. Both recollections could be correct. It could be that nickel processing initially occurred in the Step II area and later was moved to Building 31.

Evidence that supports Building 31 as at least the ultimate location for Linde's Tonawanda nickel processing is found in a 1945 plant drawing (LAPC 1945a). The visible portions of a partially obscured label on the drawing are consistent with the interpretation that it says "Nickel Plant." In addition, the drawing shows an ammonia cracking area in Building 31, and other records indicate that ammonia was used in the nickel processing [chemical operators in department C2P used ammonia

according to LAPC (1945b, p. 17), and department C2P engaged in nickel processing according to Hickey, Crawford-Brown, and Tankersley (1988, p. 28)].

Nickel processing at the Ceramics Plant has been described as follows (Hickey, Crawford-Brown, and Tankersley 1988, p. 9):

Metallic Ni slugs (small ingots) were oxidized with HNO₃, filtered, and heated to 1200 C to produce a nickel oxide (NiO). This was pulverized, mixed with ammonium chloride (NH₄Cl), and heated to form a porous mass of the oxide, which was reduced to powdered nickel by exposure to H₂. The powder was pulverized and packaged. ... It is not known whether both NiO and powdered Ni or only NiO were produced in quantity at this plant.

2.3.4 Other Radiological Activities

Early on, radioactive liquid wastes were discharged to the Tonawanda sanitary sewage system. Due to the nature of the liquids, this became a problem, and Linde began to dispose of liquid wastes in onsite wells that sometimes overflowed. Later still, liquid wastes were discharged to a drainage ditch that led to a sewer conduit (BNI 1993, pp. 1-9 to 1-15).

After MED work began at the Tonawanda site, there was potential exposure of workers to radiation and radioactivity when outdoors. Portions of the site are known to have been contaminated with radioactivity (Heatherton 1948a; ORNL 1978; BNI 1982); resuspension would have produced airborne radioactivity. One source of ground contamination and airborne radioactivity was the ore unloading process, which involved transporting ore in buggies – sometimes in bulk and sometimes in bags – from boxcars to Building 30 (see Step I Operations in Section 2.3.2.1). Outdoor areas of the site were sometimes used for storage of radioactive materials. Olevitch (1944) reports the outdoor storage of contaminated ore bags that at times numbered in the thousands. In 1948, 1 mR/hr gamma and 3,000 α dpm/100 cm² were measured from the soil in an area formerly used for storage of radioactive materials (Heatherton 1948a).

An additional source was the release of liquid effluents either to onsite wells that sometimes overflowed, or to an onsite drainage ditch (BNI 1993, pp. 1-9 to 1-15). Airborne effluents from the plant were an additional source of outdoor radioactivity.

In 1949, Linde workers unloaded drums of K-65 product that was shipped by rail from Mallinckrodt in St. Louis to the LOOW at Modeltown, New York (Wolf 1949b; Heatherton 1949a; NYOO 1949). Linde film badges were worn during this work.

At the April 18, 2005, Worker Outreach Meeting, strontium was mentioned. At the June 27, 2005, Worker Outreach Meeting, it was clarified that the strontium was in the form of a ⁹⁰Sr sealed source. This source was reportedly brought to the site in the late 1950s. The estimates of uranium exposure based on estimates of exposure periods and source term, which were based on worst-case assumptions when a parameter was not well supported by available information, would be sufficiently bounding to account for small amounts of radioactive strontium.

2.4 PROTECTIVE MEASURES

Steps were taken to protect against radiological and chemical hazards during processing (LAPC 1945, 1946a,b,e; Dupree 1983a,b). Although some protective measures were included early in the Linde program, protective measures were upgraded over time in response to both survey findings and newly available information about biological risks of exposure. These measures included limiting the time a worker was allowed to spend in a radiologically hazardous activity, provision and upgrading of

ventilation to reduce concentrations of radon and radioactive dusts in the air, and good housekeeping to reduce radioactive dust on the floor. Respirators to reduce dust and chemical exposure and gloves to reduce beta exposure to the hands were required for some of the more hazardous tasks, but these safety devices were not used in all process areas by all workers. Some workers changed into company-issued clothing when they arrived at work and changed back to their own clothing at the end of a shift. Showers were available. At some point in Linde operations, showering at the end of a shift became mandatory for some workers, and they were "wanded" by a health physicist to check for radioactivity when they left the shower.

Chemical protective measures included goggles, respirators, rubber gloves, face shields, rubber or plastic-coated aprons and sleeves, and head caps. There were more substantial protective measures for operators who worked with hydrofluoric acid.

According to interviewees, use of respirators was often at the worker's discretion, but they were "usually used" (Dupree 1983b). Inspectors reported mixed compliance with recommendations to wear respirators. The author of a June 1944 inspection report commented, "The wearing of respirators remains difficult to enforce" (Ferry 1944a). The author of an October 1944 inspection report observed, "Respirator discipline was about 80% efficient in the dumping room" (Tybout 1944a). In 1945, the same inspector witnessed the collection of dust samples by Mr. H. Seemann, Assistant to the Safety Engineer. In his report, the inspector noted, "The men wore respirators, but Mr. Seemann stated that this was the case only because he was present" (Tybout 1945a). A 1948 dust sample collector commented that when samples were collected, individuals on the day shift wore respirators but those on the evening shift did not (Hayden 1948).

No credit for safety gear (including respirators) is taken in this document.

2.5 PERSONNEL, JOB CATEGORIES, AND WORK HOURS

For Tonawanda Laboratory, two listings of employees might aid in determining whether a claimant worked there. A September 1942 Laboratory directory (LAPC 1942) lists approximately 200 employees. Several employees are linked to the Proving Lab, which might be an indicator of higher exposures once the uranium work began. A 1944 employee list (LAPC 1944a) contains approximately 120 names and similar information. It is not clear whether this list includes all employees.

For the Ceramics Plant, an April 1944 employee list contains nearly 400 names (Neuman 1944) and specifies the workers' jobs. A December 1945 job description specifies the duties of 51 categories of workers and lists a department code for each position (LAPC 1945b). Because the same title (e.g., chemical operator) was sometimes used in different departments in which the nature of the work was very different (e.g., Step I and nickel processing), knowing the department might help identify the type of activity in which a worker was involved. Table 2-2 shows Ceramics Plant department codes that were associated with various worker activities as determined in a 1988 study of worker hazards (Hickey, Crawford-Brown, Tankersley, 1988). A 1949 study reported that there were 139 Step III personnel and listed the number in each job. Names of some of the personnel were provided (Klevin 1949a, pp. 6, 80).

Table 2-2. Department codes for various worker activities.

Department	Department code ^a
Administrative services	AB, AD, AL, AM, BA, BB, BT, A/M
Chemical control, R&D	BL, HL
Engineering and development	AW
Maintenance	AN
Process Operations: Step I	CL

Step II	CM
Step III	CN
Nickel	CP, CR, C2M, C2P
Loading: General	AN, AH, LOOW
Janitors	AA, GE
Stores and supplies	AS, ASA, A8A, AT
Safety and security	AJ, A9A, A2J
Undetermined activity	CA, CS
Untitled jobs and departments	(b)

- a. From Hickey, Crawford-Brown, and Tankersley (1988, p. 27). Based in part on a plant document identifying some of the codes and in part on inference from less direct information in plant records.
- b. Not available.

The term “day” in this document refers to a calendar day. The term “workday” (wd) is used to describe a day at work. Default assumptions are 250 wd/yr and 8 hr/wd: this results in 2,000 hours of work per year. The distinction between workday and calendar day is especially important when considering internal dose rates for use in calculating organ doses, because intakes actually occur during the workday, but dosimetry calculations are usually based on integration over calendar days.

The Ceramics Plant work schedule during the production period (1943 to 1946) is described as involving 8-hour shifts 6 d/wk (Dupree 1983a,b,c). A 9-hour workday with a lunch period included is assumed because there is evidence that many employees worked overtime (Dupree 1983b, p. 4; MED undated, p.1). An 8-hour workday plus a half-hour for lunch is known to have been in effect for many of the workers in late 1948 (Klevin 1949a). The transition from a 6-day workweek to a 5-day workweek was assumed to have occurred on January 1, 1951, based on a report by interviewees that the 48-hour workweek lasted until 1950 (Dupree 1983b, p. 4).

Table 2-3 provides a list of some Linde references that include worker names and sometimes additional job information.

Table 2-3. Worker information.

Item	Reference
Tonawanda Laboratory employees and room numbers, September 2, 1942. Job titles are not stated.	LAPC 1942
Linde employees associated with contract W-7401-eng-14, July 20, 1943. Some are Tonawanda Laboratory personnel. Some might be Ceramics Plant personnel. Job titles are included.	Pew 1943
Ceramics Plant personnel with job titles, April 25, 1944.	Neuman 1944
Ceramics Plant Step III process operators, June 14, 1948.	Heatherton 1948b
Ceramics Plant Step III process area personnel (including operators, millwrights, and stores attendants), January 25, 1949.	Klevin 1949a, p. 50
Film badge exposure report listing 23 Step III personnel by name and job title, for week beginning March 28, 1949.	AEC 1949b
List of Ceramics Plant Step III process operators, August 26, 1949.	Klevin 1949b, p. 11

Based on the above, the periods and work schedule at the Ceramics Plant from the onset of MED operations through July 7, 1954, were assumed to have been as shown in Table 2-4.

Table 2-4. Ceramics Plant assumed work schedule (including lunch and breaks), 1942 to July 7, 1954.

Period	Start	End	hr/wd	wd/wk	wk/yr
Preproduction	10/01/1942	04/26/1943	9.0	6	50
Production	04/27/1943	07/31/1946	9.0	6	50
Standby	08/01/1946	09/14/1947	8.5	6	50
Rehabilitation and production	09/15/1947	06/30/1949	8.5	6	50
Cleanup	07/01/1949	12/31/1950	8.5	6	50
Cleanup ^a	01/01/1951	07/07/1954	8.5	5	50

a. Assumed date of transition from 6- to 5-day workweek (based on Dupree 1983b, p. 4).

2.6 DECONTAMINATION DURING THE MED/AEC CONTRACT PERIOD

Cleanup and decontamination activities at the Ceramics Plant facilities during the MED/AEC contract period are discussed below. No information was found on cleanup of Tonawanda Laboratory facilities, but it was noted at the April 18, 2005, Worker Outreach Meeting that Building 14 was contaminated, and later surveys indicated that residual contamination remained after AEC work (BNI 1993).

Cleanup of the Ceramics Plant began before the shutdown of Step III production, which occurred on June 30, 1949. Some Step II equipment in Building 30 was removed in March and April of 1948 by or with the assistance of a contractor (H. K. Ferguson) (Heatherton 1948c,d,e). Dismantling of Step I and remaining Step II equipment in Building 30 was under way in May 1949 (Heatherton 1949b). A contractor (Kulp Waco) assisted in some of the work (Heatherton 1949c,d).

Shortly after the shutdown, a comprehensive cleanup effort was undertaken to reduce levels of radioactivity in Building 30 to enable its release to Linde for unrestricted use (Heatherton 1950). After removal of the bulk of the process equipment, the entire building was vacuum-cleaned and flushed with water. A systematic radiation survey was conducted to identify areas of contamination. Decontamination was accomplished primarily by removing contaminated parts of the building (such as portions of the second floor balcony on which process operators had been stationed) and by abrading surfaces (mostly by sandblasting, although oxygen acetylene torches were also used).

After each area was decontaminated, it was again cleaned and flushed, and then a final radiation survey was made.

Workers who performed surface abrasion activities were provided with U.S. Bureau of Mines (USBM)-approved rubber hoods that protected the face, neck, and shoulders and had a supplied air respirator to permit breathing of uncontaminated air. Other personnel in the area wore demand respirators or, for short periods, USBM respirators approved for all dusts.

An AEC internal memorandum from March 29, 1950 reported that the decontamination of Building 30 had been completed and indicated that a decision on release of the building to Linde was to be made by April 1, 1950 (Eisenbud 1950).

Decontamination of Building 38 began with a radiation survey in November 1952 (Harris 1952). An AEC memorandum from April 1954 (Harris 1954) reported levels after decontamination. Average readings on categories of equipment to be left at the plant ranged from 0.05 to 0.6 mrep/hr beta plus gamma with the gamma component either undetectable (which meant less than twice background) or less than 5% of the total. The memorandum reported "overall" floor and wall levels to be 1.01 "mreps/hr/ft²" beta plus gamma. This was considered excessive. The memorandum cited data that indicated this could be reduced to 0.065 mreps/hr/ft² by covering contaminated floor areas with asphalt tile. It recommended release of the building to Linde once this occurred. July 7, 1954, is used

as the definitive end of the decontamination period based on the date of the final survey of the facility, which was documented in a memorandum from the NYOO to Union Carbide that asserted the decontamination requirements of the contract had been fulfilled (Eisenbud 1954).

No information was found on cleanup and decontamination activities in Buildings 31 and 37.

2.7 POST-MED/AEC OPERATIONS

The Formerly Utilized Sites Remedial Action Program (FUSRAP) began in 1976. ORNL surveyed the Linde Tonawanda site from October 18 through November 5, 1976, to determine if remediation would be required (ORNL 1978). Radiation and radioactive contamination measurements were made inside Buildings 14, 30, 31, 37, and 38; on the Tonawanda property outside the buildings; and at nearby offsite locations. Linde employees noted that Building 30 renovation occurred in the 1960s and could have resulted in elevated employee radiation exposures. Notes from the Worker Outreach Meeting on April 18, 2005, mention contamination in association with Building 57, and an additional review of the BNI (1993) remedial investigation report shows areas of residual radioactive contamination were associated with areas in or near Buildings 57, 58, and 90. The highest indoor radiation levels were found in the principal production buildings, Buildings 30 and 38. Linde was designated as a FUSRAP site in 1980. Additional radiological surveys and decontamination efforts followed (BNI 1993). These led eventually to demolition of Building 14 and all of the Linde Ceramics Plant buildings that were involved in MED/AEC work except Building 31. Table 2-1 shows demolition dates. As of 2004, Building 31 remained in use and onsite soil remediation was in progress with completion scheduled for 2007 (Pilon 2004).

3.0 ESTIMATION OF INTERNAL EXPOSURE, 1947 TO JULY 7, 1954

This section develops parameters for reconstruction of doses due to internal exposures from November 1, 1947, until July 7, 1954. HHS has determined, and NIOSH has concurred that it is not feasible to reconstruct internal exposure prior to November 1, 1947 (HHS 2005).

This section describes information related to internal dose reconstruction including Linde's uranium bioassays, airborne radioactivity concentration measurements, radon breath analyses for determination of radium body burdens, and radon air concentrations. To expedite preparation of this document, the Linde information is considered in conjunction with information from facilities that did similar types of uranium processing to establish preliminary estimates of internal intakes and exposures. These estimates are considered best estimates, until data can be further considered. It is believed that additional analysis of the data will lower at least some of the intakes and exposures that are estimated in this section.

This document assumes that Tonawanda Laboratory primary internal exposures occurred from October 1, 1942, to December 31, 1946. At the Ceramics Plant, four periods were assumed: October 1, 1942, to July 31, 1946 (operations), August 1, 1946, to September 14, 1947 (standby), September 15, 1947, to October 31, 1947 (rehabilitation), and November 1, 1947, to July 7, 1954 (operations and cleanup). From October 1, 1942, into 1946, both African and domestic ore were used for research, development, and production. Tonawanda Laboratory AEC work is assumed to have stopped radiation work after December 31, 1946, although some workers might have visited the Ceramics Plant buildings. The exact levels of contamination that remained at the Ceramics Plant and the nature of worker activities in areas of residual activity are unknown for the standby and rehabilitation periods. Exposures to uranium progeny and radon would have decreased at the Ceramics Plant after August 31, 1946, because ore was no longer processed during this period. Continued lower level exposures to uranium progeny and to radon were assumed because some radioactive waste was disposed of on the site and because initial cleanup was not completed until the end of 1954; however, for the Ceramics Plant the uranium exposures would have dominated during the post-1946 period.

The primary sources of internal radiation exposure at Linde due to MED and AEC work were natural uranium and its progeny.

3.1 ESTIMATION OF PARTICULATE INTAKES

During World War II and the time of the MED, the permissible level for natural uranium air dust concentration was set at 500 $\mu\text{g}/\text{m}^3$ for insoluble uranium compounds and 150 $\mu\text{g}/\text{m}^3$ for soluble uranium compounds. After the war, the University of Rochester in Rochester, New York, recommended lowering the permissible level to 50 $\mu\text{g}/\text{m}^3$ for all uranium compounds on the basis of chemical toxicity. This level was also stated as 70 dpm/ m^3 for natural uranium and was based primarily on animal studies. The Medical Division of the AEC NYOO thought that the maximum permissible level should be based on human data and was thus unknown. Therefore, the level of 50 $\mu\text{g}/\text{m}^3$ was generally referred to as the preferred level (PL) (AEC 1949a). Contractors of the AEC often used the term maximum allowable (air) concentration (MAC) interchangeably with PL and reported air-sampling results as multiples of the MAC (Stewart 1952; AEC 1953). When considering air concentrations that were reported in multiples of the PL or MAC, the actual assumed value of the PL or MAC should be verified.

In 1949, the Medical Division of the NYOO published a report on the health hazards at seven facilities that produced and/or processed uranium for the AEC. These facilities included Mallinckrodt Chemical Works, Harshaw Chemical Company, LAPC, Electro Metallurgical Company, and Vitro Manufacturing Company. The AEC used the information on work tasks with measured air concentrations in

breathing zones, general areas, and process areas to determine average air concentrations that were weighted by exposure times and summed these time-weighted air concentrations to determine daily time-weighted average air concentrations by job category. Up until the time of the 1949 AEC report (AEC 1949a), surveys by the NYOO indicated that out of 648 exposed workers at these plants, 9% were exposed to uranium air concentrations greater than 125 MAC (greater than 6,250 $\mu\text{g}/\text{m}^3$), 9% were exposed at 25 to 125 MAC (1,250 to 6,250 $\mu\text{g}/\text{m}^3$), and 82% were exposed to less than 25 MAC (less than 1,250 $\mu\text{g}/\text{m}^3$). Linde's maximum time-weighted exposure during this period was 33 or 32 MAC (the data in the report's text and its graph differed). As a result of the NYOO report, significant improvements were made in operational conditions such as redesign of ventilation systems, enclosing some processes, and using remote controls (AEC 1949a). By the end of 1949, exposure levels were significantly reduced at these larger plants even though production levels increased (Mason 1958).

Indications are that some of the higher routine (versus episodic) exposures occurred at the uranium ore processing facilities. The AEC did not exist until January 1, 1947, and its report (AEC 1949a) did not elaborate on internal exposures before its tenure. A general review of air concentration data, safety reports, and production and progress reports from the early 1940s through 1946 indicates that there were significant reductions in exposures due to improved engineering, process, workplace, and administrative controls brought into effect before the AEC report. This indicates that the exposures at the ore and waste processing plants in the earliest years of operations would likely have been higher than the exposures during AEC tenure. Indeed, the "tolerance" air concentration was 10 times higher for insoluble compounds during the early years and 3 times higher for soluble compounds.

After the ore processing, Linde began a standby period. It was assumed that exposures decreased to 0.1 MAC at the Tonawanda Laboratory after cleanup in 1946 until December 31, 1953. Based on reviews of later air concentrations at Linde and reviews of air concentration data from other sites, most workers' exposures would have been much lower during these periods.

The standby period at Linde Ceramics was assumed to end on September 14, 1947. Rehabilitation of the Step III process was assumed to begin on September 15, 1947, and continue through October 31, 1947.

3.2 URANIUM

During uranium research and the processing of uranium ores at Tonawanda Laboratory and the Ceramics Plant, workers might have been exposed to a variety of uranium chemical forms that encompass all lung absorption types: F, M, and S. Although some process steps might have had more or less exposure to a given lung absorption type, it is not clear how well separated these areas were before standby. In addition, workers could have worked in multiple uranium process areas. This analysis assumed that types F, M, and S were available before standby. After operations ceased in 1946, it is more likely that remaining uranium contamination would have been oxidizing and becoming less soluble. Beginning with the rehabilitation period for restart of Step III operations in 1947, it is assumed that only type M and S materials would be available. The selection of absorption type should depend on the organ of interest.

3.2.1 Uranium Urinalysis Data

Medical urinalyses for specific gravity, proteins, sugars, etc. were a requirement at Linde from the beginning of MED work, but there is no evidence that urine was analyzed for radioactivity until 1947. MED noted that tentative arrangements had been made for uranium urinalyses of certain groups of employees at Linde (Ferry 1944b), but no records are available to indicate the analyses were done. A page titled, "Schedule of Examinations, Contract AT-30-1-GEN-165" (Author unknown ca.1947), which commenced sometime in 1947 (Rennich 1947), indicates that 60 cm^3 of urine from each

employee was to be sent monthly to the University of Rochester, the location of one of the earliest bioassay analysis programs. Individual uranium urinalysis data from November 1947 to 1950 are available for some Linde Ceramics workers (LAPC 1947–1950). The period covers both Step III production in Building 38 and decontamination in Building 30. Worker radiation exposures during this period were likely to be lower than during the production period before standby because African ore was no longer being processed, Step I and II processes had ceased, and engineered safety controls had been improved.

The reported results of Linde uranium urinalyses during Step III production and later cleanup ranged from 0 to 3.10 mg/L, with many of the higher results reported in the November to December 1947 “preemployment urines.” Because cleanup/preparation activities occurred before collection of these samples, it is possible the elevated urinalysis results represented exposures that were received either during rehabilitation of the Step III equipment or perhaps from the less soluble component of uranium that was taken in during earlier operations.

In November 1948, two uranium urinalysis results, 3.10 and 0.33 mg/L, were noted as high, and Linde was requested to consider the possibility of contamination. A fluoride result from the individual with the highest uranium results was also elevated. No information was found to indicate whether these were contaminated samples, but the results are consistent with intakes of soluble uranium.

Some samples might have been collected over the weekend: one set of samples indicated that collection bottles were taken home on a Friday because there was no work for 2 days, and the bottles were returned on Monday morning at 8:00 a.m. A note on the January 1950 uranium urinalysis results states, “Please add approx[imately] 1% of conc[entrated] HCl to urine as a preservative instead of toluene.”

It appears that the University of Rochester and the AEC NYOO were performing the uranium urinalyses for Linde (Wolf 1948). The uranium fusion photofluorimetry urinalyses that were performed by the University of Rochester and the AEC NYOO were similar to those at other AEC facilities. The default detection threshold for uranium urinalysis was assumed to be 10 µg/L based on a reported sensitivity of 5 to 10 µg/L for uranium fluorimetry urinalysis in the early years (Wilson 1958). However, the January 1948 uranium urinalysis results AEC transmitted to Linde included a note that indicated the minimum detectable amount might have been much higher (Wolf 1948):

The uranium content of those samples listed as being 0.1 mg U/l or less is below the limit of accurate quantitative determination by the photofluorometric method of analysis.

February, May, June, August, and November 1948 uranium urinalysis results included a similar note, but 0.01 mg U/L was reported as the limit of accurate quantitative determination or reliable determination for photofluorometric analysis. The January 1948 determination level of 0.1 mg/L is assumed to be a typographical error because this is the same as the determination level reported for (nonradioactive) fluoride urinalysis and because there seems to be no change in the format of the reported numbers.

The AEC requested “check samples” on all uranium urinalyses that exceeded 0.1 mg/L, and noted in February 1948 that it would be appropriate to resample in about 3 months (Wolf 1948). Linde’s reply requested clarification because it had previously understood that resampling was to occur monthly (Heatherton 1948f).

Analysis of Coworker Bioassay Data for Internal Dose Assignment (ORAU 2005d) describes the general process used for analyzing bioassay data for assigning doses to individuals based on coworker results. Bioassay results described above were analyzed in accordance with this procedure

(Attachment D). The results of this analysis are presented in Tables 3-1 and 3-2. Individual uranium urinalysis results should be used to determine internal exposure to the individual when they are available. Where individual results are not available, the coworker data included in Attachment D and summarized in Tables 3-1 and 3-2 are to be used to estimate internal exposures that are favorable to claimants.

Table 3-1. Chronic intake rate for Type M uranium (pCi/d).

Start date	End date	50th-percentile value	GSD
11/01/1947	07/07/1954	74	4.0

Table 3-2. Chronic intake rate for Type S uranium (pCi/d).

Start date	End date	50th-percentile value	GSD
11/01/1947	07/07/1954	1884	4.3

3.3 RADIUM

HHS has determined, and NIOSH has concurred that it is not feasible to reconstruct internal exposure prior to November 1, 1947 (HHS 2005). Information on radon exposure prior to November 1, 1947 is provided only as a basis for extrapolation afterwards and is not intended to be used during the period in which reconstruction of internal dose has been determined to be infeasible.

All radium compounds are lung absorption type M. Radon breath analyses have been used to provide information on the amount of radium in the body and are available for some Linde workers.

Radon Breath Data

The level of radon in exhaled breath can provide information on the amount of radium in the body. Radon breath data were found for 45 samples from Linde workers between June 12, 1944, and January 17, 1945 (LAPC 1944–1945). The records indicate that Dr. R. D. Evans in Cambridge, Massachusetts, analyzed some of the samples. Room background concentrations of radon were sometimes subtracted from the results and sometimes not. In July and August 1944, room background concentrations were reported respectively as 0.6 and 0.3 pCi/L (Tybout 1944b). The measured radon levels were given for some but not all of the samples. Reported radon breath results ranged up to 2.2 pCi/L. The method of deriving the ²²⁶Ra level was not stated, but in many cases, the reported burden of radium in micrograms was numerically equal to 10% of the breath radon concentration in picocuries. Radon breath results are the starting point for dose reconstruction, so it might be necessary to back-calculate breath results from either ²²⁶Ra burdens or tolerance levels. The original records might have sufficient information for this determination. This information has not yet been tabulated for inclusion in this site profile.

3.4 URANIUM PROGENY

Ceramics Plant 1943 to 1946 Production, and Tonawanda Laboratories

HHS has determined, and NIOSH has concurred that it is not feasible to reconstruct internal exposure prior to November 1, 1947 (HHS 2005).

Ceramics Plant 1947 to 1949 Step III Production and Subsequent Initial Cleanup

During this period, refined uranium materials were handled. None of the uranium progeny would have been present in significant quantities in the refined uranium materials but, to account for uranium progeny potentially present from past activities and resuspended during decontamination and decommissioning (D&D) activities, data from the postoperations period was reviewed to determine bounding activity ratios (Attachment E). Table 3-3 presents bounding indoor uranium progeny ratios

for use for dose reconstruction for the period from November 1, 1947, through July 7, 1954. The values in this table were the highest observed values from the indoor and storm sewer sampling locations.

Table 3-3. Progeny to uranium ratios.

Progeny/U (total)	Ratio to uranium
Th-230/U	0.26
Ra-226/U	0.21
Po-210/U ^a	0.21
Ac-227/U	0.29
Pa-231/U	0.01

a. Po-210 activity not reported, assumed to be the same as parent (Ra-226)

3.5 RADON

HHS has determined, and NIOSH has concurred that it is not feasible to reconstruct internal exposure prior to November 1, 1947 (HHS 2005). Information on radon exposure prior to November 1, 1947 is provided only as a basis for extrapolation afterwards and is not intended to be used during the period in which reconstruction of internal dose has been determined to be infeasible.

More than 200 measurements of radon/U concentrations were made during 1942 to 1946 pilot plant and production processing of African ore at Linde (LAPC 1944–1946). The early measurements were made using liter glass bulbs that were evacuated immediately before sampling to below 50 μm (Skinner 1944). It is likely that the later measurements during operations were made in the same way. Early samples were analyzed at the Massachusetts Institute of Technology; later analyses appear to have been performed at the University of Rochester. The tolerance value for radon, sometimes abbreviated as TV in the old records, was 100 pCi/L.

To determine exposure due to a specified radon concentration (assumed to be ²²²Rn), the concentration *C* in picocuries per liter was converted to potential alpha energy concentration (PAEC) in units of working level (WL) using:

$$PAEC = C \times F \div (100 \text{ pCi/L per WL}) \quad (3-1)$$

where the equilibrium factor *F* was taken as 0.4, a value that is recommended by International Commission on Radiological Protection (ICRP) Publication 32 (ICRP 1981) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1993). Potential alpha energy

exposure (PAEE) in units of working level-months (WLMs) was obtained from the PAEC and the number of months of exposure *M* using:

$$PAEE = PAEC \times M \quad (3-2)$$

where a month is assumed to be 170 work hours.

3.5.1 Ceramics Plant Radon Exposures

During Ceramics Plant preproduction and initial production (which involved only domestic ore processing), the only source of radon was African ore processing at Tonawanda Laboratory. The indoor and outdoor radon concentrations to which Ceramics Plant workers were exposed were assumed to equal the outdoor concentration from Tonawanda Laboratory work. No direct measurement of this was available. An estimate was made based on the lowest measured indoor concentrations at the Ceramics Plant during African ore processing. These were viewed as indicating

the upper limit to the outdoor concentration because outdoor air was drawn indoors for ventilation. Approximately 20% of the measurements in the Ceramics Plant ore processing building yielded results of 10 pCi/L or less, with most of these results at or near 10 pCi/L. Therefore, 10 pCi/L was taken as the estimated outdoor concentration.

Measured radon concentrations during processing of African ore at the Ceramics Plant are summarized in Table 3-4. Based on geometric means (GMs), locations were grouped into three categories – high, medium, and low – and the GM and geometric standard deviation (GSD) of all results in each category were determined. Some results were reported as less-than values and these are denoted as less than the limit of detection (<LOD).

Table 3-4. Measured radon concentrations during Ceramics Plant African ore processing.

Location category/location	# of samples	GM (pCi/L) ^a	GSD	GM (pCi/L) ^a	GSD
High				99.3	3.43
Scales	5	153	2.50		
Ore box car	17	125	3.92		
Ore sampling room	24	100	3.11		
Ore dumping grill	18	88.6	2.91		
Ore storeroom	26	88.5	4.49		
Ore bin/conveyor	7	83.3	9.37		
Medium				42.5	2.72
Ore bag tumbler	17	60.2	2.53		
Ore bag wash room	8	45.1	2.78		
ball mill & classifier	24	32.5	2.74		
Low				22.4	3.17
Step 1 digestion & filtration	55	23.7	3.17		
Loading dock	1	18.0	(b)		
Receiving desk	5	12.9	2.43		

- a. In computing the GM, a <LOD value was assumed to equal the LOD.
b. GSD could not be determined.

After the end of African ore processing, concentration in the main ore processing building, Building 30, was assumed to remain at the 10-pCi/L level that was measured during the second period of domestic ore processing until the end of cleanup of Building 30. Concentrations in other Ceramics Plant buildings were also assumed to be 10 pCi/L until the end of cleanup in those buildings. Because the locations of many workers are likely to be unknown, it was assumed that all workers were exposed to 10 pCi/L of radon from November 1, 1947, through July 7, 1954. Table 3-5 lists concentrations and exposure rates.

Table 3-5. Ceramics Plant worker radon exposures rates, 1947 to 1954.

Period/work location	Time-weighted concentration (pCi/L)	Exposure rate (WLM/yr)
11/01/1947–07/07/1954		
All workers	10.0	0.480

3.5.2 Tonawanda Laboratory Radon Exposures

Few measurements were available for the Tonawanda Laboratory, so estimates of radon concentrations were based on Ceramics Plant data. African ore work at Tonawanda Laboratory appears to have occurred just before each period of African ore processing at the Ceramics Plant. The precise dates of African ore research at Tonawanda Laboratory are not known. Based on the available reports, it appears to have occurred only about half of the time that the Laboratory was engaged in MED work, with most of the African ore work concentrated in the periods immediately

before the beginnings of the two African ore processing periods at the Ceramics Plant. For dose reconstruction, it was assumed that African ore processing at Tonawanda Laboratory occurred during the entire MED period, but that the peak concentrations of radon were equal to the medium values at the Ceramics Plant. It was assumed that after MED research and initial cleanup at the Laboratory ended, the radon concentration dropped to 10 pCi/L (the level in the Ceramics Plant after it switched from African ore processing to domestic ore processing) and remained there until the end of the cleanup at the Laboratory. After the end of cleanup, radon exposure in the Laboratory was based on the highest GM PAEC that was determined for a Tonawanda site building from measurements in 1981. That value was 1.68×10^{-02} WL for Building 31 based on analysis of data in BNI (1982, Table B-3). Table 3-6 summarizes the assumed radon concentrations and resultant exposures.

Table 3-6. Tonawanda Laboratory radon exposure rates, 1947 to 1953

Period		Time-weighted concentration (pCi/L)	Exposure rate (WLM/yr)
Start	End		
Postcleanup			
11/01/1947	12/31/1953	—	0.202

Radon and Radon Progeny

The radon exposure rates that are provided here are annual PAEE rates in WLM/yr. Each value is assumed to be the median of a lognormal distribution with a GSD of 3.43. This GSD is based on the location category having the highest GSD (3.43 per Table 3-4).

3.6 INHALATION INTAKE ESTIMATES OF RADIOACTIVE PARTICULATES AT TONAWANDA LABORATORY

The airborne concentrations in Section 3.1 can be used to determine uranium intakes for Tonawanda Laboratory employees from November 1, 1947, through December 31, 1953. This analysis assumed that a worker was chronically exposed to alpha airborne concentrations as stated in Section 3.1 and summarized in Table 3-7.

Table 3-7. Assumed airborne concentrations used to estimate intakes at the Tonawanda Laboratory.

Start	End	Activity description	# MAC	α dpm/m ³	Source
11/01/1947	12/31/1953	Postcleanup	0.1	7	Uranium and progeny

This analysis assumed Linde workers were exposed to the given air concentrations for 8 hr/d, 5 d/wk, and 50 wk/yr. Time-weighted exposure studies of even the larger plants like Mallinckrodt showed that the majority of workers were exposed at lower levels than were estimated for the early 1942 to 1946 operational period. No credit is taken for breaks or working at tasks where radioactive material intakes would be much lower or nonexistent, or for the use of facemasks; on the other hand no consideration was given to the longer workweeks and work hours in the early years. In addition, because workers were exposed to multiple absorption types, but the single absorption type that produces the larger dose is used to estimate organ dose, it is believed that this estimate adequately accounts for internal exposure.

Because the early air concentration measurements would have included detection of radiations from progeny, the air concentrations that are listed in Table 3-7 as including progeny are apportioned based on the assumption of full equilibrium among uranium and its progeny, using the alpha ratios of uranium and progeny of internal dosimetric importance.

For example, the annual uranium inhalation intake due to chronic exposure at 0.1 MAC was estimated by multiplying the air concentration of 7 dpm/m³ by the alpha fraction of uranium (0.489), the ICRP Publication 66 (ICRP 1994) recommended breathing rate of 1.2 m³/hr, and the assumed 2,000 work

hours per calendar year. This results in an annual chronic inhalation intake of 8.215×10^3 dpm, which is equal to a daily intake rate of 22.5 dpm/d.

Inhalations of the uranium progeny were estimated by substituting the alpha fraction of the progeny for the alpha fraction of the uranium.

3.7 INGESTION INTAKE ESTIMATES AT TONAWANDA LABORATORY

In the case where inhalation intakes are calculated from air concentrations, ingestion intakes are also to be considered. NIOSH (2004) indicates that the ingestion rate, in terms of dpm for an 8-hour workday, can be estimated by multiplying the air concentration in dpm per cubic meter by a factor of 0.2, so the uranium ingestion rate based on an air concentration of 7 alpha dpm/m³ would be 0.563 dpm/wd. To adjust this to ingestion intake per calendar day, 0.685 dpm/wd was multiplied by 250 wd/yr and divided by 365 d/yr, which equals 0.469 dpm/d. In accordance with NIOSH (2004), the f_1 -value used for inhalation dose calculations is to be used for ingestion dose calculations.

3.8 OCCUPATIONAL INTERNAL DOSE RECONSTRUCTION ASSUMPTIONS AND SUMMARY

HHS has determined, and NIOSH has concurred that it is not feasible to reconstruct internal exposure prior to November 1, 1947 (HHS 2005).

Intake estimates and radon exposures that were estimated for Linde workers are shown in the Tables 3-8, 3-9, 3-10, and 3-11. Uranium intakes are based on the coworker data contained in Tables 3-1 and 3-2. Uranium progeny intakes were determined by applying the isotopic ratios in Table 3-3. For the ceramics plant, either the values in Table 3-8 or 3-9 should be applied (not both), whichever is most favorable to claimants along with the radon intake in Table 3-10. Tonawanda laboratory employees should be assigned the intakes in Table 3-11. For workers whose work location is considered indeterminate, intakes for the Ceramics Plant should be assumed.

Uranium bioassays are available for some workers during the period from November 1947 through January 1950. If uranium bioassays are used to reconstruct an individual's dose (as opposed to the values tabulated below), additional intakes from uranium progeny must be added using the activity ratios in Table 3-3.

Table 3-8. Internal exposure summary for the Ceramics Plant, November 1, 1947, to July 7, 1954 (based on Type M uranium).

Radionuclide	Start	End	Intake route	Absorption type	Intake or exposure	Units
U-234	11/01/1947	07/07/1954	Inhalation	M	1.64E+02 ^a	dpm/d
Th-230	11/01/1947	07/07/1954	Inhalation	M	4.26E+01 ^a	dpm/d
Ra-226	11/01/1947	07/07/1954	Inhalation	M	3.44E+01 ^a	dpm/d
Po-210	11/01/1947	07/07/1954	Inhalation	M	3.44E+01 ^a	dpm/d
Pa-231	11/01/1947	07/07/1954	Inhalation	M	1.64E+00 ^a	dpm/d
Ac-227	11/01/1947	07/07/1954	Inhalation	M	4.76E+01 ^a	dpm/d

a. Intake assuming type M uranium, value listed is GM of a lognormal distribution with GSD of 4.0.

Table 3-9. Internal exposure summary for the Ceramics Plant, November 1, 1947, to July 7, 1954 (based on Type S uranium) .

Radionuclide	Start	End	Intake route	Absorption type	Intake or exposure	Units
U-234	11/01/1947	07/07/1954	Inhalation	S	4.18E+03 ^a	dpm/d
Th-230	11/01/1947	07/07/1954	Inhalation	S	1.09E+03 ^a	dpm/d
Ra-226	11/01/1947	07/07/1954	Inhalation	M	8.78E+02 ^a	dpm/d
Po-210	11/01/1947	07/07/1954	Inhalation	M	8.78E+02 ^a	dpm/d
Pa-231	11/01/1947	07/07/1954	Inhalation	S	4.18E+01 ^a	dpm/d
Ac-227	11/01/1947	07/07/1954	Inhalation	S	1.21E+03 ^a	dpm/d

a. Intake assuming type S uranium, value listed is GM of a lognormal distribution with GSD of 4.3.

Table 3-10. Internal exposure summary for the Ceramics Plant, November 1, 1947, to July 7, 1954.

Radionuclide	Start	End	Intake route	Absorption type	Intake or exposure	Units
Rn-222	11/01/1947	07/07/1954	Inhalation	(a)	0.48E+00	WLM/yr

a. Value shown is for full year, partial years should be prorated.

Table 3-11. Internal exposure summary for the Tonawanda Laboratory, November 1, 1947, to December 31, 1953.

Radionuclide	Start	End	Intake route	Absorption type	Intake or exposure ^b	Units
U-234	11/01/1947	12/31/1953	Inhalation	M, S	2.25E+01	dpm/d
			Ingestion	(a)	4.69E-01	dpm/d
Th-230	11/01/1947	12/31/1953	Inhalation	M, S	1.10E+01	dpm/d
			Ingestion	(a)	2.29E-01	dpm/d
Ra-226	11/01/1947	07/07/1954	Inhalation	M	1.10E+01	dpm/d
			Ingestion	(a)	2.29E-01	dpm/d
Po-210	11/01/1947	07/07/1954	Inhalation	F, M	1.10E+01	dpm/d
			Ingestion	(a)	2.29E-01	dpm/d
Pa-231	11/01/1947	07/07/1954	Inhalation	M, S	5.13E-01	dpm/d
			Ingestion	(a)	1.07E-02	dpm/d
Ac-227	11/01/1947	07/07/1954	Inhalation	F, M, S	5.13E-01	dpm/d
			Ingestion	(a)	1.07E-02	dpm/d
Rn-222	11/01/1947	12/31/1953	Inhalation	-	2.021E-01	WLM/yr

a. Choose same f_i -value as used for inhalation per NIOSH (2004).

b. The dose distribution for particulate intakes is assumed to be constant. The dose distribution for radon is assumed to be lognormal with a GSD of 3.43.

4.0 ESTIMATION OF EXTERNAL EXPOSURE, 1942 TO JULY 7, 1954

Because of the SEC determination (HHS 2005) that it is infeasible to adequately reconstruct internal dose during the period October 1, 1942 through October 31, 1947, dose estimates for this period are considered partial dose estimates.

This section develops parameters for reconstruction of doses due to external exposures due to work activities from October 1, 1942, the assumed start date of MED work at Linde, until December 31, 1953. In some parts of this section, measurements and parameters for the period after 1953 are analyzed because they provide information used to estimate external exposures before 1954. Occupational medical exposures are treated in Section 5.0. Dose reconstruction for the period after 1953 is discussed in Section 6.0. Film badges were worn by some workers during some periods. For unmonitored workers and periods, doses are estimated from source term information, workplace measurements, and from available dosimetry results for workers.

Throughout this document, it is assumed that $1 \text{ mR} = 1 \text{ mrad(air)} = 1 \text{ mrad(tissue)} = 1 \text{ mrem} = 1 \text{ mrep}$.

Beta Radiation

In developing the beta dose rate estimates in this section, no attenuation due to shoes, apparel, or protective items (e.g., gloves, face shields) was considered. Attenuation due to apparel is variable and sometimes not very significant (see Table A-5). The types of protective items issued to workers varied with time, and the extent to which workers used them is uncertain.

Workers who frequently handled significant quantities of beta-emitting materials were assumed to have had higher beta doses to the hands and forearms than to the remainder of the body. The relationships assumed between contact dose rate and dose rates to other parts of the body were based in part on data from the Ceramics Plant (see Table A-6).

For the purpose of calculation of organ dose, all exposure geometries are assumed to be anterior-posterior (AP).

Burlap Bag Exposures

Based on the assessment contained in Attachment E of this TBD, NIOSH 's review of historical records indicates that the period during which the burlap bags were staged and burned is within the current SEC period. NIOSH has found no other credible evidence, other than a former employee affidavit which indicated that two pallets of filled burlap bags were in Building 30 at Linde Ceramics, to support a potential burlap bag exposure issue outside of the SEC period. If credible information is presented in an individual CATI, or documentation related to an individual claim, to establish the worker's occupational proximity to the burlap bags, dose reconstructors should use the external dose estimates provided in Attachment E to assess this external exposure scenario to support assessment of this external dose for the purpose of individual dose reconstruction.

4.1 CERAMICS PLANT BETA AND GAMMA EXPOSURE

4.1.1 Preproduction, 1942 to 1943

A systematic characterization of radiation levels in Building 30 was made in 1949 in conjunction with its decontamination (Heatherton 1950). A survey scheme called "restricted randomization" was used. The floor area was divided into 15- by 15-ft squares each of which in turn was divided into 100 small squares. In each large square, four of the small squares were selected at random and surveyed.

Total beta plus gamma radiation in millirep per hour was measured at contact at the square's center and corners and at 3 ft above the floor. A similar method was used to measure wall contamination. Before the initial survey, the building was vacuumed and flushed with water. After the initial survey, heavily contaminated portions of the building were removed or cleaned, mostly by sandblasting. Then the building was again vacuumed and flushed, and a final survey was taken. Heatherton (1950) reported the number of measurements and the lowest, mean, and highest values for each of several major plant areas. The middle columns of Table 4-1 display the results of a statistical analysis of the data.

Another comprehensive survey of Building 30 was made in 1976 (ORNL 1978). Beta plus gamma levels in millirad per hour were measured at 1 cm from the surface, and gamma levels microrentgen per hour were measured at 1 m. Table 4-2 displays the results of a statistical analysis of the data. The measured levels were similar to the postdecontamination results of 1950, which indicated little change in conditions. Because gamma measurements were reported, the beta and gamma percentages of the radiation could be estimated. These were used to estimate the beta and gamma components in Table 4-1 for the pre- and postdecontamination results.

Table 4-1. Floor and wall radiation in Building 30 before and after the 1949 to 1950 decontamination.

Time	Location	Measured beta plus gamma ^a		Estimated	
		Median (mrep/hr)	GSD	Beta (mrem/hr)	Gamma (mR/hr)
Before vacuum cleaning and flushing	Contact	(b)	(b)	2.03 ^c	0.131 ^c
	3 ft	(b)	(b)	0.676 ^c	0.131 ^c
Predecontamination (just before decontamination and after vacuum cleaning and flushing)	Contact	0.719	1.67	0.675 ^d	0.0438 ^d
	3 ft	0.240	1.67	0.225 ^d	0.0438 ^e
After decontamination	Contact	0.311	2.04	0.292 ^d	0.0189 ^d
	3 ft	0.0940	2.04	0.0883 ^d	0.0189 ^e

- Based on data in Heatherton (1950, Tables III and IV). The data were assumed to be characterized by a lognormal distribution. For the contact measurements, the mean value and a percentile value were available (the percent of results less than 1 mrep/hr was stated). These were used with the computer program LOGNORM4 (Strom and Stansbury 2000) to estimate the median and GSD. For measurements at 3 ft, the mean was available but not the percentile value. The GSD determined from the contact data was assumed to apply and used to estimate the median.
- Not available.
- Assumed to be three times higher than the predecontamination values. The factor three is based on April 1949 data; see discussion in text.
- Estimates based on beta and gamma percentages in Table 4-2.
- Assumed to equal contact gamma exposure rate.

Table 4-2. Building 30 floor radiation levels in 1976.

Parameter	GM ^a		GSD ^a	Composition of radiation at 1 cm
	Value	Units		
Beta plus gamma at 1 cm	0.253	mrad/hr	3.47	(b)
Gamma at 1 m ^c	0.0154	mR/hr	1.69	(d)
Estimated gamma at 1 cm ^e	0.0154	mR/hr	(d)	6.09%
Estimated beta at 1 cm ^f	0.238	mrad/hr	(d)	93.9%

- GM and GSD were calculated from data in Table 3 of ORNL (1978).
- Estimate made in last two lines of the table.
- Background was not subtracted from the external gamma values. Outdoor external background in the Tonawanda area was reported to be 8 to 15 µR/hr (ORNL 1978, p. 15).
- Not applicable.
- Estimated as equal to gamma at 1 m.
- Estimated as 0.253 (beta plus gamma) less 0.0154 (gamma).

The measurements just before decontamination in 1949 and 1950 were made after the building had undergone vacuum cleaning and flushing. Brief, semiquantitative reports were available for two 1-day

surveys in April 1949 before the vacuum cleaning and flushing (Blatz 1949; Wolf 1949a). Typical levels of measured gamma radiation at 3 ft on April 19 and at contact on April 22 were similar and averaged about 0.18 mR/hr, about 4 times higher than the estimated median contact gamma level before decontamination. Typical levels of measured beta at contact on April 22 averaged about 0.87 mrep/hr, about 1.3 times higher than the estimated median beta level before decontamination. The April results were the basis of the estimate in Table 4-1 that beta and gamma radiation levels before vacuum cleaning and flushing were 3 times higher than the values that were measured afterward.

In the 1976 survey, Building 30 was the most contaminated building on the site (ORNL 1978). The levels for Building 30 were assumed to apply to all buildings on the site.

For the preproduction period, it was assumed that there was no significant external beta or gamma exposure indoors for Ceramics Plant workers because the buildings were under construction or new. Some exposure while outdoors was possible because the transport of ore to Tonawanda Laboratory (Building 14) and the work there could have produced some site contamination. Resultant outdoor radiation levels are very likely to have been less than floor and wall radiation levels inside Building 14 because the indoor and outdoor sources would have been comparable but the outdoor sources could spread over a larger area and were subject to dispersal by the weather. The radiation levels before vacuuming and flushing that are estimated in Table 4-1 are taken as an estimate of the levels in Building 14 and also as an upper limit estimate of site outdoor radiation levels. Ceramics Plant workers were assumed to have been exposed to these levels for 0.5 hr/d. Table 4-3 shows estimated annual exposure rates.

Table 4-3. Preproduction beta and gamma radiation levels.

Beta (rem/yr) ^a	Gamma (R/yr) ^a	GSD ^b
1.01E-01	1.97E-02	3

a. Based on Table 4-1 beta and gamma levels at 3 ft before vacuum cleaning and flushing. Assumed exposure period: 0.5 hr/wd, 6 wd/wk, 50 wk/yr. The beta and gamma rates are for the whole body.

b. Estimated on the basis of the GSD values in Tables 4-1 and 4-2.

The beta dose rate was assumed to apply to the whole body with no added dose to the hands and forearms because it is unlikely that there was any significant handling of radioactive materials by Ceramics Plant workers in this period.

4.1.2 **Production, 1943 to 1946**

4.1.2.1 **Beta**

No beta film badge data were found for 1943 to 1946. There were beta film badge data for 1947 to 1949, but none of the data pertained to Steps I or II, as these processes were no longer in operation. For 1943 to 1946, one report of workplace beta exposure rates was found. Solid samples from the Ceramics Plant were sent on January 23, 1944, to laboratories of the Medical Section of the MED for measurement of beta radiation. Results were reported as "Beta Radiation Roentgens/8 Hr Day" (Ferry 1944c) and are reproduced here in the first five columns of Table 4-4. The roentgen is technically defined only for photon radiation; beta dose should be expressed in absorbed dose units such as rad or rem. However, because there is an approximate numerical equivalence between these units, it is assumed here that the roentgen unit used is equivalent to shallow dose at 0.07 mm in rem.

From the fact that no distance values were reported with the measurements and from later discussion of the measurements in MED correspondence (Thomas 1944), it is apparent that contact exposure

rates were reported. This is supported by the similarity of the results to contact dose rates for various natural uranium materials (see Table A-1).

The fourth and fifth columns of Table 4-4 contain the allowable times of exposure based on a 3.0-R/wk tolerance level and the actual hours of exposure per week as stated in the MED report. For the L-30 tailings sample, the actual exposure time was stated to be 50 hr/wk, much greater than the allowable exposure time of 18 hours. A MED memorandum (Hadlock 1944) questioned this discrepancy. It brought the following MED response (Thomas 1944):

No action has been taken on the Captain Ferry's recommendation that the exposure time to L-30 tailings be limited to 18 hours. The primary reason for this is the fact that the estimated fifty hours is based on the time which a man is actually within range of the radiation whereas the Medical Section's allowable exposure time is based on contact of the tailings directly with the hands....

Table 4-4. Beta radiation exposure rates measured at Linde Ceramics, January 23, 1944.

From MED report of data during processing of L-30 African ore ^a					Estimated worker dose rate (rem/yr) ^d
Sample #	Sample location	Beta radiation (R/8-hr day) ^b	Allowable time of exposure per worker (hr/wk) ^c	Actual time of exposure per worker (hr/wk)	
13	L-30 Ore, Step I	0.1	150	50	31
9	L-30 Tailings, Step I	1.4	18	50	263
12	Barium Cake, Step I	0.8	30	0.33	2
14	A. L. Cake, Step I	1.3	18	9	73
15	PbS Cake, Step I	0.2	120	2	3
16	Soda Salt, Step I	0.5	48	9	28
10	Iron Cake, Step II	0.8	30	3	15
11	N.G. Cake, Step II	4.2	6	6	158

- Results reported by the MED for measurements made on solid samples sent from Linde Ceramics January 23, 1944 (Ferry 1944c).
- Units are those stated in the MED report.
- The MED allowable time of exposure was based on the then-effective tolerance levels of 0.5 R/d and 3.0 R per 6-day week for beta radiation.
- Except for Sample #9 (L-30 tailings), the dose rate is based on an assumed 50-week year and the dose rate and actual hours of exposure per week stated by the MED. For the worker handling L-30 tailings, the dose rate is estimated based on information in the MED letter (Thomas 1944) cited in the text. The dose rate when the worker is "within range of the radiation" is estimated as half of the contact dose rate. If the source is sufficiently large and there is no shielding, a distance of 1.6 m from the tailings would be required to reduce the dose rate by a factor of 2 (see Table A-4). The dose estimate calculation is as follows:

Location	(rem/8hr)	hr/wk	hr/yr	rem/yr
Hands in tailings	1.4	10	500	88
Within range of radiation	0.7	40	2,000	175
Total				263

The Linde operating and safety sections have estimated that the average time a worker spends with his hands in the tailings is six to eight hours one week. The maximum time is never over ten hours one week and even then heavy rubber gloves are worn.

The last column of Table 4-4 shows worker doses derived from the data. These range from 2 to 263 rem/yr.

It is striking that the 1943 to 1946 dose rates in Table 4-4 are much higher than the 1947 to 1949 rates Section 4.1.4.1 discusses. For 1943 to 1946 Step I process operators, the beta dose rate was estimated as 263 rem/yr. For 1947 to 1949, the job with the highest beta dose rate was that of a Step III process operator, and film badge data indicate that the beta dose rate was only about

2 rem/yr (approximate value of annual $D_D + D_M$; see Table 4-16 later in this section). Despite the high estimates, the 1943 to 1946 data does not appear unreasonable. The dose rates in Table 4-4 are typical of contact dose rates for uranium materials (see Table A-1). The worker exposure times were debated and reviewed within the MED. In the MED's interpretation of the data, with allowances for the protective measures (e.g., gloves) the rates were within the limit in effect at the time, 3.0 R per 6-day week (Ferry 1944c) or 150 R/yr. Therefore, the estimates in Table 4-4 are considered a valid basis for dose reconstruction.

4.1.2.1.1 Estimation of Worker Doses

Beta doses for specific jobs are estimated below and summarized in Table 4-24 at the end of this section.

1943 to 1946 Loaders, Step I Process Operators, Step II Process Operators, Ball Mill Operators, and Weighmasters

The calculated dose in Table 4-4 for sample 13 was assumed to apply to a loader. The doses for samples 9 and 11 were assumed to be the doses to the most highly exposed Step I and Step II process operators, respectively. The dose for the most highly exposed process operator was assigned to all process operators in a step. A ball mill operator was assigned the same dose as a Step I process operator because the ball mill operators performed some of the tasks of process operators when not operating the ball mill (see job description for CL-3, Chemical Operator C on p. 13 of LAPC 1945b). Reductions for shielding by apparel and containers were not taken into account in estimating doses because of insufficient information. The dose rates in Table 4-4 are based on contact measurements, so they represent dose rates to the hands and forearms. For all but the Loader, dose rates to the remainder of the body were taken to be one-third of the contact dose rates. This reduction was based on data in Table A-6 (see Hands and Forearms Dose in Section 4.1.4.1). For the loader, dose rates for the remainder of the body were assumed to equal the contact dose rates because Loaders frequently hand carried ore bags, pushed carts of ore, and worked in the close vicinity of large ore piles.

The weighmaster was responsible for verifying weights of all materials (incoming, product, and byproduct; see p. 12 of LAPC 1945b) and so had frequent close contact with these materials. Furthermore, a radiological survey data sheet from March 1944 indicates that at that time the weighmaster was stationed for 8 hr/d at a location 4 ft from a pile of ore bags. The data in Table 4-4 and Table A-1 indicate that processed materials and byproducts had about 15 times the beta dose rate of ore. Therefore, the weighmaster was assigned the same beta exposure rate as a Step I process operator.

The dose rates in Table 4-4 were based on measurements on a particular batch of African L-30 ore. For a given type of ore, beta dose rates to ore handlers in Step I would be approximately proportional to ore grade (the weight percent of U_3O_8 in the ore). Ore type (African or domestic) would also matter. For the fully preredefined ore (which the domestic ore used at Linde might have approximated) the electron energy release per uranium decay is only 39% of that for African ore (compare Table A-2 and Table A-3). Beta dose rates in Steps II and III would be independent of ore grade. Dependence on ore type should have been weak because most radioactive impurities would have been removed in Step I.

To use the data in Table 4-4 to estimate time-averaged beta dose rates applicable to the entire 1943 to 1946 production period at Linde, the ratio of the average dose rates to those in Table 4-4 was estimated. Table 4-5 documents the determination of the ratio. The grade range of the L-30 ore that was used at Linde was 8% to 12% (Aerospace Corporation 1981, Table B-1). To obtain the highest ratio, it was assumed that the measurements in Table 4-4 were made on the lowest L-30 ore grade, 8%. It was also assumed that beta dose was proportional to electron energy that is released per

decay and that the worker doses were proportional to the mass of ore processed. With these assumptions, it was estimated that average doses would have been 0.84 of the doses that would be predicted by using the data in Table 4-4. Therefore, the estimated dose rates in Table 4-4 were multiplied by 0.84 to obtain time-averaged dose rates for 1943 to 1946 production. The results are in Table 4-6, which summarizes the results of all beta dose rate estimates in this section and divides the job categories into three groups (high, medium, and low).

1943 to 1946 Workers with Jobs Analogous to 1947 to 1949 Jobs

Workers in 1943 to 1946 who held jobs analogous to ones in 1947 to 1949 were assigned 3 times the 1947 to 1949 beta dose rates. The factor of 3 increase accounts for potential exposure to radiation from waste products from unrefined uranium ore and for the possibility that procedures in 1943 to 1946 did not involve as much radiological protection. (Tables A-2 and A-3 indicate unrefined uranium materials release approximately 2.6 times as much electron energy per uranium decay as refined uranium materials. In addition, the plant had a health physicist in 1947 to 1949 but not in 1943 to 1946.) Workers with jobs analogous to those assigned to the medium beta exposure category for 1947 to 1949 were assigned dose rates of 17.6 rem/yr to the hands and forearms and 5.85 rem/yr to the remainder of the body.

Table 4-5. Dependence of beta dose rate on ore type.

Approximate processing period ^a	Ore ID ^a	Ore type ^a	Electron energy released per decay (MeV/nt) ^b	Average grade ^a	Average beta dose rate relative to 8% L-30 ^c	Mass processed (MT) ^a	Mass-weighted average beta dose rate relative to 8% L-30 ^d
06/1943 to 11/1943	Not stated	Domestic & scrap	0.447	15.0%	0.72	1,000	0.028
12/1943 to 10/1944	L-30	African	1.157	10.8%	1.35	8,504	0.447
10/1944 to 11/1944	L-50	African	1.157	6.7%	0.84	1,486	0.048
12/1944 to 02/1946	L-19	Domestic	0.447	14.0%	0.68	6,102	0.161
02/1946 to 07/1946	R-10	African	1.157	3.5%	0.44	8,492	0.145
06/1946 to 07/1946	Q-20	African	1.157	17.7%	2.21	82	0.007
					<i>Sum:</i>	<i>25,666</i>	<i>0.84</i>

a. Source: Aerospace Corporation (1981), Table B-1. MT = metric ton (1,000 kg).

b. Per Table A-2. nt = nuclear transformation.

c. $(\text{Electron Energy Released per Decay}) \times (\text{Average Grade}) \div 8\%$.

d. The value for each ore ID is $(\text{Mass Processed}) \times (\text{Average Beta Dose Rate Relative to 8\% L-30}) / (\text{Total Mass Processed})$. The sum of the values is the approximate ratio of the average 1943 to 1946 ore beta dose to the ore dose due to 8% L-30 ore.

Table 4-6. Assigned beta dose rates, 1943 to 1946.

Category/job	Median dose rate (rem/yr)		GSD
	Hands and forearms	Remainder of body	
High	Varies^a	74	
Ball Mill Operator	221	74	1.52
Step I Process Operator	221	74	1.52
Weighmaster	221	74	1.52
Step II Process Operator	158	53	1.52
Loader	26	26	1.52
Medium	17.6	5.85	
Chemist/Lab Technician	17.6	5.85	2.65
Engineer	17.6	5.85	2.65
Janitor	17.6	5.85	2.65
Laundry Worker	17.6	5.85	2.65
Maintenance Worker	17.6	5.85	2.65
Ore Sampler	17.6	5.85	2.65
Seamster, Seamstress	17.6	5.85	2.65
Step III Process Operator	17.6	5.85	2.65
Tool Crib Worker	17.6	5.85	2.65
Low	3.00	3.00	
Draftsman	3.00	3.00	2.65
Fire Inspector	3.00	3.00	2.65
Guard	3.00	3.00	2.65
Nickel Operator	3.00	3.00	2.65
Nurse	3.00	3.00	2.65
Office Worker	3.00	3.00	2.65
Plant Superintendent, Asst. Supt.	3.00	3.00	2.65
Shipping and Receiving Clerk	3.00	3.00	2.65
Storekeeper	3.00	3.00	2.65
Tank Farm Operator	3.00	3.00	2.65

a. See Section 4.1.2.1.3.

Workers with jobs analogous to those assigned to the low beta exposure category for 1947 to 1949 were assigned a beta dose rate of 3 rem/yr to the whole body. Table 4-6 shows the assignments.

1943 to 1946 Workers Ore Sampler

The ore sampler was considered to have an exposure potential similar to that of a chemist and was assigned dose rates of 17.6 rem/yr to the hands and forearms and 5.85 rem/yr to the remainder of the body.

4.1.2.1.2 Outdoor Dose Rate

The average outdoor beta dose rate to which workers would have been exposed during production was assumed to be at most equal to the indoor level in Building 30 based on the reasoning in Section 4.1.1. Therefore, the outdoor beta rate was estimated as 0.676 mrem/hr (based on beta dose rate at 3 ft before vacuum cleaning and flushing in Table 4-1). For 0.5 hr/wd exposure, 6 wd/wk, and 50 wk/yr, the average worker exposure would have been 0.1 rem/yr. This is negligible in comparison with the indoor doses, given the approximate nature of the estimates, and was ignored.

4.1.2.1.3 Categories

Table 4-6 summarizes assigned beta dose rates for the 1943 to 1946 production period. All are considered to be median values of a lognormal distribution. The dose rates that were derived from the 1943 to 1946 data in Table 4-4 were judged to be based on near-maximum exposure parameters. They were assigned a GSD of 1.52, which corresponds to a distribution in which the ratio of 95th-

percentile value to median is equal to a factor of 2. The other dose rates were considered to be more uncertain. They were assigned a GSD of 2.65, which corresponds to a distribution in which the ratio of 95th-percentile value to median is equal to a factor of 5.

To simplify dose reconstruction and take into account the uncertainties of the estimates, jobs were grouped into three categories – high, medium, and low – based on beta dose to the “remainder of the body” (all parts of the body except the hands and forearms). For all jobs in each category, the beta dose to the remainder of the body was assumed to be the highest value among the jobs in the category.

Hands and Forearms Guidelines

If beta dose to the hands and forearms is needed for a particular dose reconstruction, it should be obtained as follows:

- For the low and medium categories, the values in Table 4-6 should be used.
- For the ball mill operator, Step I process operator, and weighmaster, the value in Table 4-6 should be used.
- For the Step II process operator, the dose to the hands and forearms should be taken as 3 times the remainder-of-the-body dose *for the high category* or 221 rem.
- For the Loader, the dose to the hands and forearms should be taken as equal to the remainder-of-the-body dose *for the high category* or 74 rem.

4.1.2.2 Gamma

Gamma film badge data are available for Step I process workers for a portion of the 1943 to 1946 production period. The data covers the period from January 31, 1944, through February 26, 1945, except for a 3-week gap from April 18 to May 5, 1944, for which data were not obtained due to a film handling error (Ferry 1944d). Badges were usually worn for about a week, but during the first 3 months some of the badging periods were longer (2 to 4 weeks). In the data analysis, each multiweek measurement was treated as a set of individual weekly results with each equal to the weekly average that was determined from the multiweek measurement. For example, a 4-week result of 300 mR was treated as four individual 1-week results of 75 mR.

About 20 workers were typically badged in each period – about 10 to 12 Loaders and 7 to 9 processors. It is not known whether all Step I personnel were badged. Film badges were provided by the Medical Section of the MED (presumably the University of Rochester).

From January 31, 1944, through March 27, 1944, results were in units of roentgen per 8-hour day (the designations "Roentgen," "R," and "r" in different reports of the data were interpreted as synonymous). After March 27, 1944, results were reported in tolerance units (designated "fractions of tolerance" or "times tolerance"). The MED tolerance value for gamma radiation in this period was stated as 0.1 R/8-hr day and also as 0.5 R/wk and 0.6 R/wk (Ferry 1944e; Tybout 1945c). Linde employees are reported to have worked a 6-day 48-hour workweek (Dupree1983a,b). For analysis of the gamma data, a 6-day workweek was assumed. To obtain roentgen per week, results in roentgen per 8-hour day were multiplied by 6 and results in tolerance units were multiplied by 0.6.

Some of the gamma results were reported in the form "<X," where the value of X varied. The average of the X values was 44 mR/wk. In the analysis of the data, 44 mR/wk was taken as the LOD, and results reported as "<X" or zero were considered to be <LOD results. However, all nonzero results, even if below 44 mR/wk, were treated as ≥LOD results.

During the first part of the measuring period, the plant processed radium-containing L-30 African pitchblende ore. In an analysis of plant operations (Aerospace Corporation 1981, Table B-1), it was estimated that processing of the African ore began in December 1943 and continued through November 1944 and that processing of domestic ore with minimal radium content began in December 1944. The film badge data showed a sharp drop in the number of \geq LOD results during the first 2 weeks of November with the low point during the week ending November 12, so this was taken as the date when processing of the African ore ended. Exposures to workers were averaged separately for the periods from January 31 to November 12, 1944 (41 weeks) and November 13, 1944 to February 26, 1945 (15 weeks).

The data identified each worker's job activity. The job activities were grouped into categories. Each category consisted of jobs that were judged to have similar exposure potential based on job descriptions and the data. Table 4-7 lists the job activities and the category to which each was assigned.

African Ore

Table 4-8 displays statistical characteristics of the film badge data for the period from January 31, 1944 to November 12, 1944, when African ore was processed. For each category, a lognormal distribution was assumed and the following parameters were determined:

- The number of film badge measurements,
- f_D = dosimeter fraction = the fraction of results in a year at or above the LOD,
- f_M = missed fraction = the fraction of results in a year below the LOD,
- m_D = GM of all results above the LOD, and
- The GSD of all results above the LOD based on the assumption that their distribution was lognormal.

Table 4-7. Job categories for Step I gamma dose analysis, 1943 to 1946.

Job activity ^a	Category
Ball mill	Ball mill operator
Ball mill operator	Ball mill operator
Cleaning up plant	Cleanup
Loader	Loader
Loader (handling ore)	Loader
Loader foreman	Loader
Ore sampler	Ore sampler
Sampler	Ore sampler
Barreling of tails from Moore filter	Process operator
Chief operator	Process operator
Digest	Process operator
Digest & V.P.	Process operator
Eimco & prod. precipitation	Process operator
Foreman	Process operator
Lead removal	Process operator
Making ore digest in Pachuca tanks	Process operator
Moore filter operator	Process operator
Moore operator	Process operator
Moore tailings	Process operator
Moore tailings/Moore operator	Process operator

Job activity ^a	Category
Moore's	Process operator
Pachuca digest	Process operator
Pachuca tanks	Process operator
Product precipitation	Process operator
V.P. press	Process operator
V.P. removal	Process operator
Weighmaster	Weighmaster

a. Job activity descriptions are from the film badge records.

Table 4-8. Step I gamma exposure data for African ore processing, January 31 to November 12, 1944.

Category	# Weekly results	Dosimeter fraction f_D	Missed fraction f_M	For results in dosimeter fraction	
				GM m_D (mR/wk)	GSD
Ball mill operator	17	0.9412	0.0588	93	1.81
Loader	507	0.8383	0.1617	123	2.00
Ore sampler	36	0.5000	0.5000	109	2.61
Process operator	202	0.6980	0.3020	71	1.93
Weighmaster	31	0.8387	0.1613	100	2.15

The subscripts D and M denote dosimeter dose and missed dose, respectively, as defined by NIOSH (2007b, pp. 30 and 32). For the current set of data, the value of f_D was estimated as the number of \geq LOD results divided by the number of measurements, and f_M was estimated as the number of $<$ LOD results divided by the number of measurements. (Case-by-case consideration is required when the number of measurements is very low. Such situations are dealt with in Sections 4.1.4.1 and 4.1.4.2.)

The estimated median annual dosimeter dose D_D for a 50-week year is shown in Table 4-9. This was calculated as follows:

$$D_D = 50f_D m_D \tag{4-1}$$

Table 4-9. Step I gamma exposure rate parameters for African ore processing, January 31 to November 12, 1944.

Category	D_D^a (R/yr)	GSD ^b	D_M^a (R/yr)	GSD	$D_D + D_M$
Ball mill operator	4.37	2.61	0.06	1.52	4.44
Loader	5.17	2.61	0.18	1.52	5.35
Ore sampler	2.72	2.61	0.55	1.52	3.27
Process operator	2.47	2.61	0.33	1.52	2.80
Weighmaster	4.21	2.61	0.18	1.52	4.39

- a. Each dose value represents the median of a lognormal distribution.
- b. Highest GSD for D_D values in Table 4-8 is assumed to apply to all categories.

For simplicity and because a GSD value based on small number of measurements might not be valid, the highest GSD in Table 4-8 was assigned to every job category.

In accordance with NIOSH (2007b), the annual missed dose was assumed to have a lognormal distribution with median D_M and the 95% confidence limit D_{M95} . For a 50-week year, these were calculated as follows:

$$D_M = 50f_M(LOD/2) \tag{4-2}$$

$$D_{M95} = 50f_M(LOD) \tag{4-3}$$

A GSD of 1.52 was calculated from D_M and D_{M95} . The results for D_M are in Table 4-9.

Domestic Ore

The analysis of exposure data for the period November 13, 1944, to February 26, 1945, when domestic ore with minimal radium content was being processed, was similar to that made for the preceding period. The results are displayed in Table 4-10 and Table 4-11. For routine processing of domestic ore, the weighmaster and ball mill operator were assigned the highest annual dose. Most of this dose is missed dose.

Table 4-10. Step I gamma exposure data for cleanup and domestic ore processing, November 13, 1944, to February 26, 1945.

Category	# Weekly results	Dosimeter fraction f_D	Missed fraction f_M	For results in dosimeter fraction	
				GM m_D (mR/wk)	GSD
Ball Mill Operator	0	(a)	(a)	(a)	(a)
Cleanup ^b	15	0.3333	0.6667	30.0	1.00
Loader	164	0.0061	0.9939	34.2	(c)
Ore Sampler	11	0.0000	1.0000	0.0	(d)
Process Operator	74	0.1486	0.8514	32.9	1.17
Weighmaster	11	0.1818	0.8182	35.5	1.27

- Not available because no weekly data was reported.
- Cleanup was an occasional short-term activity that was not part of routine domestic ore processing.
- Not available because only one result was \geq LOD.
- Not available because no results were \geq LOD.

The results obtained for this period also apply to the processing of scrap and residues from uranium processing. The uranium processing would have removed most of the content of radium and radium progeny.

Table 4-11. Step I gamma exposure rate parameters for cleanup and domestic ore processing, November 13, 1944, to February 26, 1945.

Category	D_D^a (R/yr)	GSD	D_M^a (R/yr)	GSD	$D_D + D_M$	Relative $D_D + D_M^b$
Ball mill operator ^c	0.32	1.27	0.90	1.52	1.22	28%
Cleanup ^d	0.50	1.27	0.73	1.52	1.23	(e)
Loader	0.01	1.27	1.09	1.52	1.10	21%
Ore sampler	0.00	1.27	1.10	1.52	1.10	34%
Process operator	0.24	1.27	0.94	1.52	1.18	42%
Weighmaster	0.32	1.27	0.90	1.52	1.22	28%

- Each dose value represents the median of a lognormal distribution.
- $D_D + D_M$ for domestic ore processing as percent of its value for same category for African ore processing.
- There were no measured data available for the ball mill operator. This category was assigned the same dose as weighmaster because of the similarity of their exposure potential and because of the possibility that processing of some types of domestic ore might require handling by the Ball Mill Operator.
- Cleanup was an occasional short-term activity that was not part of routine domestic ore processing.
- Not available.

4.1.2.2.1 Estimation of Worker Doses

African Ore

Step I Process Workers

The annual gamma exposures of the monitored Step I workers (Table 4-9) were considered to be sufficiently similar that all could be assigned the same value. For dose reconstruction purposes, all were assigned an exposure rate of 5.35 R/yr, the highest value of $D_D + D_M$ in Table 4-9, and a GSD of 2.61, the highest GSD in Table 4-9.

Other Workers

For other workers, most of the task-related sources of gamma exposure were probably comparable to or weaker in effect than they were for Step I process workers. Step II and Step III process workers were handling refined uranium materials with much lower gamma emission rates because much of the radium and radium progeny had been removed. Nickel process workers were handling nonradioactive materials. In general, support personnel – such as laboratory, maintenance and janitorial personnel – had less frequent exposure to radium-containing materials or dealt with smaller quantities or worked at greater distances from the materials. They also worked in less dusty environments and so had less exposure to airborne radioactivity and to floor and wall contamination.

One source of gamma exposure, however, was more dependent on worker location than on worker task. This was radiation from large quantities of ore that were stored in ore piles. A report of radiation surveys on March 2 and 3, 1944 (Ferry 1944f) identified two 200,000-lb piles of 10% ore and one 300,000-lb pile of 10% ore "in the receiving room" as well as one 30- by 30- by 12-ft pile of 8% ore at an unspecified location (percentages specify weight % of U_3O_8). Based on an analysis of typical pitchblende ore at Linde, the ore density was estimated as 3.25 g/cm³ (Aerospace Corporation 1981, Table C-1). Therefore, the 30- by 30- by 12-ft pile contained approximately 2 million lb of ore and was the largest of the four piles.

The probable location of the ore was the shipping and receiving platform at the south end of Building 30 (Figure 2-3). This would have placed the ore near the "grizzly enclosure" through which ore was dumped onto the conveyor belt at the start of Step I processing. A letter to Linde reporting on a March 2, 1944, inspection recommended cleaning up and rearranging the platform so that ore would be stored in its southeast corner (Cranch 1944a), and a letter from the Ceramics Plant on May 8, 1944, indicated compliance with this recommendation (Rehm 1944b).

In Ferry (1944f), an exposure rate of 0.23 R/8-hr day was reported at 1.5 ft from the 30- by 30- by 12-ft pile. Potential exposures at more distant locations were estimated by mathematical analysis. For the region very close to an ore pile, the dependence of exposure rate on distance was determined by fitting data from Linde pilot plant studies for a 4- by 5- by 20-ft pile of 8% ore (Skinner 1944; Wiesendanger 1944). The fit was obtained using the MicroShield computer program (MicroShield Team 2003), which is based on the point kernel methodology. The values from the program were multiplied by a single scaling factor that was chosen to provide a best fit to the measured data. The adjustment compensated for simplifications in the modeling. Figure 4-1 shows the data and the fit. Gamma exposure rates measured during pilot plant studies at Linde Ceramics (Skinner 1944) are shown by the diamond symbols. The rectangles show the fit to the data with distance assumed to be measured along the perpendicular bisector of a 4- by 20-ft. face. The ore grade (8%) was assumed to be that determined in the analyses reported by Wiesendanger (1944, p. 18). The data covers the range of 0 to 10 ft from the 4- by 20-ft face. The adjusted MicroShield output fit the data to within $\pm 10\%$ between 3 ft and 10 ft from the face. The results were extended to larger distances and to a 30- by 30- by 12-ft pile by more MicroShield calculations that were scaled with the same factor.

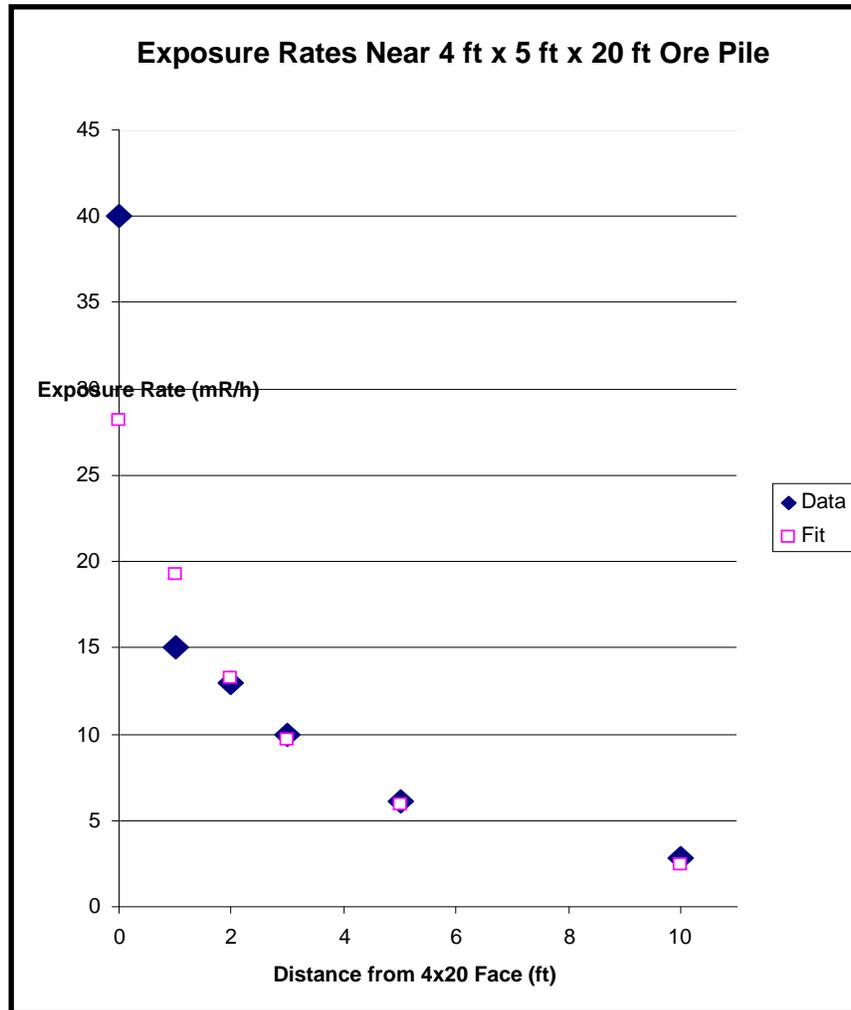


Figure 4-1. Fit to gamma exposure data for a 4- by 5- by 20-ft pile of 8% African pitchblende ore.

Figure 4-2 shows the MicroShield results and an analytic function fit to them. The diamond-shaped symbols show calculated values of exposure rate as a function of distance from the pile center. Distance is measured along the perpendicular bisector of a 12- by 30-ft face. The values were calculated using MicroShield (MicroShield Team 2003). The line is a plot of the analytic function obtained by a least-squares fit to the MicroShield results. The function is:

$$(1/r^2) \times \exp[a \times \exp(-b \times r) + (c-d \times r)] \quad (4-4)$$

where $a = 1.906$, $b = 3.126 \times 10^{-02}$, $c = 7.660$, and $d = 1.521 \times 10^{-03}$. The fit agreed with the calculated values to within $\pm 3.0\%$ over the range of 16 to 2,000 ft from the center of the pile.

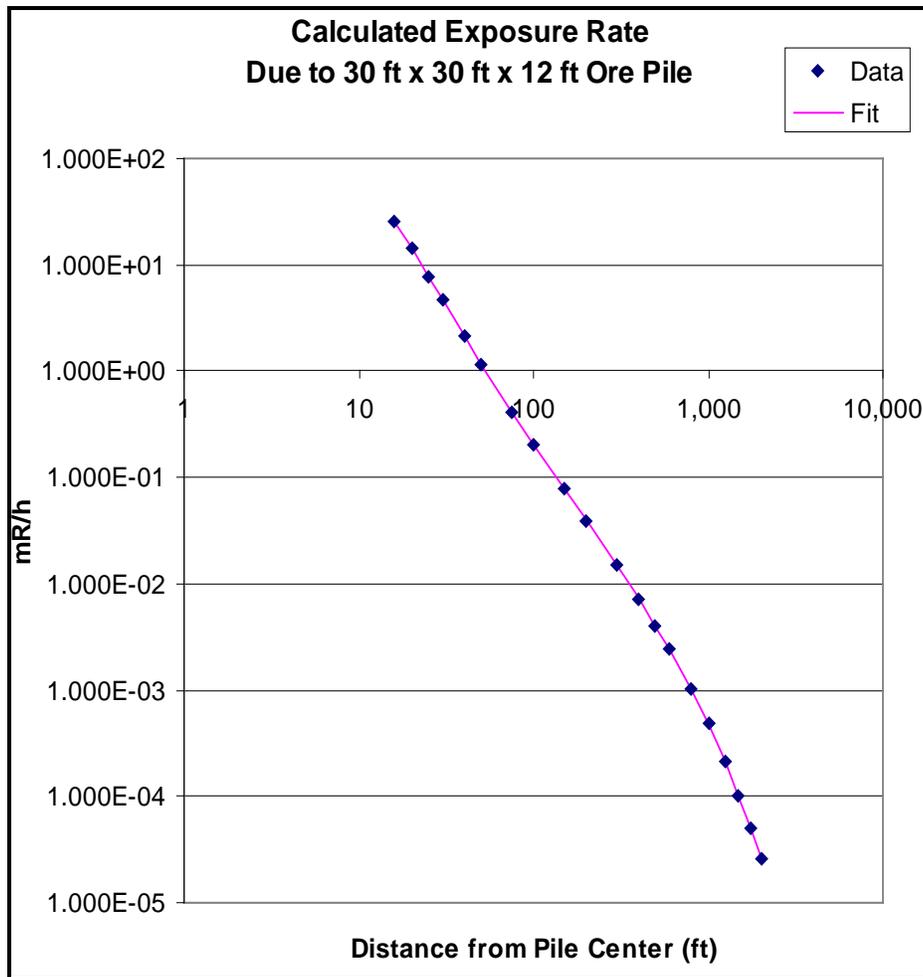


Figure 4-2. Calculated exposure rates and analytic fit for a 30- by 30- by 12-ft pile of 8% African pitchblende ore.

The function facilitates calculation of exposures at arbitrary distances. As a check on the methodology, the analytic function was used to calculate the exposure rate at a point where it had been measured, which was 1.5 ft from the face. The result was 0.19 R/8 hr, which is 17% below the measured value. This degree of difference is consistent with the uncertainties typical of this type measurement and the approximations inherent in the MicroShield code.

The calculated results are expected to overestimate radiation levels well away from the pile. The calculations account for air attenuation, but not for attenuation due to objects such as walls, floors, and equipment. In addition, the calculations are based on distance along the perpendicular bisector of a pile face. Exposure rate at any distance is lower for a point not on the perpendicular bisector.

To estimate the impact on the other workers in Building 30, who did not wear dosimeters, exposure rates due to a 30- by 30- by 12-ft pile in the southeast corner of Building 30 were calculated for various facilities in the building. In each case, the exposure rate was calculated for the point closest to the center of the pile. The calculated rates are in Table 4-12. They range from 0.28 R/yr (for the laboratory) to 4.9 R/yr (for the lunchroom). The results indicate a potential for exposures to the other workers in Building 30 comparable to the exposures to Step I process workers.

Table 4-12. Estimated maximum exposure rates in selected Building 30 facilities due to 30-by 30- by 12-ft pile of 8% ore in southeast corner.

Facility	Distance (ft) ^a	Exposure rate (R/yr) ^b
Bag washer room	73	1.09E+00
Laboratory	128	2.81E-01
Locker & wash rooms	43	4.46E+00
Lunchroom	42	4.89E+00
Sampling room	57	2.10E+00

- a. Distance is the distance from the pile center to the closest point that is inside the facility and 3 ft above the floor.
b. Based on 2,550 hr/yr exposure.

Although few of the other workers spent the major portion of their work time near the southeast corner of Building 30, some might have worked near other ore piles, near tailings piles, or near large quantities of ore in process. Because the locations and quantities of these other sources are not known in sufficient detail, any worker who spent a substantial amount of time in Building 30 had a potential for significant gamma exposure. Such workers included not only the production personnel in the building, but also nurses (whose office was there), maintenance personnel (who came there to maintain, repair, or refurbish), janitors, personnel who used locker rooms or the lunchroom, and office personnel who might have had to regularly visit the building (e.g., product accountants, industrial relations representatives, the fire marshal, and engineers). Last, it appears that there were office personnel who were permanently stationed in the building. A February 1944 letter from the plant addressing the frequency of required medical examinations states that it would not be appropriate to reduce the examination frequency for all office personnel because “we have some stenographers and clerks, stores clerks, etc., who work in the main building and are from time to time exposed to the same hazards as the operating personnel” (Holmes 1944a). In view of the likely difficulty of establishing that a particular worker did not spend a substantial portion of time in Building 30, for dose reconstruction it is assumed that all plant personnel had a significant potential for gamma exposure. All Ceramics Plant employees were assigned a gamma dose of 5.35 R/yr for the whole body, based on the results for the most exposed group of monitored process workers (Table 4-9).

Domestic Ore

During domestic ore processing, the gamma exposure rates were lower because the ore contained lower proportions of radium and other uranium series progeny than African ore. However, it is difficult to estimate how much lower because of uncertainty as to how much African ore radioactivity remained in the preprocessed ores at Linde (Section 2.2). The value of $D_D + D_M$ for Step I process operators during domestic ore processing (Table 4-11) is 42% of the value during African ore processing (Table 4-9). This difference is judged not to be large enough to justify the complication of using lower doses for periods of domestic ore processing. Therefore, for dose reconstruction during the 1943 to 1946 production period, the gamma exposure rate of 5.35 R/yr was assumed to apply for the whole period.

4.1.2.2.2 Outdoor Exposure Rate

The average outdoor gamma exposure rate to which workers could have been exposed during production was assumed to be at most equal to the indoor level in Building 30 based on the reasoning in Section 4.1.1. Therefore, the outdoor gamma rate was estimated as 0.131 mR/hr based on the level before vacuuming and flushing in Table 4-1. For 0.5 hr/wd exposure, 6 wd/wk, and 50 wk/yr, the average worker exposure would have been 0.020 R/yr. This is negligible in comparison with the indoor exposures given the approximate nature of the estimates and was ignored.

4.1.3 Standby, 1946 to 1947

Little information is available about the status of activities during the standby period. It is likely that the onsite staff consisted primarily of a small number of management and janitorial personnel – both of whom worked primarily in an office environment – and guards. For dose reconstruction, each worker during standby was classified as either a guard or a general worker, and worker time was assumed to have been spent in an office building, in production buildings, and outdoors. Averaged over the entire standby period, each worker's allocation of time was assumed to have been as indicated by the occupancy factors in Table 4-13.

Table 4-13. Ceramics Plant beta and gamma radiation rates during standby.

Parameter	Category			Time-weighted radiation rate ^a	
	Office	Production	Outdoors	Beta (rem/yr)	Gamma (R/yr)
Beta (mrem/hr)	0.000	0.676	0.676	(b)	(b)
Gamma (mR/hr)	0.000	0.131	0.131	(b)	(b)
Occupancy factor					
General worker	0.833	0.111	0.056	3.04E-01	5.91E-02
Guard	0.756	0.111	0.133	4.46E-01	8.67E-02

- Based on 9.0 hr/d exposure, 6 d/wk, 50 wk/yr. Based on the underlying data and judgment, a GSD of 3 is assigned. The beta and gamma rates are for the whole body.
- Not applicable.

Gamma radiation levels were measured at six locations in Building 30 on October 22, 1946. Measurements were made at 1 in. from the surface of interest. The results were reported as 0 R/8 hr for four of the locations and 0.005 R/8 hr (0.625 mR/hr) for the other two locations (each near an ore dumping grill) (Howland 1946). Because the dumping grill was one of the most contaminated spots in the plant, the exposure rate there was not considered typical of the conditions that would have been encountered upon occasional entry during standby. Instead, the indoor gamma and beta levels for a production building were taken as the values in Table 4-1 before vacuum cleaning and flushing. Outdoor gamma and beta levels were taken as equal to the indoor rates based on the reasoning used above in the discussion of the preproduction period. The gamma and beta radiation rates in an office building were assumed to be zero.

Table 4-13 summarizes the calculation of annual radiation rates based on the above parameters.

Because there would have been little need for direct handling of radioactive materials by Ceramics Plant workers in this period, beta dose rate to the hands and forearms was taken as equal to the beta dose rate to the remainder of the body.

4.1.4 Rehabilitation and Production, 1947 to 1949

4.1.4.1 **Beta**

For part of the period from 1947 to 1949, weekly film badge measurements of beta and gamma exposure were available (LAPC undated b). The data had been "de-identified" by removal of personnel names (Wallace 2003), but many of the records were labeled with a job title. The data file contained about 6,000 records from January 7, 1948 through December 12, 1949. By comparison with a copy of a laboratory film badge report (AEC 1949b), it was determined that the date identified the beginning of the week when the badge was worn. For records before March 15, 1948, badges were processed by the University of Rochester (Heatherton 1948g, Osinski 1948a); thereafter, they were processed by the AEC New York Directed Operations Office Radiological Laboratory (Osinski 1948b; AEC 1949b). When use of the badges was initiated, the intention was for them to "be available for use by all entering a contaminated area" (Heatherton 1947).

The computer file had three columns of data but no labels to indicate units or type of radiation. The third column was obviously the total radiation dose. The first column was determined to be beta radiation and the second gamma radiation by comparison with a laboratory film badge report (AEC 1949b). The report stated both the beta and gamma units to be "exposure, mr." Progress reports by the Linde health physicist referred to the film badge results sometimes as "mr" and sometimes as "mrep" (Heatherton 1949d,e). The beta units are designated here as mrem and are assumed for purposes of dose reconstruction to be equivalent to shallow dose at 0.07 mm, $H_p(0.07)$. Before March 15, 1948, a beta value below the limit of detection was reported as "<80." After March 15, 1948, the limit of beta detection was not explicitly stated, but it was deduced to be 35 mrem from an examination of the data. Some of the results were reported as "0", "*" or "***". These were interpreted as meaning less than the LOD.

The beta film badge data was analyzed to determine dose rates for various job categories. Approximately one-third of the badge records were labeled with the job title NA. These were ignored because it could not be determined which had been worn by a worker and which had been used for other purposes (e.g., as controls or to measure process dose). Job titles that were specified in the records were binned into categories that combined jobs that were judged to have had similar exposure potential. Table 4-14 displays the job titles in each category.

Table 4-14. Job categories for 1947 to 1949 Step III film badge analysis.

Job title	Category	Job title	Category
AEC	Office	Maint g l	Maintenance
Asst engineer	Engineer	Maint group leader	Maintenance
Asst supt	Superintendent	Maintenance	Maintenance
Carpenter	Maintenance	Millwright A	Maintenance
Chem oper	Process operator	Millwright C	Maintenance
Chem oper A	Process operator	Moveman	Loader
Chem oper B	Process operator	Painter	Maintenance
Chem oper C	Process operator	Painter B	Maintenance
Chem oper G L	Process operator	Personnel	Office
Chemist	Chemist	Pipefitter	Maintenance
Control engr	Engineer	Process foreman	Process operator
Electrician	Maintenance	Prod accounting	Office
Electrician hlpr	Maintenance	Property dept	Office
Fire chief	Engineer	Safety engr	Engineer
Foreman (unspecified type)	(a)	Seamster	Seamster
Group leader (unspecified type)	(a)	Security agent	Office
Health physicist	Engineer	Shift storekpr	Storekeeper
Janitor	Janitor	Shift stores att	Storekeeper
Labor foreman ^o	Loader	Shipping & rec	Storekeeper
Laundry helper	Laundry worker	Storekeeper	Storekeeper
Laundry worker	Laundry worker	Superintendent	Superintendent
Loader	Loader	Tool crib keeper	Storekeeper
Loader foreman	Loader	Trades helper	Maintenance
Mail girl	Office	Truck driver	Truck driver
Maint	Maintenance	Weighmaster	Weighmaster
Maint foreman	Maintenance	Welder	Maintenance

- There were two records with the job title Foreman and one with the job title Group Leader. They were not included in the gamma dose analysis because the title was not descriptive enough to identify the work activity.
- From available data (Heatherton 1949b; AEC 1949b), it was deduced that the worker with the job title Labor Foreman was supervising loaders.

Table 4-15 displays statistical characteristics of the beta film badge data. The data were assumed to have a lognormal distribution. The parameters f_D , f_M , and m_D were defined as in the analysis of the 1943 to 1946 gamma dosimetry data (Section 4.1.2.2). For categories in which there were 50 or more badge results, f_D was taken as equal to the number of results at or above the LOD divided by the total number of badge measurements and f_M was taken as $(1 - f_D)$. Categories with fewer than 50 results were examined on a case-by-case basis. If the workers in the category were rarely badged, it was

assumed that they only occasionally entered the Linde radiation area. The value assigned to f_D was the number of results at or above the LOD divided by 50, which is the number of workweeks per year. The missed fraction f_M was taken as (1/50) times the highest number of results below the LOD for any member of the category. In the present case, this alternative method was applied to the categories Office and Superintendent.

Table 4-15. Step III beta dose data, 1947 to 1949.

Job	# Badges	Dosimeter fraction f_D	Missed fraction f_M	For results \geq LOD	
				GM m_D (mrem/wk)	GSD
Chemist	183	0.0055	0.9945	95	(a)
Engineer	243	0.0535	0.9465	113	2.12
Janitor	261	0.0421	0.9579	132	2.17
Laundry	115	0.1565	0.8435	106	1.65
Loader	304	0.0559	0.9441	78	1.47
Maintenance	913	0.0526	0.9474	146	1.62
Office	9	0.0000	0.0600	(b)	(b)
Process operator	1,814	0.1527	0.8473	145	1.81
Seamster	44	0.0909	0.9091	141	1.31
Storekeeper	207	0.0048	0.9952	120	(a)
Superintendent	3	0.0000	0.0400	(b)	(b)
Truck driver	18	0.0000	1.0000	(b)	(b)
Weighmaster	61	0.0492	0.9508	136	1.42

a. Only one result was \geq LOD; GSD could not be determined.

b. No results \geq LOD; GM and GSD could not be assigned.

The estimated median annual dosimeter dose D_D and the median annual missed dose D_M for a 50-week year and their GSDs were determined in the same way as for the 1943 to 1946 gamma data (Equations 4-1, 4-2, and 4-3 in Section 4.1.2.2). Because badges would not have been worn until workers arrived indoors, an outdoor beta dose rate of 0.10 rem/yr (from Section 4.1.2.1.2) was added to the D_M values. For the office worker and superintendent, the outdoor contribution was larger than the indoor D_M value, so the outdoor GSD of 3 was assigned. For the other categories, the outdoor contribution was not the major portion of the sum, so the GSD was taken as not changed by the addition. Table 4-16 displays the results.

For most jobs, the largest contribution to $D_D + D_M + OD$ was missed dose D_M . The production workers in 1947 to 1949 were probably scattered among three buildings – Building 38, the location of the Step III processing facilities; Building 30, which contained a loading dock, locker rooms, lunchroom, nurses' office, and chemistry laboratory; and Building 31, which contained shop facilities. None of the buildings had been decontaminated. The average beta radiation level in Building 30 for this period was estimated (Section 4.1.1) as 0.676 mrem/hr (value before vacuuming and flushing in Table 4-1), which is equivalent to 34.5 mrem/wk and 1.7 rem/yr for a person spending 8.5 hr/d, 6 d/wk, and 50 wk/yr in the building. This is comparable to the film badge LOD for beta radiation (35 mrem/wk) and so might have been a substantial portion of the missed dose. Based on this estimate of 1.7 rem/yr of possible dose and the lowest film badge $D_D + D_M$ value in Table 4-16 of approximately 1 rem/yr for workers, who were regularly badged, it was assumed that all workers, even office workers, received a beta dose of at least 1 rem/yr. Office workers were included because it is unknown which office workers spent substantial portions of their time in production buildings. Some workers who might

Table 4-16. Beta dose rates for Step III, 1947 to 1949.

Job	D_D^a		$D_M + OD^a$		$D_D + D_M + OD$ (rem/yr)
	(rem/yr)	GSD ^b	(rem/yr)	GSD	
Process operator	1.11	2.17	0.84	1.52	1.95
Laundry	0.83	2.17	0.84	1.52	1.67
Seamster	0.64	2.17	0.90	1.52	1.54
Maintenance	0.38	2.17	0.93	1.52	1.31
Weighmaster	0.33	2.17	0.93	1.52	1.26
Engineer	0.30	2.17	0.93	1.52	1.23
Janitor	0.28	2.17	0.94	1.52	1.22
Loader	0.22	2.17	0.93	1.52	1.15
Chemist	0.03	2.17	0.97	1.52	1.00
Storekeeper	0.03	2.17	0.97	1.52	1.00
Truck Driver	(c)	(c)	0.98	1.52	0.98
Office	(c)	(c)	0.15	3.00	0.15
Superintendent	(c)	(c)	0.14	3.00	0.14

- Each D_D and D_M value represents the estimated median of a lognormal distribution. OD = estimated outdoor dose rate.
- The highest GSD from Table 4-15 was assumed for all categories for which a GSD can be assigned.
- No result \geq LOD.

have had offices in the office building might also have spent much of their workday in the production area (e.g., engineers, health physicist, and fire marshal), and some clerical workers might have actually had work locations in the production area [discussion near the end of Section 4.1.3.2.1 and Holmes (1944a)].

Categories

For dose reconstruction, the jobs were grouped into two categories – medium and low. The medium category was assigned a dose rate of 1.95 rem/yr. Workers whose jobs might have required frequent handling of radioactive materials were placed in the medium category. The tool crib attendant was assigned to the medium category because of the possible handling of contaminated tools. The truck driver was placed in the medium category because it was the practice at the plant in 1943 to 1946 for truck drivers to work as loaders when not driving a truck (LAPC 1945b, p. 10); it was assumed that the same practice applied from 1947 to 1949. Engineers and the plant health physicist (considered a type of engineer) were placed in the medium category because of their roles in closely monitoring and troubleshooting production activities.

The low category was assigned a dose rate of 1.00 rem/yr. Assigned to it were most office workers, the superintendent, and storekeepers. It also included guards and the fire marshal.

A list of jobs with the category assignment of each is provided in Section 4.4.

Rehabilitation

Beta dose rates during rehabilitation were assumed to be the same as during production to account for exposures while cleaning contaminated facilities, setting up, and testing equipment.

Hands and Forearms Dose

Film badges were worn on the chest (Heatherton 1948h). Measurements during various Step III process operations showed that dose rates to other areas of the body differed from dose rates at the film badge location with the difference dependent on the operation and the area of the body (Heatherton 1948h). The results are shown in Table A-6. Based on these data, it was estimated for this site profile that the average dose to the hands and forearms of a worker handling radioactive

material was 3 times the chest dose and that average dose to the remainder of the body was equal to the chest dose. For each body area, the estimate was based on the average ratio for the studied operations with the result rounded up to the nearest integer. No credit was taken for wearing gloves. For dose reconstruction, a hands and forearms dose of 5.85 rem/yr was assumed for the medium category. Workers in the low category were assumed to have a hands and forearms dose of 1 rem/yr, which is the same as the dose assigned to the remainder of the body.

4.1.4.2 Gamma

As discussed in Section 4.1.4.1, weekly film badge measurements of beta and gamma exposure during 1947 to 1949 production were available (LAPC undated b). As noted, the measurement units were specified as "mr" or "mrep." It is assumed here that for gamma radiation the units were equivalent to milliroentgen. Results reported as "0", "**", or "***" were interpreted as meaning less than the LOD. For records before March 15, 1948, a gamma value below the LOD was reported as "0" or "<50." For records after March 15, 1948, the limit of gamma detection was not explicitly stated but was deduced to be 45 mR from an examination of the data. A few scattered reports of nonzero exposures below 45 mR were judged not to reflect routine measuring capabilities.

The procedure for analyzing the gamma data and determining annual gamma exposures was the same as that for the analysis of the beta data (Section 4.1.4.1). Table 4-17 summarizes the statistical characteristics of the gamma data.

Table 4-17. Step III gamma exposure data, 1947 to 1949.

Category	# Badges	Dosimeter fraction f_D^a	Missed fraction f_M^b	For results \geq LOD	
				GM m_D (mR/wk)	GSD
Chemist	183	0.0164	0.9836	82	1.41
Engineer	243	0.0247	0.9753	145	2.13
Janitor	261	0.0115	0.9885	62	1.27
Laundry	115	0.0783	0.9217	81	1.46
Loader	304	0.0789	0.9211	141	2.14
Maintenance	913	0.0164	0.9836	87	1.38
Office	9	0.0200	0.0400	80	(c)
Process operator	1,814	0.0309	0.9691	86	1.52
Seamster	44	0.0000	1.0000	(d)	(d)
Storekeeper	207	0.0048	0.9952	65	(c)
Superintendent	3	0.0200	0.0400	50	(c)
Truck driver	18	0.0000	1.0000	(d)	(d)
Weighmaster	61	0.0000	1.0000	(d)	(d)

- f_D = fraction of measurements \geq LOD.
- f_M = fraction of measurements $<$ LOD.
- Only one result was \geq LOD; GSD could not be determined.
- No results \geq LOD; GM and GSD could not be assigned.

The estimated median annual dosimeter dose D_D and median annual missed dose D_M for a 50-week year and their GSDs were determined in the same way as for the 1947 to 1949 beta data (Section 4.1.4.1). Because badges would not have been worn until workers arrived indoors, an outdoor gamma exposure rate of 0.02 R/yr (Section 4.1.2.2.2) was added to the D_M values. Because the outdoor contribution was not the major portion of any of the sums, the GSD was taken as not changed by the addition. Table 4-18 displays the gamma exposure rates that were determined.

Table 4-18. Gamma exposure rates for Step III, 1947 to 1949.

Job	D_D^a		$D_M + OD^a$		$D_D + D_M + OD$ (R/yr)
	(R/yr)	GSD ^b	(R/yr)	GSD	
Loader	0.56	2.14	1.06	1.52	1.61
Laundry	0.32	2.14	1.06	1.52	1.37
Engineer	0.18	2.14	1.12	1.52	1.30
Process operator	0.13	2.14	1.11	1.52	1.24
Maintenance	0.07	2.14	1.13	1.52	1.20
Chemist	0.07	2.14	1.13	1.52	1.19
Janitor	0.04	2.14	1.13	1.52	1.17
Storekeeper	0.02	2.14	1.14	1.52	1.15
Seamster	(c)	(c)	1.14	1.52	1.14
Truck driver	(c)	(c)	1.14	1.52	1.14
Weighmaster	(c)	(c)	1.14	1.52	1.14
Office	0.08	2.14	0.06	1.52	0.14
Superintendent	0.05	2.14	0.06	1.52	0.11

- Each D_D and D_M value represents the estimated median of a lognormal distribution. OD = estimated outdoor dose rate.
- The highest GSD from Table 4-17 was assumed for all categories for which a GSD can be assigned.
- No results \geq LOD.

As in the case of 1947 to 1949 beta dose (end of Section 4.1.4.1), it is to be expected that there was a contribution to gamma dose due to floor and wall contamination in the buildings. The average gamma radiation level in Building 30 for this period is estimated in Section 4.1.1 as 0.131 mR/hr (value before vacuuming and flushing in Table 4-1), which is equivalent to 6.7 mR/wk and 0.34 R/yr for a person who spent 8.5 hr/d, 6 d/wk, and 50 wk/yr in the building. This is below the film badge LOD for gamma radiation (45 mR/wk). Any clerical personnel who worked in production buildings (see Holmes 1944a) were assumed to have received this estimated floor and wall radiation plus the 0.14 R/yr that was received by the occasionally badged office worker for a total of 0.48 R/yr. Because it might not be easy to identify which clerical personnel worked in a production building, all unbadged or infrequently badged personnel were assumed to have received 0.48 R/yr.

Categories

For dose reconstruction, the jobs were grouped into two categories – medium and low – with the gamma category assignment for each job the same as its 1947 to 1949 beta category assignment (Categories discussion in Section 4.1.4.1). Jobs in the medium gamma category were assigned an exposure rate of 1.61 R/yr for the whole body. Jobs in the low category were assigned an exposure rate of 0.48 R/yr for the whole body.

Rehabilitation

Gamma exposure rates during rehabilitation were assumed to be the same as during production in order to account for exposures while cleaning contaminated facilities, setting up, and testing equipment.

4.1.5 Cleanup, 1949 to July 7, 1954

Cleanup of the Ceramics Plant is discussed in Section 2.6. Floor and wall radiation levels, which were measured at the start and end of the 1949 to 1950 decontamination of Building 30, were available and are summarized in Table 4-1. In addition, results were available from film badge measurements of beta and gamma radiation during the 1948 removal of equipment from Building 30. These results are summarized in Table 4-19. Because the results in Table 4-19 are film badge measurements, they include floor and wall radiation in addition to radiation from contaminated equipment.

Table 4-19. Beta and gamma radiation measured during equipment removal, 1948.

Beta dose rate			
D_D (rem/yr) ^a	GSD	D_M (rem/yr) ^a	GSD
1.99	1.53	0.52	1.52
Gamma exposure rate			
D_D (R/yr) ^a	GSD	D_M (R/yr) ^a	GSD
0.89	1.70	0.94	1.52

a. D_D and D_M are dosimeter dose and missed dose, respectively, as defined in NIOSH (2007b), pp. 30 and 32.

For external dose reconstruction, each worker is classified in one of the following categories:

- Cleanup worker,
- Cleanup support worker, and
- Non-cleanup worker.

A cleanup worker is defined as a worker who was directly engaged in the removal of radioactive equipment, components, or contamination (e.g., by sandblasting, vacuuming, or washing) for a substantial portion of the workday. This category includes equipment operators (such as a sandblaster operators) and laborers who were involved in moving and cleaning activities. A cleanup support worker is one who spent a substantial portion of the workday in the building or area being decontaminated to support the cleanup activities but was not actively engaged in the removal activities. Examples are the plant health physicist and a stores worker in a building being cleaned. All remaining plant personnel are considered non-cleanup workers. For a cleanup worker, the radiation estimate for both beta and gamma was taken as:

$$D_D + D_M + OD \quad (4-5)$$

where D_D and D_M were taken from Table 4-19. The parameter OD is the outdoor dose rate. As for the preproduction and standby periods, it was estimated as equal to the estimated indoor floor and wall level at 3 ft before vacuum cleaning and flushing in Table 4-1. A cleanup support worker was assumed to have only half as much exposure to indoor radiation. The radiation level estimate was taken as:

$$0.5(D_D + D_M) + OD \quad (4-6)$$

for both beta and gamma. Finally, a non-cleanup worker was assumed to have only 5% of the exposure to gamma radiation of a cleanup worker and to have a beta exposure equal to that calculated for Tonawanda Plant worker's after 1946 (numbers were not adjusted for exposure time). The radiation level was estimated as:

$$0.05(D_D + D_M) + OD \quad (4-7)$$

for gamma radiation. The beta radiation values specified are for all parts of the body. Table 4-20 presents the results.

The beta dose rates in Table 4-20 are based primarily on film badge measurements. The film badges were worn on the chest (Heatherton 1948h). The hands and forearms would have been closer than the chest to radioactive materials during some of the steps involved in cleanup (e.g., dismantling and removing equipment, and scrubbing contaminated surfaces). For dose reconstruction, the beta dose rate to the hands and forearms of a cleanup worker was taken as 3 times that to the remainder of the body. The factor three was based on measurements discussed in Hands and Forearms Dose in Section 4.1.4.1.

Table 4-20. External dose reconstruction parameters for cleanup.

Period/category	Beta ^a		Gamma ^b	
	Median (rem/yr) ^c	GSD ^d	Median (R/yr) ^c	GSD ^d
07/01/1949–12/31/1950, 6-day week				
Cleanup worker	2.61E+00	4.04	1.85E+00	4.04
Cleanup support worker	1.36E+00	4.04	9.34E-01	4.04
Non-cleanup worker	3.26E-01	3.00	1.11E-01	4.04
01/01/1951–07/07/1954, 5-day week				
Cleanup worker	2.18E+00	4.04	1.54E+00	4.04
Cleanup support worker	1.13E+00	4.04	7.78E-01	4.04
Non-cleanup worker	3.26E-02	3.00	9.26E-02	4.04

- For the cleanup support and non-cleanup workers, the indicated beta rate is to the whole body. For the cleanup worker, the rate is to all parts of the body except the hands and forearms. For these, the rate is 3 times higher. See text.
- Gamma exposure rates are for the whole body.
- Annual rates based on 8.5 hr/wd indoors, 0.5 hr/wd outdoors, 50 wk/yr, except as noted for the non-cleanup worker.
- The GSD for the beta value for the non-cleanup worker is the estimated GSD for outdoor beta dose. The other GSD values are based on the assumption that for indoor exposure the 95th-percentile value is 10 times the median.

4.2 TONAWANDA LABORATORY BETA AND GAMMA EXPOSURE

For external dose reconstruction, workers at Tonawanda Laboratory are classified into two categories – research and office. The research category includes all personnel who performed hands-on work in research facilities (laboratories, fabrication facilities, or pilot plants) or who provided some type of support for these facilities that involved working in or very close to them. It includes scientists; technicians; and shop, maintenance, stores, and janitorial personnel. The office category includes all personnel who had primarily desk jobs although they might occasionally have visited the research facilities. It includes secretaries, clerks, draftspersons, and high-level managers. Three periods (R&D, cleanup, and postcleanup) are considered for Tonawanda Laboratory external dose reconstruction. Data on worker doses were not available for Tonawanda Laboratory, but survey results indicated that radiation levels during pilot plant operations were similar to later measurements at the Ceramics Plant. Therefore, radiation level estimates were based to a large extent on the estimates for workers who did similar work at the Ceramics Plant. Table 4-21 shows the assumed annual radiation rates and their bases.

4.3 NEUTRON EXPOSURE

No neutron exposure measurements are available for the Linde site. Neutron production by means of the alpha-neutron reaction would have resulted in a relatively small neutron dose component during Step I conversion of African ore to purified U₃O₈; Step II conversion of U₃O₈ to UO₂; and Step III conversion of UO₂ to UF₄. Neutron dose rates per gram of natural uranium in the compounds that were processed at Linde are presented in Table 4-22.

The following assumptions were made about the conversion from neutron production rate from the alpha-neutron reaction to an annual dose at the receptor point:

- Point source geometry was used to produce a nominal ambient neutron dose rate.
- Point source strength was based on the daily rate of U₃O₈ handling or UF₄ production. Self-shielding within the source-target compound matrix was assumed to be negligible.
- A ²³⁸U:²³⁵U composition of 99.3% to 0.711% by weight for natural uranium was assumed.

Table 4-21. Tonawanda Laboratory beta and gamma radiation, 1942 to 1953.

Period		Job	Beta				Gamma		
			rem/yr		GSD	Basis ^a	R/yr ^b	GSD	Basis ^a
Start	End		Hands & forearms	Remainder of body					
R&D									
10/01/1942	07/31/1946	Research	1.11E+02	3.70E+01	1.52	A	5.35E+00	2.61	F
		Office	3.00E+00	3.00E+00	2.65	B	5.35E+00	2.61	B
Cleanup									
08/01/1946	12/31/1946	Research	7.83E+00	2.61E+00	4.04	C	1.85E+00	4.04	C
		Office	1.01E-01	1.01E-01	3.00	D	1.11E-01	4.04	D
Postcleanup									
01/01/1947	12/31/1953	All	3.26E-01 ^c	3.26E-01 ^c	(d)	E	6.80E-02	(d)	E

- a. Basis:
- One-half of value for most exposed Ceramics Plant process worker during 1943 to 1946 production (Step I process operator). The factor of 2 reduction allows for the lower intensity of research work in comparison with production. For example, the amount of material processed and the day-to-day hands on radiation work would have been significantly lower than for the Step I to III operators.
 - Based on Ceramics Plant office worker during 1943 to 1946 production.
 - Cleanup worker during Ceramics Plant decontamination.
 - Non-cleanup worker during Ceramics Plant decontamination.
 - Building 30 postcontamination level (Table 4-1) for 8.5 hr/wd plus outdoor level on Tonawanda site for 0.5 hr/wd. Outdoor level assumed equal to Building 30 level before vacuum cleaning and flushing (Table 4-1). A 6-day week was assumed.
 - Based on most exposed Ceramics Plant process worker during 1943 to 1946 production (Step I process operator).
- b. Where the gamma exposure rate estimate was based on dosimetry data for the Ceramics Plant (available as values of D_D and D_M) plus possibly also outdoor dose OD , the gamma exposure rate for Tonawanda Laboratory was approximated as the sum of the parameters (e.g., $D_D + D_M + OD$). Gamma exposure rates are for the whole body.
- c. The increased beta radiation level for office workers after the end of cleanup is due in part to allowing for the possibility that any worker could have been stationed anywhere in the facility once it was all considered clean.
- d. Not estimated.

Table 4-22. Natural uranium per gram dose rates at 1 ft.

Chemical form	Dose rate ^a (rem/hr-gram)
African ore (U_3O_8) with alpha emitting progeny in secular equilibrium through Ra-226	2.05E-11
Purified UO_3 and UO_2 with no alpha emitting progeny	7.91E-12
UF4/UF6 without alpha emitting progeny	6.62E-10

- a. ORAUT-OTIB-0024 (ORAUT 2005a) data used to calculate the alpha-neutron dose rates is from Shleien, Slaback, and Birky (1998), Salmon and Hermann (1992), Reilly et al. (1991), and DOE (2000).
- The entire mass of uranium compounds was conservatively assumed to be attributable to the uranium (source) content.
 - Average neutron energy from alpha-neutron reactions was 2 MeV.
 - Dose equivalent rate-to-fluence rate conversion factor for 2 MeV was 1.3×10^{-4} rem/hr per neutron/cm²-s.
 - The work year consisted of 8 hr/d, 6 d/wk, and 50 wk/yr.

During the Step I and Step II conversion processes in Building 30 (Ceramics Plant) the bounding neutron dose rate would be attributable to operations that involved handling of African Ore with alpha-emitting progeny in secular equilibrium through ²²⁶Ra. This arises from the fact that the African ore feed material contained alpha-emitting progeny that contributed to the alpha-neutron production rate. As indicated in Table 4-22, the African ore form produced neutron dose rates that are 2.6 times greater than the purified UO_3 and UO_2 with no alpha-emitting progeny. In addition, during Step I processing, water, a neutron moderator, was added to the digestion process after ore milling.

Similarly, during Step II processing, uranyl nitrate hexahydrate was added to ether, an organic hydrocarbon, and the solution was washed with water. The presence of these neutron moderators in the Step I and Step II processes would decrease the average neutron energy and consequently reduce the dose equivalent rate-to-fluence rate conversion factor. As a consequence, the dose that was received by loaders (or "Movemen") would be bounding for all personnel who were engaged in Step I and Step II processing activities. As indicated in the Table 4-22, during the Step III conversion process in Building 38, the neutron dose rate from UF_4 is almost 85 times greater than from the UO_2 feed material. Therefore, the dose contribution from handling UO_2 feed material can be neglected.

As discussed in Section 2.3.2, the Linde Ceramics Plant (Building 30) processed approximately 26,000 MT (26 million kilograms) of ore over a period of 37 months beginning in June 1943 and ending in July 1946. Assuming a 6-day workweek for 50 wk/yr, and a uniform rate of ore processing, 28,111 kg/wd (5,622 kg of uranium) were handled at Linde. The assumption favorable to claimants that all of the ore was African ore has been made although 30% of the ore was known to be preprocessed and would contain significantly less alpha-emitting progeny. The assumption favorable to claimants that all of the ore was 20% U_3O_8 by weight has also been made although the Linde site literature indicates that the ore contained 3% to 20% U_3O_8 by weight. According to the available Linde literature, the highest weekly production rate (Step III) of UF_4 at the Linde Ceramics Plant (Building 38) was 41,624 pounds (Kent 1949a) or 3,147 kg/d.

The only potentially significant source of neutron exposure at Linde would have been neutrons produced by the alpha-neutron reaction in materials where uranium was mixed with elements of low atomic number such as fluorine and oxygen. Ceramics Plant (Buildings 30 and 38) personnel are assumed to be exposed to one-tenth of the daily production amount of U_3O_8 or UF_4 at a distance of 1 ft. This quantity of material is an estimate that is favorable to claimants of the time-averaged amount of material likely to have been close to the maximally exposed worker during a work shift. The factor of 10 reduction takes into account several factors: that the plant operated around the clock so that each shift dealt with only one-third of a day's throughput; that many workers were involved in each type of operation so that each worked closely with only a portion of a shift's throughput; that an individual who worked in the vicinity of a large quantity of material (e.g., barrels of finished product) would on the average have been much more than 1 ft away because of the large volume it would have occupied; and that even a worker in a job that involved being close to large quantities of material also had other activities at larger distances from the source term.

Major uranium-related projects at Tonawanda Laboratory were as follows:

- R&D for Steps I, II and III. This work occurred primarily from October 1942 to December 1943 (Jenness and Ewing 1943). The largest-scale efforts were pilot plant projects. The Step I pilot plant produced 2 to 3 t of U_3O_8 per week in November 1942 (Bonsib 1942). The Step III equipment could convert up to 90 lb of UO_2 to UF_4 in a single run (LAPC 1946c, p. 84).
- Conversion of UF_6 to UO_3 . This work appears to have been done after November 1943 (because it is not mentioned in the progress report for work from October 1942 to November 1943; Jenness and Ewing 1943). Interim reports were issued from July 1944 through July 1945, and a final report was issued in May 1946 (LAPC 1946d, p. 111). Typical runs involved use of a 150-lb cylinder of UF_6 and produced a few pounds of product.
- Grinding UF_4 . The laboratory conducted research on grinding UF_4 at an unknown time between October 1942 and May 1946 (LAPC 1946c, p. 89). The work involved processing 2,750 lb of UF_4 . The description of the program suggests that its duration was short (a few weeks).

Based on the above and allowing for date uncertainties and the storage of materials before and after processing or research, the following model was used to estimate neutron doses at Tonawanda Laboratory:

- Ore containing 3 t of U_3O_8 was processed per week, which corresponds to a daily processing rate of 454 kg from October 1, 1942, through February 29, 1944.
- Exposures were to 100 lb of UF_4 or UF_6 per week daily from October 1, 1942, to July 31, 1946. This accounts for the Step III and UF_6 to UO_3 work.
- Exposures were to 3,000 lb of UF_4 for 2 months at some point between October 1, 1942, and July 31, 1946. This accounts for the UF_4 grinding research. The neutron dose in a year is equivalent to that which would be produced by continuous exposure to 500 lb of UF_4 for a year. Because the dates of the work are uncertain, it was assumed that there was continuous exposure to 500 lb of UF_4 from October 1, 1942, to July 31, 1946.

To reflect all types of UF_4 and UF_6 work, a daily source term of 600 lb (272 kg) was assumed. All source terms (both oxide and fluoride) were divided by 3 to account for the fact that no worker would be within close range of the source material at all times. This yielded a daily processing rate of 151 kg of U_3O_8 and a continuous exposure to 90.7 kg of UF_4 or UF_6 . Tonawanda Laboratory (Building 14) personnel were assumed to be exposed to these source amounts at a distance of 1 ft. Table 4-23 summarizes the model parameters and presents calculated dose rates.

Table 4-23. Neutron dose rates and annual doses from the alpha-neutron sources.

Location/time period	Process	Alpha source	Target atom	Daily source term (g)	Dose rate at 1 foot (rem/hr)	Dose rate (rem/yr)
Building 30 06/01/1943–07/31/1946	Steps I and II	African ore 20% U by weight	Oxygen	5.62E+6	1.15E-5	2.77E-2
Building 38 07/25/1943–08/31/1946 ^a 09/15/1947–09/30/1949 ^a	Step III	UF_4	Fluorine	2.76E+6	2.08E-4	5.0E-1
Tonawanda Laboratory (Building 14) 10/01/1942–02/29/1944	Steps I and II	U_3O_8	Oxygen	1.51E+5	3.10E-6	7.44E-3
Tonawanda Laboratory (Building 14) 10/01/1942–07/31/1946	Step III; UF_4 grinding; UF_6 process gas to UO_3	UF_4 or UF_6	Fluorine	9.07E+4	6.01E-5	1.44E-1

a. The period of exposure was extended beyond the end of the production period to account for inventory left on hand. UF_4 that was produced at Linde was shipped to Electromet. The dates when shipping of all Linde inventory was completed were estimated from data in a Linde progress report (Kent 1949b) and data on production at Electromet (DOE undated, pp. 23-24).

4.4 EXTERNAL DOSE RECONSTRUCTION SUMMARY, OCTOBER 1, 1942, TO JULY 7, 1954

This section summarizes guidelines and parameters for reconstruction of doses due to external radiation during October 1, 1942, to July 7, 1954 except for doses due to occupational medical exposure, which are addressed in Section 5.0. The parameters that are provided in this section are for use when individual worker data are unavailable or inadequate. Because of the SEC determination (HHS 2005) that it is infeasible to adequately reconstruct internal dose during the period

October 1, 1942 through October 31, 1947, dose estimates for this period are considered partial dose estimates.

For dose reconstruction, exposures for different jobs have been grouped into categories. Table 4-24 specifies the categories and the annual radiation doses or exposures assigned to each. For the production periods at the Ceramics Plant, categories were designated high, medium, and low. In other cases, designations more descriptive of the work activity are used.

Table 4-24. Summary of annual external exposure from AWE operations, 1942 to 1953.

Year ^a	Work category	Beta (rem) ^a		Gamma (R) ^a	Neutron (rem) ^{a,b}
		Hands & forearms	Rest of body		
Ceramics Plant (Buildings 30, 31, 37, and 38)					
1942 ^c	All workers	2.55E-02	2.55E-02	4.97E-03	(d)
1943 ^e	High	1.51E+02 ^f	5.05E+01	3.65E+00	3.41E-01 ^g
		5.05E+01 ^h			
	Medium	1.20E+01	3.97E+00		
	Low	2.08E+00	2.08E+00		
1944 1945	High	2.21E+02 ^f	7.40E+01	5.35E+00	5.00E-01 ^g
		7.40E+01 ^h			
	Medium	1.76E+01	5.85E+00		
	Low	3.00E+00	3.00E+00		
1946 ⁱ	High	1.28E+02 ^f	4.32E+01	3.11E+00	3.33E-01 ^g
		4.32E+01 ^h			
	Medium	1.04E+01	3.59E+00		
	Low	1.93E+00	1.93E+00		
1947 ⁱ	Medium	2.04E+00	8.91E-01	5.37E-01	1.48E-01 ^g
	Low	6.10E-01	6.10E-01	2.03E-01	
1948	Medium	5.85E+00	1.95E+00	1.61E+00	5.00E-01 ^g
	Low	1.00E+00	1.00E+00	4.80E-01	
1949	Medium/low ^k	6.85E+00	2.28E+00	1.73E+00	3.74E-01 ^g
	Cleanup				
	Non-cleanup ^l	6.60E-01	6.60E-01	2.94E-01	(d)
1950	Cleanup ⁿ	7.83E+00	2.61E+00	1.85E+00	(d)
1951	Non-cleanup ^o	3.26E-01	3.26E-01	1.11E-01	
1952					
1953					
1954 ^m					
Tonawanda Laboratory (Building 14)					
1942 ^c	Research	2.80E+01	9.33E+00	1.35E+00	3.63E-02
	Office	7.56E-01	7.56E-01		
1943	Research	1.11E+02	3.70E+01	5.35E+00	1.44E-01
	Office	3.00E+00	3.00E+00		
1944	Research	1.11E+02	3.70E+01	5.35E+00	1.44E-01
1945	Office	3.00E+00	3.00E+00		
1946	Research ^p	6.78E+01	2.26E+01	3.88E+00	8.36E-02 ^q
	Office ^r	1.78E+00	1.78E+00	3.15E+00	
1947 1948 1949 1950 1951 1952 1953	All workers	3.26E-01	3.26E-01	6.80E-02	(d)

a. Total annual exposure (dose) for the designated year. Prorated based on calendar year and applicable notations below.
b. Because of the possible difficulty in determining whether a worker was working with oxide or fluoride materials, each worker was assigned the larger neutron dose due to fluorides.

- c. Exposure for the period from October 1 through December 31, 1942 only.
- d. Neutron dose rate was negligible.
- e. Values prorated: For January 1 through April 26, 1943 (preproduction period), applicable values from Table 4-1 applied; for April 27 to December 31, 1943, applicable 1944 to 1945 values applied.
(Example calculation: $1943 \text{ high-ball mill operator} = 0.315 \times 1.01\text{E-}01 + 0.685 \times 2.21\text{E+}02 = 1.51\text{E+}02$).
- f. Based on 221 rem/yr for ball mill operator, Step I and Step II process operators, and weighmaster.
- g. The Building 38 neutron dose rate for Step III processing was assumed to apply from April 27, 1943, to August 31, 1946, and from September 15, 1946, to September 30, 1949. The neutron dose rate was negligible from September 1, 1946, to September 14, 1949 (standby), and after September 30, 1949 (cleanup and postcleanup). The period of neutron exposure extended beyond the end of production in 1946 and 1949 due to remaining inventory of UF₄.
- h. Based on 74 rem/yr for loader per Section 4.1.2.1.3.
- i. Values prorated: For January 1 to July 31, 1946, applicable 1944 to 1945 values applied; for August 1 to December 31, 1946 (standby period), applicable values from Table 4-4 (guard) applied.
- j. Values prorated: For January 1 to September 14, 1947 (standby period), applicable values from Table 4-4 (guard) applied; for September 15 to December 31, 1947, applicable 1948 values applied.
- k. Values prorated: For January 1 to June 30, 1949 (Step III production), applicable 1948 medium values applied; for July 1 to December 31, 1949, 1950 to 1953 cleanup values applied.
- l. Values prorated: For January 1 to June 30, 1949 (Step III production), applicable 1948 low values applied; for July 1 to December 31, 1949, 1950 to 1953 non-cleanup values applied.
- m. Exposure for the period of January 1 to July 7, 1954 only.
- n. All cleanup workers and cleanup support workers as defined in Section 4.1.5 are assigned to the cleanup exposure category. Parameters are those of the cleanup worker for a 6-day week in Table 4-20.
- o. All non-cleanup workers as defined in Section 4.1.5 are assigned to the non-cleanup exposure category. Parameters are those of the non-cleanup worker for a 6-day week in Table 4-20.
- p. Values prorated: For January 1 to July 31, 1946, applicable 1944 to 1945 values applied; for August 1 to December 31, 1946, applicable values from Table 4-21 (cleanup-R&D scenario) applied.
- q. Includes neutron exposures through July 31, 1946.
- r. Values prorated: For January 1 to July 31, 1946, applicable 1944 to 1945 values applied; for August 1 to December 31, 1946, applicable values from Table 4-21 (cleanup-office scenario) applied.

Where the dose or exposure estimates were based on dosimetry parameters (dosimeter dose D_D and missed dose D_M) plus possible outdoor dose OD , the dose was estimated as the sum of the parameters ($D_D + D_M + OD$). Each estimate is considered to be the median of a lognormal distribution. A GSD of 3 was assigned to all beta and gamma dose estimates based on the typical GSD levels estimated for the underlying data; that is, beta and gamma doses were assigned as lognormal distributions with GSDs of 3 and an acute exposure rate. Neutron doses were assigned as a constant distribution and a chronic exposure rate.

Prorating of exposures over less than a year is not straightforward for all periods. If doses are to be prorated, the footnotes to Table 4-24 should be checked to determine how the dose should be distributed throughout the year. Beta doses were assigned as electrons with energy >15 keV. Gamma doses were assigned as photons with energy from 30 to 250 keV, which is favorable to claimants. Neutrons are assigned as neutrons of 0.1- to 2-MeV energy.

Table 4-25 shows how Ceramics Plant production jobs were assigned to the various categories. For 1943 to 1946, the assignments were based on Table 4-25 and the discussion in Section 4.1.2.1.3. For 1947 to 1949, the assignments were based on Tables 4-16 and 4-18 and the discussion in Section 4.1.4.2. In each case, some job titles that reflect subcategories of titles in the earlier tables were added.

For the Ceramics Plant cleanup period, the cleanup category includes both cleanup workers and cleanup support workers as defined in Section 4.1.5. For Tonawanda Laboratory, the research and office categories are defined in Section 4.2.

If the exact job of a worker is not listed, dose reconstruction should be based on the most similar job.

Table 4-25. Ceramics Plant worker beta and gamma external exposure categories for production periods

1943–1946 production		1947–1949 production	
Job	Beta category	Job	Beta and gamma category ^a
Ball mill operator	High	A operator	Medium
Chemist	Medium	B operator	Medium
Draftsman	Low	C operator	Medium
Engineer	Medium	Chemist	Medium
Fire inspector	Low	Fire marshal	Low
Guard	Low	First aid nurse	Low
Janitor	Medium	Foreman, labor	Medium
Lab technician	Medium	Foreman, loader	Medium
Laundry worker	Medium	Foreman, maintenance ^b	Medium
Loader/moveman	High	Foreman, step III	Medium
Maintenance worker ^b	Medium	Group leader, maintenance ^b	Medium
Nickel operator	Low	Group leader, step III	Medium
Nurse	Low	Guard	Low
Office worker ^c	Low	Janitor step III	Medium
Ore sampler	Medium	Janitor, outside step III	Low
Plant superintendent, asst supt	Low	Lab technician	Medium
Seamster, seamstress	Medium	Laundry man	Medium
Shipping & receiving clerk	Low	Loader/moveman	Medium
Step I process operator	High	Maintenance ^b	Medium
Step II process operator	High	Office employee, AEC	Low
Step III process operator	Medium	Office employee, Linde ^c	Low
Storekeeper/stock clerk	Low	Shipping & receiving clerk	Low
Tank farm operator	Low	Storekeeper/stock clerk	Low
Tool crib attendant	Medium	Timekeeper	Low
Truck driver/operator	High	Tool crib attendant	Medium
Weighmaster	High	Truck driver/operator	Medium
		Weighmaster	Medium

- The category assignments are the same for beta and gamma radiation.
- Maintenance personnel include all craftspersons who constructed, fabricated, repaired, or refurbished (e.g., carpenter, electrician, instrument repairman, lathe operator, mason, millwright, oiler, painter, pipe fitter, sheet metal worker, trades helper, and welder).
- Office workers include accountant, bookkeeper, clerk, comptometer operator, draftsman, industrial relations representative, mail person, plant superintendent and assistant superintendent, product accountant, property department worker, secretary, security agent, stenographer, telephone operator, and typist.

5.0 OCCUPATIONAL MEDICAL EXPOSURE

Because of the SEC determination (HHS 2005) that it is infeasible to adequately reconstruct internal dose during the period October 1, 1942 through October 31, 1947, dose estimates for this period are considered partial dose estimates.

5.1 CERAMICS PLANT EMPLOYEES

Preemployment, periodic, and termination chest X-rays were required for at least some of the workers at Ceramics Plant. On certain occasions, pelvis X-rays were also required.

5.1.1 Chest X-rays

The earliest record that was found of a requirement for chest X-rays at Linde is in a report of a conference on worker safety at Linde held March 31, 1943 (Brimm and Neumann 1943). The conference report called for a preemployment medical examination that included fluoroscopic chest examination. A September 4, 1943, letter from the Medical Section of the MED recommended initial and periodic examinations that included chest X-rays (Van Horn 1943a). Available medical records indicate that chest X-rays were regularly administered to workers in 1943 and later years. Based on the correspondence and the indications of plant practice found in the medical records, the assumptions below are provided for use in reconstruction of doses due to chest X-rays.

Ceramics Plant X-ray Assumptions

1. Applicability: These parameters apply to all job categories at the Ceramics Plant.
2. X-Ray Category and Frequency:
 - a. Preemployment: Taken before starting employment at Linde Ceramics. These X-rays were also required for Linde employees who transferred to the Ceramics Plant from other parts of the company.
 - b. Periodic
 - (1) Before August 13, 1943, taken at 3-month intervals.
 - (2) From August 13, 1943, through December 31, 1944, taken at 6-month intervals.
 - (3) From January 1, 1945, on, taken at 12-month intervals.
 - c. Termination: Taken at termination of employee participation in MED/AEC work at Linde (either due to employee leaving or the work ending).
3. Methodology:
 - a. Before July 16, 1943, by fluoroscopy of the lungs.
 - b. On or after July 16, 1943, by taking a 14- by 17-in. radiographic film.
4. Period: The chest X-ray program was assumed to have started on November 16, 1942, and ended on December 31, 1953.

Bases of Assumptions

1. Applicability: A MED letter (Van Horn 1943a) recommended chest X-rays for "those persons working in direct contact with special materials" (Van Horn 1943a), where the term "special materials" appears to have denoted materials that contained uranium or uranium and radium (Ferry 1944b). When the medical examination program at the Ceramics Plant was

established, it was decided that all employees should receive the same physical examinations and rechecks (Cranch 1944b). By January 1944, after reports from the early examinations did not indicate any noticeable medical hazard, discussions were under way on reducing the frequency of examinations for those clerical workers who had no occasion to go into operating areas (Cranch 1944b). The suggestion was made that the examination frequency be reduced for office personnel working in the office annex building but not for certain clerical help (described as "some stenographers and clerks, stores clerks, etc."), who worked in the main building and were "from time to time exposed to the same hazards as operating personnel" (Holmes 1944a). A reduced frequency for guards was also suggested. By November of 1944, all employees were to have a preemployment examination, which included a chest X-ray. Employees "working in the plant or who have occasion to come in contact with any portion of the process or the materials" were given periodic examinations and a termination examination. However, employees "not having occasion to contact the process in any way" were exempt from the periodic and termination examinations (Holmes 1944b). From the foregoing, it is clear that some employees were not subject to periodic and termination X-rays. However, it is not clear how those employees can be identified. Therefore, the general assumption for dose reconstruction is that all employees were subject to the same chest X-ray requirements.

2. X-Ray Category and Frequency: Preemployment, periodic, and termination X-rays are discussed in various 1943 correspondence. A 3-month periodic interval was stipulated in the report of March 31, 1943, conference on Linde Step II safety (Brimm and Neuman 1943). A 6-month interval was specified in a letter that was distributed August 13, 1943 (Cranch 1943). No medical records that exemplified a 3-month interval were found, but the available medical records for 1943 appear to be incomplete. Available worker files in which the first indicated chest X-ray date was July 1943 or later are consistent with a periodic interval of approximately 6 months for X-rays in 1944 and a periodic interval of 12 months after 1944.
3. X-Ray Type: As noted, the March 31, 1943, safety conference stipulated that the preemployment exam should include fluoroscopic chest examination. A medical record indicates chest examination by "fluoroscope, lungs" in a preemployment examination on March 31, 1943 (Claim File *number redacted*, DOE Response *number redacted*, p. 23). A comment in the notes of a safety conference on May 7, 1943, indicates that the fluoroscopic examinations did not involve the use of film. The conference participants recommended the use of X-ray film to have a permanent record of the chest condition (Brimm 1943b). The earliest chest X-ray found in available worker files was a radiographic film from July 16, 1943 (Claim File *number redacted*, DOE Response *number redacted*, p. 28). The type of film X-rays that were taken at Linde (radiographic rather than photofluorographic) and their size (14- by 17-in.) was determined from several pieces of evidence:
 - (a) Some of the claimant files contain data sheets from the Black Rock Clinic, where Linde X-rays were taken, that state the size to be 14- by 17-in. (e.g., Claim File *number redacted*, DOE Response *number redacted*, p. 61).
 - (b) Approximately 60 arbitrarily selected Linde Air Products X-ray films in the DOE Oak Ridge Office vaults were pulled and viewed. All were 14- by 17-in. (Beck 2004).
 - (c) In 1949, Linde requested proposals for microfilming various records on cards and X-ray films. A response to this request indicated that 3,000 14- by 17-in. X-ray films were involved and mentions no other size (Medhurst 1949).

One piece of evidence that suggests the use of photofluorographic X-ray techniques was found, a purchase requisition from November 4, 1944, for 3 gross (432) of 4.5- by 10-in. Type F X-ray film (LAPC 1944b). The size of this film was appropriate for photofluorographic

stereoscopic chest X-rays (Cardarelli et al. 2002, p. 492). However, the following factors suggest it was not used for such X-rays:

- (1) No photofluorographic film images were found in the Linde claim files.
 - (2) The purchase requisition was issued by Linde and called for delivery of the film to the "Laboratory." If the film had been for chest X-rays, it probably would have been issued by the Black Rock Clinic – the only location for taking X-rays that was indicated in the Linde medical files that were examined – and delivered there.
 - (3) The purchase requisition stated the film was for "research on army contract #W-7405 Eng. 26." This contract supported research at the Tonawanda Laboratory (Brimm and Schubert 1945b), which suggests that the film was for use in such research. It is unlikely that the laboratory had its own worker X-ray program because other correspondence indicates a common program for the Ceramics Plant and the Proving Laboratory, the portion of Tonawanda Laboratory that was involved in developing uranium processing techniques (Cranch 1943).
4. Period: November 16, 1942, is the date on which Linde entered into contract W-7401 eng-14 for its work for the MED (Section 2.1.2). It is likely that the medical examination requirements were not implemented until some time after this date, but exactly how long after is not known. A letter to the Linde Safety Steering Committee on August 13, 1943, indicated that preemployment examinations were already a regular practice (Cranch 1943). The earliest document found that referred to the X-ray requirements was the report of the March 31, 1943, safety conference, but the program might have been established before that date. Production work at the Ceramics Plant is assumed to have ended on June 30, 1949; cleanup work is assumed to have ended on December 31, 1953. It is likely that employees who participated in the cleanup work were required to have chest X-rays. In the absence of specific information, it is assumed that other employees were also required to have chest X-rays.

5.1.2 Pelvis/Lumbar Spine X-rays

A letter from the MED Medical Section to Linde on September 4, 1943, recommended initial and annual pelvis X-rays for workers "who will be exposed to fluorine or fluorine compounds" (Van Horn 1943a). However, on January 11, 1944, the MED recommended that pelvis X-rays be omitted from both preemployment and followup examinations (Warren 1944). To assess company practice, Linde medical records were checked. The review was limited in its scope because only a small portion of the records for the period were available – records of EEOICPA claimants and records in general Linde files – because of other compensation claims that had been filed against the company. Eight records were found that showed X-rays during the period from September 4, 1943, January 11, 1944. The records indicated that all of the subjects had chest X-rays, but only one also had a pelvis X-ray (Various authors 1950, p. 67). The name of the worker for whom the pelvis X-ray was indicated was found in a Ceramics Plant employee list from April 1944 (Neuman 1944). The list indicated that the employee worked in Step II, an activity that did not involve handling of fluorine or fluorine compounds.

Additional information was found in Linde correspondence files. When the recommendation to end pelvis X-rays was relayed to the Ceramics Plant, the plant administration advised the corporate office "that we have never made any pelvic X-rays of any of the people working in the Ceramics Plant" (Holmes 1944c). The corporate office checked with the medical doctor in its Industrial Toxicology Department who had oversight over medical procedures at the Ceramics Plant. The doctor wrote:

It is my understanding that no arrangement had as yet been made for the taking of pelvic x-rays of employees at the Ceramics plant. When this was discussed some time

ago it was decided that in view of the possible fluorine exposure it might be advisable later, perhaps at the WCX plant, to include pelvic x-rays when our facilities would make this more feasible. For this reason, a space was provided in the form for "laboratory examinations." ... The opinion at present is that there would be no need at the Ceramics Plant to include pelvic x-rays in the physical examinations. (Cranch 1944c)

These records indicate that Linde did not institute routine pelvis X-ray examination of its employees in response to the September 4, 1943 recommendation from the MED. The indication of a single pelvis X-ray in the medical records might have related to a special situation for that employee. While dose reconstruction should include the X-ray examinations performed for screening in the particular employees medical record, this particular record is not interpreted as evidence that Linde instituted a general policy of taking pelvis X-rays of a particular category of employees in response to the MED letter (Van Horn 1943a).

In the review of employee medical records, it was noticed that the record of a female employee had the notations "LMP 2/10/44" and "LMP 3/4/44" in the row on the report form for recording pelvis X-ray results. Other pages of the employee's record had similar monthly entries, but they were in a section that began in the succeeding row of the report that was designated for recording results of "Other Tests." This was interpreted as indicating that the two entries on the pelvis X-ray row had been entered on that row in error. The entries were interpreted as recording the date of the last monthly period in compliance with suggestions made by the MED (Van Horn 1943b).

Pelvis X-rays of Linde employees were taken at a later time. The Ceramics Plant progress report for the week ending December 21, 1947 stated, "Complying with instructions received from the health authorities of the AEC, pelvis X-rays are being taken of all Ceramics Plant employees. It is expected that this program will be completed before the end of the year" (LAPC 1948). Employee medical records confirm that X-rays of the pelvis were taken. Images of X-ray films with the records indicate that 14- by 17-in. films were taken and that the long direction of the film was parallel to the length of the body, an orientation like that for standard lumbar spine X-rays and different from the 17- by 14-in. orientation (the 14-in. dimension parallel to the length of the body) for standard pelvis X-rays. In each of the available files that had copies of pelvis X-ray films, there were two images of the pelvis. It was difficult to determine whether these were images of two portions of one X-ray exposure or whether two X-ray exposures had been taken at one session. To avoid underestimation of worker doses, for dose reconstruction it was assumed that two exposures were taken.

In June 1949 as the plant was nearing shutdown, it wrote the AEC to ask whether a pelvis X-ray should be included in the termination medical examination of all workers whether or not they had access to contaminated areas (Kent 1949c). A statement of the decision in this matter was not found. Employee medical records indicated that X-rays of the pelvis were taken at termination (around the end of June 1949), but the number of records was not sufficient to indicate whether they were taken of all employees. The X-ray film images available had characteristics similar to those from the end of 1947.

Based on the foregoing, the assumptions below are provided for use in reconstruction of doses due to X-rays of the pelvis.

Assumptions

1. Applicability: These parameters apply to all job categories at the Ceramics Plant.
2. Occasions: Pelvis X-rays were taken at the following times:
 - a. Near the end of 1947: A pelvis X-ray was taken of every Ceramics Plant employee in November or December 1947.

- b. At employee termination: A pelvis X-ray was taken of every Ceramics Plant employee who terminated after November or December 1947.
3. Number: Two exposures were taken at each occasion.
4. Methodology: A 14- by 17-in. radiographic film was taken (17 in. parallel to the length of the body), a format similar to that for lumbar spine X-rays.

5.1.3 X-Ray Dose Reconstruction Guidelines

Dose reconstruction should consider information specific to the subject to the extent that it is available, adequate, and is representative of X-ray screening examinations covered under the EEOICPA (i.e., dose from X-ray examinations conducted as a result of occupational injuries are not to be included in dose reconstructions). The guidelines in this section are for use when the records for an individual worker are not available or are incomplete. The guidelines are for use only to the extent that they are not inconsistent with the worker's records. For example, if the medical records are complete and indicate a lower or higher examination frequency than stated in the assumptions provided above, the data in the medical records should be used.

X-ray doses shall be determined in accordance with the latest revision of the project technical information bulletin *Dose Reconstruction from Occupationally Related Diagnostic X-Ray Procedures* (current version is ORAUT 2005b) when applicable. Before using the guidelines therein, dose reconstructors shall confirm that the assumptions on which they are based are applicable.

In relation to the above, attention is called to the following:

- For many employees, medical records are available that show the dates and types of the X-rays taken.
- Often, images of the actual X-rays are also available in claimant files.
- Some chest X-rays in Linde claimant files show portions of the chin. This indicates that positioning, and perhaps also collimation, was not as good as in current practice.
- X-rays of the pelvis thus far examined in Linde claimant files had the format of lumbar spine X-rays. The lumbar spine X-ray doses in the X-ray technical information bulletin might be more suitable for these cases than the pelvis X-ray doses.

5.2 TONAWANDA LABORATORY EMPLOYEES

The medical X-ray requirements for Ceramics Plant employees appear to have also applied to Tonawanda Laboratory employees who worked in pilot plant projects (Cranch 1943; Brimm 1943c). The extent to which the requirements were extended to other Tonawanda Laboratory employees is not known. In the absence of this information and in view of the likely difficulty of establishing whether or not a particular worker was involved in handling radioactive materials, it is assumed for dose reconstruction that chest X-rays were required of every Tonawanda Laboratory employee in the period of MED work unless it can be shown that the employee was not involved in MED projects.

The following assumptions are made about the frequency of X-rays of Tonawanda Laboratory employees:

1. Applicability: These parameters apply to all job categories at Tonawanda Laboratory.

2. X-ray Category and Frequency:
 - a. Initial X-ray when the worker started working on an MED contract.
 - b. Periodic X-rays at the same frequency as specified for Linde Ceramics.
 - c. Termination X-ray at termination of employee participation in MED/AEC work at Linde.
3. Methodology: Same as for the Ceramics Plant.
4. Period: MED-related work at Tonawanda Laboratory was assumed to have started on October 1, 1942, and ended on December 31, 1946.

Dose reconstruction guidelines are the same as for Ceramics Plant employees.

6.0 ESTIMATION OF EXPOSURES FROM RESIDUAL CONTAMINATION AFTER 1953

This section develops parameters for reconstruction of doses due to internal and external exposures at the Ceramics Plant starting July 8, 1954 and Tonawanda Laboratory starting January 1, 1954.

Initial cleanup of Tonawanda Laboratory was assumed to be complete on December 31, 1946. Tonawanda Laboratory worker radiation exposures from January 1, 1947, to December 31, 1953, are discussed in Sections 3.0 and 4.0.

It was assumed that beginning on January 1, 1954, Tonawanda Laboratory employees could have been exposed to residual contamination for 2,000 hr/yr.

6.1 INTERNAL EXPOSURE

Airborne Radioactivity

In recent years, outdoor air radioactivity has been measured in conjunction with the site soil remediation program (USACE 2004). Table 6-1 displays the highest monthly average air concentrations of ²²⁶Ra, ²³⁰Th, and ²³⁸U for July 2000 through June 2004. Assuming that the measured ²³⁸U is part of a natural uranium source term, the total uranium concentration would be the ²³⁸U concentration divided by the fraction of activity due to ²³⁸U (0.4886), which is 4.3×10^{-4} pCi/m³. The activity ratios of ²³⁰Th and ²²⁶Ra to uranium are 0.84 and 1.7, respectively.

Table 6-1. Highest monthly outdoor airborne radionuclide concentrations at Linde Tonawanda site, 2000 to 2004.

Nuclide	Highest monthly concentration (pCi/m ³) ^a
Ra-226	7.5E-04
Th-230	3.6E-04
U-238	2.1E-04

a. Per analysis of data from USACE (2004).

Building 30 was found in 1976 to be the most contaminated building on the site (ORNL 1978). The indoor airborne uranium concentration in 1976 was measured as 1.9×10^{-2} pCi U/m³ (ORNL 1978, Table 4-2). This larger uranium air concentration was used to estimate a chronic intake. To maintain the consistent intake units and estimate the annual intake, the uranium air concentration of 1.9×10^{-2} pCi/m³ was multiplied by 2.22 dpm/pCi, a breathing rate of 1.2 m³/hr, and 2,000 hr/yr. The annual intake rate was estimated at 100 dpm/yr for all Tonawanda employees beginning in 1955. Dividing by 365 d/yr gives a daily uranium inhalation intake rate of 0.277 dpm/d. The ²³⁰Th and ²²⁶Ra daily inhalation intake rates would be 0.233 and 0.471 dpm/d, respectively. Ingestion intake rates were estimated using the steps in Section 3.7. The summarized intake results are shown in Table 6-2. It is unlikely that uranium would be in a chemical form consistent with absorption type F during the residual contamination period, so it was assumed that only types M and S would be inhaled during this period. Thorium-230 could be type M or S, and ²²⁶Ra is type M.

Workers noted that Building 30 renovations occurred in the 1960s that could have influenced air concentrations. Specific details of the renovation, including the actual period of renovation, dust control measures, location of work and occupancy of areas, are not available. It is reasonable to assume that renovations could have resulted in elevated airborne radioactivity. Because a maximum value of measured air concentration was used to estimate the intakes during the residual exposure period, a factor of 14 was assumed to be reasonable to describe the uncertainty at the 95th percentile that is associated with the possibility of elevated intakes during Building 30 renovations. So for organ doses, the distribution was assumed to be lognormal with a GSD of 5.

Other progeny are partially accounted for by the assigned radon exposure.

Radon Progeny

Fifty-five measurements of radon progeny concentration were made in 1976 and 1981 in the Tonawanda site buildings that were used in MED/AEC work (ORNL 1978, pp. 17 and 84; BNI 1982, p. B-24). The 1981 survey was more comprehensive and yielded significantly higher concentrations, so the 1976 results were ignored. Building 31 had the highest radon progeny concentration. The GM of the PAEC was 1.68×10^{-2} WL with a GSD of 1.89 (based on analysis of data in BNI 1982, Table B-3). No correction was made for natural background radon, because its value was unknown. Based on 12 work months per year, the radon exposure was estimated as 2.01×10^{-1} WLM/yr, and is listed in summary Table 6-2 in the next section.

6.2 EXTERNAL BETA AND GAMMA EXPOSURE

As noted, Building 30 was found in 1976 to be the most contaminated building on the site (ORNL 1978). Measured floor and wall radiation levels in Building 30 in 1976 were compared with similar measurements from 1950 immediately after its decontamination (see Section 4.1.1 and Heatherston 1950). The results were similar, but the 1950 values were slightly higher.

Outdoor gamma radiation levels at 1 m above the surface on and near the Tonawanda site were measured in 1976 and 1981. Natural background gamma radiation levels in the Tonawanda area were said to be 8 to 15 μ R/hr (ORNL 1978, p. 15; BNI 1982, p. B-12). ORNL 1978 (p. 15) reported only isolated areas with levels significantly higher than background; readings in these areas were described as very nonuniform and varying from background up to 250 μ R/hr. Regions with readings above about 20 μ R/hr were indicated in a figure in the report (Fig. 26). Figure B-5 of BNI (1982) summarized the combined results of the two studies. Locations and values were shown for readings ≥ 25 μ R/hr. BNI (1982, p. B-12) stated that the points of maximum radiation that were determined in the ground surveys were slightly displaced from but in general agreement with those that were determined in a 1979 aerial radiological survey. The total number of reported readings ≥ 25 μ R/hr was 16. The net readings (after subtraction of 8 μ R/hr to correct for background) had a GM of 94 μ R/hr and a GSD of 3.95. This was taken as an estimate of worker exposure rate when outdoors. This estimate was assumed to apply starting January 1, 1954, at the Tonawanda Laboratory and July 8, 1954, at the Ceramics Plant. No credit was taken for the soil remediation at the site that began in 2000 because the remediation has not been completed (Pilon 2004). The estimate is probably an overestimate for the following reasons: measurements were reported only for areas that were identified as having above-background radiation levels, these areas occupied much less than half of the open area of the site (based on Fig. B-5 of BNI 1982), and the reported measurements were not averages over these areas but only readings at a few hot spots.

The beta dose rate at 3 ft above the ground that corresponded to the adopted value of gamma exposure rate was estimated as 4.38×10^{-1} mrem/hr, which is 4.66 times the gamma rate where 4.66 is the ratio of beta mrem/hr at 3 ft to gamma mR/hr at 3 ft for the floors and walls in Building 30 after decontamination (Table 4-1). It is assumed that the GSD for the beta dose rate would be the same as for the photon dose rate.

Because the radiation levels seemed to remain fairly constant, and because the levels were fairly low, the Tonawanda Laboratory postcleanup exposures, based on Building 30 contamination levels, were used to estimate the external exposure rate. No adjustments for changes in work hours were made. Table 6-2 summarizes the results. The radiation energy distributions were assumed to be same as those during the operational period.

Table 6-2. Annual internal and external exposure to residual radioactivity.

Internal	Start/End Date ^a	Exposure	Absorption type	Intake (dpm/d)	IREP distribution
U-234	(b)	Inhalation	M, S	2.77E-01	Lognormal GSD 5
	(b)	Ingestion	(c)	5.78E-03	Lognormal GSD 5
Th-230	(b)	Inhalation	M, S	2.32E-01	Lognormal GSD 5
	(b)	Ingestion	(c)	4.84E-03	Lognormal GSD 5
Ra-226	(b)	Inhalation	M	4.71E-01	Lognormal GSD 5
	(b)	Ingestion	(c)	1.01E-02	Lognormal GSD 5
				WLM/yr	
Rn-222	(b)	Inhalation	-	2.01E-01	Lognormal GSD 1.89
External	Start	Exposure	Basis		
	(b)	Penetrating	Survey instrument	0.068 R/yr	Lognormal GSD 3
	(b)	Non-penetrating	Survey instrument	0.326 rem/yr	Lognormal GSD 3

- January 1, 1954, start date applies to Tonawanda Laboratory; for the Ceramics Plant, the higher dose values that are associated with D&D operations (Sections 3.0 and 4.0) should be applied until July 7, 1954, and the values cited in this table apply starting on July 8, 1954, and should be prorated accordingly.
- The exposure end data has been designated as July 2006 (Turcic 2007).
- Choose same f_1 -value as for inhalation per NIOSH (2004).

6.3 NEUTRON EXPOSURE

Because only small quantities of radioactive material were on the site in the postcleanup period, there were no significant neutron exposures.

7.0 ATTRIBUTIONS AND ANNOTATIONS

All information requiring identification was addressed via references integrated into the reference section of this document.

REFERENCES

- AEC (U.S. Atomic Energy Commission), 1949a, *Health Hazards in NYOO Facilities Producing and Processing Uranium (A Status Report - April 1, 1949)*, New York Operations Office, Medical Division, New York, New York, April 18. [SRDB Ref ID: 3931]
- AEC (U.S. Atomic Energy Commission), 1949b, NYDO Radiological Laboratory Film Badge Report for Ceramics Plant for Week Beginning March 28. [SRDB Ref ID: 3965, p. 2]
- AEC (U.S. Atomic Energy Commission), 1953, *Simonds Saw and Steel Company, Occupational Exposure to Uranium*, New York Operations Office, February 18. [SRDB Ref ID: 11996]
- Aerospace Corporation, 1981, *Evaluation of the 1943-to-1946 Liquid Effluent Discharge from the Linde Air Products Company Ceramics Plant*, ATR-82(7963-04)-2, December. [SRDB Ref ID: 16979, p. 805]
- Author unknown, ca. 1947, "Schedule of Examinations, Contract AT-30-1-GEN-165." [SRDB Ref ID: 12382, p. 3]
- Author unknown, undated, "Linde Urinalysis." [SRDB Ref ID: 4002]
- Beck, J., 2004, "Linde Air X-rays," e-mail to R. Medora, Oak Ridge Associated Universities, Oak Ridge, Tennessee, July 8. [SRDB Ref ID: 14579]
- Blatz, H., 1949, "Report on a General Radiation Survey at Linde Air Products Company, Div. of Union Carbide & Carbon Corp, Ceramics Plant, Tonawanda," memorandum, April 19. [SRDB Ref ID: 8836, p. 18]
- BNI (Bechtel National, Inc.), 1982, *Preliminary Engineering Evaluation of Remedial Action Alternatives, Linde Air Products Site, Tonawanda, New York*, Formerly Utilized Sites Remedial Action Program (FUSRAP), BNI-010-05-29-59A, November. [SRDB Ref ID: 14704]
- BNI (Bechtel National, Inc.), 1993, *Remedial Investigation Report for the Tonawanda Site, Tonawanda, New York*, DOE/OR/21949-300, Volume I, Oak Ridge, Tennessee, February. [SRDB Ref ID: 16304]
- Bonsib, R. S., 1942, *Preliminary Safety Survey, Metal Production Operations of the University of Chicago. Metallurgical Laboratory Project (October 30 to December 12, 1942)*, University of Chicago, New York, New York, December 22. [SRDB Ref ID: 17124, p. 5]
- Brimm, E. O., 1943a, *Processing of African Ores*, M-4549, Tonawanda Laboratory, Linde Air Products Company, Tonawanda, New York, May 7. [SRDB Ref ID: 3766]
- Brimm, E. O., 1943b, *Safety Precautions in Ceramics Plant*, Linde Air Products Company, Tonawanda, New York, May 12. [SRDB Ref ID: 8925]
- Brimm, E. O., 1943c, *Safety Conference on Handling of African Ores Precautions in Ceramics Plant*, Linde Air Products Company, Tonawanda, New York, August 16. [SRDB Ref ID: 8907, p. 5]
- Brimm, E. O., and C. F. Schubert, 1945a, "Research on Conversion for TF_6 to TO_3 ," Memorandum P.G.-13, Linde Air Products Company, Tonawanda, New York, May 29. [SRDB Ref ID: 8948]

- Brimm, E. O., and C. F. Schubert, 1945b, "Operation of Pilot Plant for Conversion for TF_6 to TO_3 ," Memorandum P.G.-16, Linde Air Products Company, Tonawanda, New York, July 18. [SRDB Ref ID: 7650; contains Export Controlled Information]
- Brimm, E. O., and F. L. Neuman, 1943, *Report of Safety Conference on Hazards and Safety Precautions for Step II – Ceramics Plant*, Linde Air Products Company, April 8. [SRDB Ref ID: 16318, p. 19]
- Bryan, F. A., 1945, "Dust Sample Results from Chandler Plant," memorandum to Lt. R. A. Tybout, EIDMM-2b, MD723.1, U.S. Engineer Office, Manhattan District, Oak Ridge, Tennessee, May 4. [SRDB Ref ID: 16979, p. 677]
- Cardarelli, J., H. Spitz, C. Rice, R. Buncher, H. Elson, and P. Succop, 2002, "Significance of Radiation Exposure from Work-Related Chest X-Rays for Epidemiological Studies of Radiation Workers," *American Journal of Industrial Medicine*, volume 42, pp. 490–501. [SRDB Ref ID: 4037]
- Cember H., 1983, *Introduction to Health Physics, Second Edition*, Pergamon Press, New York, New York.
- Chapman, J. L., E. C. Kent, V. Osinski, and D. L. Voisinet, 1948, *Continuous Process for Step III in the Ceramics Plant*, LAP-4, Linde Air Products Company, Tonawanda, New York, September 29. [SRDB Ref ID: 7662]
- Coleman, R. L., C. G. Hudson, and P. A. Plato, 1983, "Depth-Dose Curves for ^{90}Sr and Natural and Depleted Uranium in Mylar," *Health Physics*, volume 44, number 4, pp. 395–402. [SRDB Ref ID: 12288]
- Cornell, P. G., 1942, "Letter Contract No. W-7401 eng-14," letter to Linde Air Products Company, Manhattan Engineer District, New York, New York, November 16. [SRDB Ref ID: 16979, p. 407]
- Cranch, A. G., 1943, "Form for History and Physical Examination for Use in Ceramics Plant and Proving Laboratory," memorandum to Safety Committee (L. I. Dana, C. E. Center, G. Failla, and A. G. Cranch), August 13. [SRDB Ref ID: 12382, p. 23]
- Cranch, A. G., 1944a, "Ceramics Plant Safe Practices," letter to S. P. Murphy (Linde Air Products Company), Industrial Toxicology Branch, New York, New York, March 3. [SRDB Ref ID: 16979, p. 71]
- Cranch, A. G., 1944b, "Physical Examination Program – Ceramics Plant," letter to S. P. Murphy (Linde Air Products Company), New York, New York, January 4. [SRDB Ref ID: 12382, p. 13]
- Cranch, A. G., 1944c, untitled letter to S. P. Murphy (Linde Air Products Company), New York, New York, February 2. [SRDB Ref ID: 12382, p. 10]
- Dana, L. T., 1941, untitled letter to Leo Szilard (Columbia University), Tonawanda Laboratory, Tonawanda, New York, July 18. [SRDB Ref ID: 14615]
- DOE (U.S. Department of Energy), 2000, *Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities*, DOE Standard, DOE-STD-1136-2000, Washington, D.C., August. [SRDB Ref ID: 4617]

- DOE (U.S. Department of Energy), undated, *Elimination Report for the Former Electro Metallurgical Company, Niagara Falls, New York*, draft report, Formerly Utilized Sites Remedial Action Program. [SRDB Ref ID: 9036, p. 21]
- Dreveskracht, L. R., 1945, "Record of Negotiations, Linde Air Products Company, Contract No. W-17-028 Eng 29," U.S. Army Corps of Engineers, May 21. [SRDB Ref ID: 16979, p. 278]
- Dupree, B., 1983a, "Visit with [Name redacted; Privacy Act information], Tonawanda Area Director of Uranium Development," memorandum to Linde File, Linde Vol. 2, M.S. 8/1, Oak Ridge Associated Universities, Oak Ridge, Tennessee, March 15. [SRDB Ref ID: 3923]
- Dupree, B., 1983b, "Meeting with Six Linde Employees Who Worked in the Ceramics Plant: (Revised)," AU0004820 CD, memorandum to Linde File, Oak Ridge Associated Universities, Oak Ridge, Tennessee, May 25. [SRDB Ref ID: 3908, p. 4]
- Dupree, E. A., 1981, "Interview with [Name redacted; Privacy Act Information], A Former Linde Employee," memorandum to Linde File, Oak Ridge Associated Universities, Oak Ridge, Tennessee, April 10. [SRDB Ref ID: 3745, p. 16]
- Dupree, E. A., 1983c, "Linde Ceramics Plant: Interview with [Name redacted; Privacy Act Information]," AU0004849, memorandum to Linde Ceramics Plant File, Oak Ridge Associated Universities, Oak Ridge, Tennessee, December 2. [SRDB Ref ID: 3900, p. 4]
- Eisenbud, M., 1950, "Release of Linde Step #1 and #2 Building," memorandum to F. H. Belmore, U.S. Atomic Energy Commission, New York Operations Office, March 29. [SRDB Ref ID: 8836, p. 1]
- Eisenbud, M., 1954, memorandum to Paul B. Pew, Linde Air Products Company, July 12. [SRDB 35732, p. 11]
- Elliott, L. J., 2006, letter to Peter M. Turcic, Office of Compensation Analysis and Support, National Institute for Occupational Safety and Health, Cincinnati, OH, February 23. [SRDB Ref ID: 48222]
- Ferry, J. L., 1944a, "Inspection of Linde Ceramics Plant, Tonawanda, New York," memorandum to the Maj. J. E. Vance, EIDMM-3a, U.S. Engineer Office, Madison Square Area, New York, New York, June 3. [SRDB Ref ID: 5869, p. 3]
- Ferry, J. L., 1944b, "Progress Report of the Special Materials Division of the Medical Section," memorandum to S. L. Warren (Knoxville, Tennessee), U.S. Engineer Office, New York, New York, January 3. [SRDB Ref ID: 14490, p. 3]
- Ferry, J. L., 1944c, "Radiation Hazards," memorandum to Area Engineer, Tonawanda Area EIDMM-3a, U.S. Engineer Office, New York, New York, , February 29. [SRDB Ref ID: 5894, p. 3]
- Ferry, J. L., 1944d, "Gamma Radiation at Linde Ceramics Plant, " memorandum to the Area Engineer, U.S. Engineer Office, New York, New York, June 3. [SRDB Ref ID: 16650, p. 3]
- Ferry, J. L., 1944e, "Medical Hazard from Radiation" memorandum to the Area Engineer, Tonawanda Area, U.S. Engineer Office, New York, New York, , April 20. [SRDB Ref ID: 8980, p. 9]

- Ferry, J. L., 1944f, "Medical Survey of the Linde Ceramics Plant," memorandum to the Area Engineer, Madison Square Area, Tonawanda, New York, from Medical Corps, March 21. [SRDB Ref ID: 8980, p. 3]
- Frame, P. W., J. D. Berger, C. F. Riemke, L. A. Young, W. O. Helton, R. D. Condra, and C. F. Weaver, 1981, *Radiological Survey of the Liquid Disposal Pathways Formerly Used by Linde Air Products Division (Union Carbide Corporation) Tonawanda, New York, Oak Ridge Associated Universities, Oak Ridge, Tennessee, October 8.* [SRDB Ref ID: 16979, p. 773]
- Gates, M. E., 1946, "Description of Uranium Producing Processes," memorandum to the Area Engineer (Madison Square, New York, New York), U.S. Army Corps of Engineers, Manhattan District, Oak Ridge, Tennessee, October 17. [SRDB Ref ID: 16979, p. 79]
- Hadlock, C., 1944, "Radiation Hazards," memorandum to Area Engineer, Tonawanda Area, EIDM-0-27-a-MB, U.S. Engineer Office, Madison Square Area, March 5. [SRDB Ref ID: 8980, p. 26]
- Harris, W. B., 1952, "Dismantlement of Linde Air Products Co., Contract No. AT-(30-1)-GEN-165, Radiation Survey of November 17-20, 1952," memorandum to F. B. Belmore, U.S. Army Corps of Engineers, December 18. [SRDB Ref ID: 11142, pp. 15-17 and 22-23]
- Harris, W. B., 1954, "Decontamination of Linde Air Products Co., Contract No. AT-(30-1)-GEN-165, Radiation Survey of April 11-15, 1954," memorandum to R. L. Kirk, U.S. Atomic Energy Commission, New York Operations Office, April 23. [SRDB Ref ID: 11142, p. 2]
- Hayden, R. E., 1948, "Dust Hazards at Linde Air Products Ceramics Plant," memorandum to Merrill Eisenbud (U.S. Army Corps of Engineers), U.S. Atomic Energy Commission, May 27. [SRDB Ref ID: 9839, p. 178]
- Heatherton, R. C., 1947, "Progress Report, Health Physics Department," Linde Air Products Company, Kenmore, New York, December 21. [SRDB Ref ID: 7665, p. 90]
- Heatherton, R. C., 1948a, "Progress Report," Linde Air Products Company, Kenmore, New York, , December 20. [SRDB Ref ID: 14524, p. 54]
- Heatherton, R. C., 1948b, untitled letter to R. E. Hayden (U.S. Atomic Energy Commission), Linde Air Products Company, Kenmore, New York, June 14. [SRDB Ref ID: 16316, p. 22]
- Heatherton, R. C., 1948c, "Health Physics Department Progress Report," Linde Air Products Company, Kenmore, New York, April 12. [SRDB Ref ID: 14524, p. 106]
- Heatherton, R. C., 1948d, "Health Physics Department Progress Report," Linde Air Products Company, Kenmore, New York, April 19. [SRDB Ref ID: 14524, p. 105]
- Heatherton, R. C., 1948e, "Health Physics Department Progress Report," Linde Air Products Company, Kenmore, New York, May 3. [SRDB Ref ID: 14524, 103]
- Heatherton, R. C., 1948f, untitled letter to B. S. Wolf (U.S. Atomic Energy Commission), Linde Air Products Company, Kenmore, New York, March 4. [SRDB Ref ID: 16979, p. 110]
- Heatherton, R. C., 1948g, "Monthly Report, Health Physics for January 1948, L.A.P. Contract W7401 Eng. 14," letter to Medical Advisor's Office (Office of New York Directed Operations), Linde Air Products Company, Kenmore, New York, February 16. [SRDB Ref ID: 16979, p. 90]

- Heatherton, R. C., 1948h, "Health Physics Department Progress Report," Linde Air Products Company, Kenmore, New York, February 9. [SRDB Ref ID: 7665, p. 77]
- Heatherton, R. C., 1949a, "Unloading K-65 from Railroad Car at Modeltown," letter to B. S. Wolf (U.S. Atomic Energy Commission), Linde Air Products Company, Kenmore, New York, March 25. [SRDB Ref ID: 3943, p. 1]
- Heatherton, R. C., 1949b, "Progress Report, " Linde Air Products Company, Kenmore, New York, May 9. [SRDB Ref ID: 14524, p. 18]
- Heatherton, R. C., 1949c, "Progress Report, " Linde Air Products Company, Kenmore, New York, July 18. [SRDB Ref ID: 14524, p. 5]
- Heatherton, R. C., 1949d, "Progress Report, " Linde Air Products Company, Kenmore, New York, July 25. [SRDB Ref ID: 7678, p. 3]
- Heatherton, R. C., 1949e, "Progress Report," Linde Air Products Company, Kenmore, New York, June 13. [SRDB Ref ID: 7678, p. 12]
- Heatherton, R. C., 1949f, "Progress Report," Linde Air Products Company, Kenmore, New York, June 20. [SRDB Ref ID: 7678, p. 10]
- Heatherton, R. C., 1950, *Decontamination and Survey of Uranium Refinery Plant*, U.S. Atomic Energy Commission, NYO-1536, December 14. [SRDB Ref ID: 16847, p. 133]
- HHS (Health and Human Services), 2005, *Designating a Class of Employees from Linde Ceramics Plant, Niagara Falls, NY*, December 8. [SRDB Ref ID: 48223]
- Hickey, J. L. S., D. Crawford-Brown, and W. G. Tankersley, 1988, *Occupational Exposure of Workers to Chemicals and Radiation During Uranium Processing at the Linde Ceramics Plant 1943-1949*, ORAU 88/A-16, Oak Ridge Associated Universities, Oak Ridge, Tennessee, January. [SRDB Ref ID: 9834]
- Holmes, A. R. 1944a, "Physical Examination Program – Ceramics Plant," letter to S. P. Murphy, Linde Air Products Company, Tonawanda, New York, February 10. [SRDB Ref ID: 12382, p. 7]
- Holmes, A. R. 1944b, untitled letter to E. L. Van Horn (U.S. Engineer Office), Linde Air Products Company, Tonawanda, New York, November 14. [SRDB Ref ID: 12382, p. 5]
- Holmes, A. R. 1944c, untitled letter to S. P. Murphy, Linde Air Products Company, Tonawanda, New York, January 26. [SRDB Ref ID: 12382, p. 11]
- Howland, J. W., 1946, "Possible Hazards at Linde Ceramics and Electro-Metallurgical Plants," memorandum to the Area Engineer, U.S. Engineer Office, Rochester, New York, November 19. [SRDB Ref ID: 9849]
- Hunter, D., 1949, "Record of Negotiations for Supplemental Agreement to Contract W-7405 Eng-276, Harshaw Chemical Company," memorandum to J. C. Clarke, September 26. [SRDB Ref ID: 16847, p. 13]
- ICRP (International Commission on Radiological Protection), 1981, *Limits for Inhalation of Radon Daughters by Workers*, Publication 32, Pergamon Press, Oxford, England.

- ICRP (International Commission on Radiological Protection), 1994, *Human Respiratory Tract Model for Radiological Protection*, Publication 66, Pergamon Press, Oxford, England.
- Jenness, L. G., and R. Ewing, 1943, *Summary of Research, Development, and Pilot Plant Operation at the Laboratory of the Linde Air Products Company, Tonawanda, New York, October 1942 to November 1943*, attachment to letter from J. F. Eversole to P. B. Pew, Linde Air Products Company, Tonawanda, New York, November 11. [SRDB Ref ID: 3744, pp. 29-33]
- Kent, E. C., 1947, "Plant Progress Report, September – 1947," letter to A. R. Holmes, Linde Air Products Company, Tonawanda, New York, October 1. [SRDB Ref ID: 8954, pp. 212-220]
- Kent, E. C., 1949a, "Ceramics Plant Progress Report for Week Ending March 27, 1949," Linde Air Products Company, Tonawanda, New York, March 28. [SRDB Ref ID: 9839, p. 145]
- Kent, E. C., 1949b, "Ceramics Plant Progress Report for Week Ending July 24, 1949," Linde Air Products Company, Tonawanda, New York, July 26. [SRDB Ref ID: 16979, p. 31]
- Kent, E. C., 1949c, untitled letter to F. J. Epp (U.S. Atomic Energy Commission), Linde Air Products Company, Tonawanda, New York, June 7. [SRDB Ref ID: 12382, p. 4]
- Klevin, P. B., 1949a, *Occupational Exposure to Radioactive Dust, Linde Air Products*, U.S. Atomic Energy Commission, New York Operations Office, New York, New York, January 25. [SRDB Ref ID: 9119]
- Klevin, P. B., 1949b, *Occupational Exposure to Radioactive Dust, Linde Air Products*, U.S. Atomic Energy Commission, New York Operations Office, New York, New York, August 1. [SRDB Ref ID: 8857]
- LAPC (Linde Air Products Company), 1942, *Laboratory Directory*, Linde Air Products Company, Tonawanda, New York, September 2. [SRDB Ref ID: 16318, p. 23]
- LAPC (Linde Air Products Company), 1943–1946, miscellaneous reports of dust uranium concentrations at Linde Ceramics Plant, Tonawanda, New York. [SRDB Ref ID: 3744, pp. 83–85; 5791, pp. 3–30; 5876, pp. 6–7; 7720, p. 4; 7721, p. 4; 16716, p. 11; 8980, pp. 6–8]
- LAPC (Linde Air Products Company), 1944a, "MD Personnel," Tonawanda, New York, September 20. [SRDB Ref ID: 8947, p. 4]
- LAPC (Linde Air Products Company), 1944b, "Requisition for Material," 434898, Tonawanda, New York, November 6. [SRDB Ref ID: 8941, p. 3]
- LAPC (Linde Air Products Company), 1944–1945, miscellaneous reports of breath radon measurements for Linde Ceramics workers, Tonawanda, New York. [SRDB Ref ID: 5908, p. 3; 5875, pp. 3 and 5; 8982, pp. 3–8; 5872, pp. 3–5; 8801, pp. 3–7]
- LAPC (Linde Air Products Company), 1944–1946, miscellaneous reports of radon concentrations at Linde Ceramics Plant, Tonawanda, New York. [SRDB Ref ID: 8803, pp. 17, 20, 22, 31, 32, 34–36; 16650, pp. 23, 24, 33, 34, 39, 40; 14499, pp. 5–7, 10, 11, 13; 5875, pp. 7, 10, 11, 13, 14; 5876, pp. 2–13; 5894, pp. 11–14; 16716, pp. 5, 8, 13, 16, 19, 22, 26; 8980, p. 7]
- LAPC (Linde Air Products Company), 1945a, "Property Location Plan, Ceramics Plant Area," Drawing AMX-1[illeg.], Tonawanda, New York, April 10. [SRDB Ref ID: 11142, p. 38]

- LAPC (Linde Air Products Company), 1945b, *Job Descriptions Ceramics Plant*, Tonawanda, New York, December 7. [SRDB Ref ID: 3744, p. 115]
- LAPC (Linde Air Products Company), 1945c, *Linde Industrial Hazard Bulletin*, Tonawanda, New York, March 7. [SRDB Ref ID: 16717, p. 16]
- LAPC (Linde Air Products Company), 1946a, *Step II Construction, Process and Operation Report*, Tonawanda, New York, October 1. [SRDB Ref ID: 3746]
- LAPC (Linde Air Products Company), 1946b, *Step III Construction, Process and Operation Report*, Tonawanda, New York, October 1. [SRDB Ref ID: 3750]
- LAPC (Linde Air Products Company), 1946c, *Final Report in Accordance with the Terms of Contract No. W-7401-eng-14 – Ceramics Section*, Tonawanda, New York, May 10. [SRDB Ref ID: 7652; contains Export Controlled Information]
- LAPC (Linde Air Products Company), 1946d, *Final Report on Conversion of K-25 Process Gas to Uranium Trioxide, for Contract No. W-7405 Eng. 26, Sub No. 2*, Tonawanda, New York, May 3. [SRDB Ref ID: 3778; contains Export Controlled Information]
- LAPC (Linde Air Products Company), 1946e, *Step I Construction, Process and Operation Report*, Tonawanda, New York, October 1. [SRDB Ref ID: 3735]
- LAPC (Linde Air Products Company), 1947–1950, miscellaneous reports of uranium and fluorine urinalysis data for Linde Ceramics workers, Tonawanda, New York. [SRDB Ref ID: 11148, pp. 1–29; 8955, pp. 1–48]
- LAPC (Linde Air Products Company), 1948, Ceramics Plant Progress Reports for the weeks ending February 29, 1948, through April 11, 1948, Tonawanda, New York. [SRDB Ref ID: 9839, pp. 35–57]
- LAPC (Linde Air Products Company), undated a, "Linde Steps I and II," Tonawanda, New York. [SRDB Ref ID: 8836, p. 16]
- LAPC (Linde Air Products Company), undated b, file "linde_fb_sep84," Tonawanda, New York. [SRDB Ref ID: 4111]
- Marshall, J. C., 1943, "Contractor: The Linde Air Products Company, New York, New York; Contract for: Design, Engineering, Construction, Equipping, and Operation of a plant for the production of various products," Contract No. W-7401 eng-14, U.S. Army Corps of Engineers, January 18. [SRDB Ref ID: 16979, p. 345]
- Martin, J. L., 1945, untitled letter, to E. W. Moscript (U.S. Army Engineer), Linde Air Products Company, Tonawanda, New York, November 16. [SRDB Ref ID: 16979, p. 300]
- Mason, M. G., 1958, *Symposium on Occupational Health Experience and Practices in the Uranium Industry: Session I – A Summary of Fifteen Years of Experience with Dust Problems in the Refining and Fabrication of Uranium*, [SRDB Ref ID 7886, pp. 17-23]
- MED (Manhattan Engineer District), undated a, Data Sheets for Industrial Hazard Rating, Linde Ceramics Plant, Substance: Ore, Medical Section. [SRDB Ref ID: 16713, pp. 3-45]

- Medhurst, A. E., 1949, untitled letter to M. Trost (Linde Air Products Company), Langtry Photo Service, Buffalo, New York, August 12. [SRDB Ref ID: 12383, pp. 28-29]
- MicroShield Team, 2003, *MicroShield Version 6 User's Manual*, Grove Engineering, Rockville, Maryland,.
- Murphy, S. P., 1945, "Safety Precautions, Ceramics Plant," memorandum to T. J. Coleman, Linde Air Products Company, Tonawanda, New York. [SRDB Ref ID: 16979, p. 610]
- Neuman, F. L., 1944, untitled letter to W. G. Thomas, Linde Air Products Company, Tonawanda, New York, April 26. [SRDB Ref ID: 7658]
- NIOSH (National Institute for Occupational Safety and Health), 2004, *Estimation of Ingestion Intakes*, OCAS-TIB-009, Rev. 0, Office of Compensation Analysis and Support, Cincinnati, Ohio, April 13.
- NIOSH (National Institute for Occupational Safety and Health), 2007a, *Radiation Exposures Covered for Dose Reconstructions Under Part B of the Energy Employees Occupational Illness Compensation Program Act*, OCAS-IG-003, Rev. 0, Office of Compensation Analysis and Support, Cincinnati, Ohio, November. [SRDB Ref ID: 35987]
- NIOSH (National Institute for Occupational Safety and Health), 2007b, *External Dose Reconstruction Implementation Guideline*, OCAS-IG-001, Rev. 3, Office of Compensation Analysis and Support, Cincinnati, Ohio, November.
- NIOSH (National Institute for Occupational Safety and Health), 2007c, *NIOSH Response: Linde TBD Issues*, Office of Compensation Analysis and Support, Cincinnati, Ohio, November 29.
- NYOO (New York Operations Office), 1949, *Monthly Status Report for March, 1949*, New York, April 7. [SRDB Ref ID: 6291, p. 66]
- Olevitch, E., 1944, *Step I - L-30 Ore*, July 15. [SRDB Ref ID: 3740, p. 40]
- ORAUT (Oak Ridge Associated Universities Team), 2005a, *Estimation of Neutron Dose Rates from Alpha-Neutron Reactions in Uranium and Thorium Compounds*, ORAUT-OTIB-0024, Rev. 00, Oak Ridge, Tennessee, April 7.
- ORAUT (Oak Ridge Associated Universities Team), 2005b, *Dose Reconstruction from Occupationally Related Diagnostic X-Ray Procedures*, ORAUT-OTIB-0006, Rev. 03 PC-1, Oak Ridge, Tennessee, December 21.
- ORAUT (Oak Ridge Associated Universities Team), 2005c, *Technical Information Bulletin: Estimation of Radium-226 Activity in the Body from Breath Radon-222 Measurements*, ORAUT-OTIB-0025, Rev. 00, Oak Ridge, Tennessee, April 5.
- ORAUT (Oak Ridge Associated Universities Team), 2005d, *Technical Information Bulletin: Analysis of Coworker Bioassay Data for Internal Dose Assignment*, ORAUT-OTIB-0019, Rev 01, Oak Ridge, Tennessee, October 7. [SRDB Ref ID: 19438]
- ORAUT (Oak Ridge Associated Universities Team), 2006, *Generating Summary Statistics for Coworker Bioassay Data*, ORAUT-PROC-0095, Rev. 00, Oak Ridge, Tennessee, June 5.

- ORNL (Oak Ridge National Laboratory), 1978, *Formerly Utilized MED/AEC Sites Remedial Action Program, Radiological Survey of the Former Linde Uranium Refinery, Tonawanda, New York, Final Report*, DOE/EV-0005/5, Oak Ridge, Tennessee, May. [SRDB Ref ID: 14620]
- Osinski, V., 1948a, "Ceramics Plant Progress Report for the Week Ending on January 4, 1948," Linde Air Products Company, Tonawanda, New York, January 6. [SRDB Ref ID: 9839, p. 13]
- Osinski, V., 1948b, "Ceramics Plant Progress Report for the Week Ending March 21, 1948," Air Products Company, Tonawanda, New York, March 22. [SRDB Ref ID: 9839, p. 44]
- Pew, P. B., 1943, untitled letter to G. Vanden Buick (U.S. Engineer Office), July 20. [SRDB Ref ID: 3875, pp. 1-5]
- Pilon, R. L., 2004, untitled attachment to "RE: Request or Information on Linde Site Cleanup and Remediation," e-mail to G. R. Davidson, October 8. [SRDB Ref ID: 14580]
- Rehm, C. W., 1944a, untitled letter to E. L. Van Horn, (Area Engineer, Tonawanda Area), Linde Air Products Company, Tonawanda, New York, June 19. [SRDB Ref ID: 3744, pp. 83-85]
- Rehm, C. W., 1944b, untitled letter to S. P. Murphy, Linde Air Products Company, May 6. [SRDB Ref ID: 3956, p. 1]
- Reilly, D., N. Ensslin, H. Smith, Jr., and S. Kreiner, editors, 1991, *Passive Nondestructive Assay of Nuclear Materials*, NUREG/CR-5550, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, D.C., March. [SRDB Ref ID: 16525]
- Rennich, G., 1947, "Uranium-Thorium Branch Semi-Annual Report to Congress," memorandum to E. M. Velten, AECPR-21, U.S. Atomic Energy Commission, New York, New York, December 1. [SRDB Ref ID: 10256, pp. 8-11]
- Robinson, B. W., 1945, "Sampling and Weighing of Material Purchased from LAP Under Contract W-17-028 eng 29," memorandum to files, Manhattan Engineering District, August 20. [SRDB Ref ID: 16979, p. 297]
- Salmon, R., and O. W. Hermann, 1992, *ALPHN: A Computer Program for Calculating (α , n) Neutron Production in Canisters of High-Level Waste*, ORNL/TM-12239, Martin Marietta Energy Systems, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October. [SRDB Ref ID: 14588]
- SC&A (S. Cohen & Associates), 2006, *Review of the NIOSH Site Profile for the Linde Ceramics Plant and Tonawanda Laboratory, Tonawanda, New York*, SCA-TR-TASK1-0014, Vienna, Virginia, July 14.
- SC&A (S. Cohen & Associates), 2008, *SC & A Assessment of NIOSH Response: LINDE TBD Issues November 29, 2007*, working draft, Vienna, Virginia, January 3.
- Shleien, B., L. A. Slaback, Jr., and B. K. Birky, editors, 1998, *Handbook of Health Physics and Radiological Health, Third Edition*, Williams & Wilkins, Baltimore, Maryland, January.
- Skinner, G. M., 1944, *Radiation Measurements in the Proving Laboratory During Processing of African Pitchblende Ore*, Research Notes No. 275, Linde Air Products Company, Tonawanda, New York, February 11. [SRDB Ref ID: 8910]

- Stewart, R. S., 1952, *Production Report on the Rolling of Two Hundred and Eighteen Uranium Billets at Bethlehem Steel Corporation's Lackawanna Plant on March 15, 1952*, National Lead Company of Ohio, Lackawanna, New York, March 21. [SRDB Ref ID: 11582, p. 37]
- Strom, D. J., and P. S. Stansbury, 2000, "Determining Parameters of Lognormal Distributions from Minimal Information," *American Industrial Hygiene Association Journal*, volume 61, pp. 877-880. [SRDB Ref ID: 13722]
- Thomas, W. G., 1944, "Radiation Hazards," memorandum to C. Hadlock, EIDM-T-12, Office of the Area Engineer, Tonawanda, New York, March 8. [SRDB Ref ID: 8980, p. 24]
- Turcic, P. M., 2007, "Linde Ceramics Plant," EEOICPA Circular No. 07-07, U.S. Department of Labor, Washington, D.C. [SRDB Ref ID: 40373]
- Turcic, P. M., 2008, memorandum to P. R. Worthington, U.S. Department of Labor, Washington, D.C., May 21.
- Tybout, R. A., 1944a, "Visit to Tonawanda Area – 18 and 19 October 1944," Lt. J. Howland, October 20. [SRDB Ref ID: 8980, p. 21]
- Tybout, R. A., 1944b, "Results of Breath Sample Analyses," memorandum to the District Engineer (U.S. Engineer Office), Corps of Engineers, August 15. [SRDB Ref ID: 8982, p. 6]
- Tybout, R. A., 1945a, "Dust Exposure to Loaders," memorandum to Maj. J. L. Ferry, U.S. Engineer Office, Rochester Area, Rochester, New York, May 23. [SRDB Ref ID: 5873, p. 3]
- Tybout, R. A., 1945b, "Dust Sample Results from Chandler Plant," memorandum to Capt. Fred A. Bryan, EIDMM-4c, EIDMM-2b, MD723.1, U.S. Engineer Office, Manhattan District, Rochester, New York, May 4. [SRDB Ref ID: 16979, p. 678]
- Tybout, R. A., 1945c, "Industrial Health Control Tests," memorandum to the Area Engineer, U.S. Engineer Office, Manhattan District, Rochester, New York, March 12. [SRDB Ref ID: 16650, pp. 42-43]
- UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 1993, *Sources and Effects of Ionizing Radiation*, UNSCEAR 1993 Report to the General Assembly, with Scientific Annexes, United Nations, New York, New York.
- USA (United States of America), 1944, "Supplemental Agreement No. 4 to Contract No. W-7401 eng-14, with Linde Air Products Company," August 16. [SRDB Ref ID: 16979, p. 335]
- USACE (U.S. Army Corps of Engineers), 1998, *Demolition of Linde FUSRAP Site Building 30 Complete*, News Release #98-46, Buffalo, New York, September 21. [SRDB Ref ID: 14577]
- USACE (U.S. Army Corps of Engineers), 2002, *Fact Sheet Former Linde Site Tonawanda, New York*, Formerly Utilized Sites Remedial Action Program (FUSRAP), Buffalo, New York, October. [SRDB Ref ID: 14628]
- USACE (U.S. Army Corps of Engineers), 2003, *Record of Decision for the Building 14 Operable Unit, Linde Site, Tonawanda, New York*, Buffalo, New York, April. [SRDB Ref ID: 14623]
- USACE (U.S. Army Corps of Engineers), 2004, *Air Monitoring Data*, Buffalo, New York. [SRDB Ref ID: 14703]

- USEO (U.S. Engineer Office), 1945, "Contract to Linde Air Products Company, New York, New York," W-17-028 eng-29, War Department, Madison Square Area, New York, New York, May 4. [SRDB Ref ID: 16979, p. 266]
- Van Horn, E. L., Capt., 1943a, untitled letter to T. J. Coleman (Linde Air Products Company), U.S. Army Corps of Engineers, September 4. [SRDB Ref ID: 8908, p. 5]
- Van Horn, E. L., Capt., 1943b, untitled letter to Dr. E. L. McCandless (Linde Air Products Company), War Department, U.S. Engineer Office, Kenmore, New York, September 9. [SRDB Ref ID: 7686, p. 10]
- Van Horn, E. L., Capt., 1945, untitled letter to A.R. Holmes (Linde Air Products Company), U.S. Engineer Office, Kenmore, New York, February 22. [SRDB Ref ID: 21817]
- Various authors, 1950, file containing medical and other records related to a workmen's compensation claim against Linde. [SRDB Ref ID: 11156]
- Wallace, P., 2003, "Notes on Linde Data," Center for Epidemiologic Research, Oak Ridge Associated Universities, Oak Ridge, Tennessee, August 18. [SRDB Ref ID: 4107]
- Warren, S. L., 1944, "Routine Pelvic Films on Special Materials Employees," memorandum to Area Engineer, EIDMM-3, Manhattan District, New York, New York, January 11. [SRDB Ref ID: 5815, p. 4]
- Wiesendanger, R., 1944, *Pilot Plant Operations on African Ore, Tonawanda Laboratory, Linde Air Products Company, Tonawanda, New York*, M-4541, U.S. Atomic Energy Commission, May 26. [SRDB Ref ID: 3757]
- Wilson, R. H., 1959, "The Hanford Uranium Bio-assay Program," *Symposium on Occupational Health Experience and Practices in the Uranium Industry, Held in New York City, October 15 – 17, 1958*, HASL-58, U.S. Atomic Energy Commission, New York Operations Office, New York, New York, September, p. 77. [SRDB Ref ID: 7886, p. 89]
- Wolf, B. S., 1948, "Results of Uranium and Fluoride Analyses," letter to R. C. Heatherton (Linde Air Products Company), U.S. Atomic Energy Commission, New York, New York, February 27. [SRDB Ref ID: 16979, pp. 96-98]
- Wolf, B. S., 1949a, "Linde Air Products Co., Division of Union Carbide & Carbon Corp, Ceramics Plant, Tonawanda, N.Y. – Decontamination of Main Building," memorandum to F. M. Belmore, U.S. Atomic Energy Commission, New York, New York, May 12. [SRDB Ref ID: 16316, p. 13]
- Wolf, B. S., 1949b, untitled letter to E. O. Kent (Linde Air Products Company), U.S. Atomic Energy Commission, New York, New York, March 16. [SRDB Ref ID: 16316, p. 17]

GLOSSARY

carnotite

Mineral of the form $K_2(UO_2)_2(VO_2)_2 \cdot 3(H_2O)$ found in Colorado and Utah and mined for its uranium and vanadium content. Much of the domestic ore processed at Linde Ceramics Plant derived from tailings from carnotite ore. Preprocessing of this material before shipment is believed to have removed much of its radium content (Aerospace Corporation 1981).

day (d)

As used in this Linde document, a day refers to a calendar day unless otherwise described. A calendar day is any 24-hour day in a year. There are at least 365 calendar days in a year. A workday (wd) refers to a day that is assigned for work. The length of a workday depends on the amount of time spent on the job. Default assumptions are that there are 8 hours in a workday and 250 workdays in a year. At Linde, the number of hours per workday and the number of workdays per year for some employees were higher than the defaults for the early years.

Linde database

Set of records of Linde Ceramics Plant operations available to the National Institute for Occupational Safety and Health dose reconstruction project.

N.G. or NG Cake

Filter cake produced in Step II processing at Linde. There were two types of cakes produced called OK and N.G.

pitchblende

Mineral containing uranium oxide (UO_x) of variable composition ranging between UO_2 and U_3O_8 as well as radium. Raw ore from Africa was processed for its uranium content at Linde Ceramics Plant the raw ore was not preredefined and so contained all of the natural uranium radioactive progeny including radium.

Step I, Step II, and Step III

Sequential uranium production processes at Linde:

- Step I, conversion of ore to U_3O_8 (black oxide)
- Step II, conversion of U_3O_8 to UO_3 (orange oxide) to UO_2 (brown oxide)
- Step III, conversion of UO_2 to UF_4 (green salts)

torbernite

Mineral in the form of $Cu(UO_2)_2(PO_4)_2 \cdot 8-12(H_2O)$ processed for its uranium content. Like the African pitchblende processed at Linde, torbernite was not preredefined before its arrival at Linde and so contained all of the natural uranium radioactive progeny including radium.

**ATTACHMENT A
BETA RADIATION**

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This attachment contains data that was used in analyzing exposures of workers to beta radiation.

Table A-1. Maximum beta surface dose rates from various uranium-containing materials.

Source	Beta surface dose rate	
	mrad/hr ^{a,b}	rad/8 hr
Slab of U metal	233	1.86
UO ₂	207	1.66
UO ₃	204	1.63
U ₃ O ₈	203	1.62
UF ₄	179	1.43

- a. From Table 2-7 on p. 2-18 of DOE (2000).
- b. Beta surface dose rate in air through a polystyrene filter 7 mg/cm² thick.

Table A-2. Electron energy released by refined uranium.

	Principal nuclides	Electron energy per decay of nuclide (MeV/nt) ^a	Electron energy per decay of parent (MeV/nt) ^a	% of total
U-238 series	U-238	0.010	0.005	1.1
	Th-234	0.060	0.029	6.6
	Pa-234m	0.822	0.402	89.8
	U-234	0.013	0.006	1.4
U-235 series	U-235	0.049	0.001	0.2
	Th-231	0.165	0.004	0.8
		Total:	0.447	

- a. nt = nuclear transformation.

**ATTACHMENT A
BETA RADIATION**

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Table A-3. Electron energy released by unrefined natural uranium ore.

	Principal nuclides	Electron energy per decay of nuclide (MeV/nt)^a	Electron energy per decay of parent (MeV/nt)^a	% of total
U-238 series	U-238	0.010	0.005	0.4
	Th-234	0.060	0.029	2.5
	Pa-234m	0.822	0.402	34.7
	U-234	0.013	0.006	0.5
	Th-230	0.015	0.007	0.6
	Ra-226	0.004	0.002	0.2
	Rn-222	0.000	0.000	0.0
	Po-218	0.000	0.000	0.0
	Pb-214	0.293	0.143	12.4
	Bi-214	0.659	0.322	27.8
	Po-214	0.000	0.000	0.0
	Pb-210	0.038	0.019	1.6
	Bi-210	0.389	0.190	16.4
Po-210	0.000	0.000	0.0	
U-235 series	U-235	0.049	0.001	0.1
	Th-231	0.165	0.004	0.3
	Pa-231	0.065	0.001	0.1
	Ac-227	0.016	0.000	0.0
	Th-227	0.053	0.001	0.1
	Ra-223	0.076	0.002	0.1
	Rn-219	0.006	0.000	0.0
	Po-215	0.000	0.000	0.0
	Pb-211	0.456	0.010	0.9
	Bi-211	0.010	0.000	0.0
	Tl-207	0.493	0.011	1.0
	Total:		1.157	

a. nt = nuclear transformation.

ATTACHMENT A BETA RADIATION

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Table A-4. Estimated attenuation of beta radiation with distance.

Distance from surface (m)	Relative dose rate ^a	
	Refined natural uranium ^b	Unrefined natural uranium ore or ore byproducts ^c
0.0	1.00	1.00
0.3	0.80	0.88
0.94	0.50	0.66
1.0	0.48	0.64
1.6	0.31	0.50
2.0	0.23	0.42
3.0	0.11	0.27
5.0	0.025	0.11
8.5 ^d	0.000	0.024
10.0	(e)	0.012
12.6 ^f	(e)	0.000

- a. Only exponential attenuation due to air is considered. Additional reduction would come from geometric dispersion, which is ignored here.
- b. Dose rate assumed to vary with distance as $\exp(-0.0074x)$, where x is distance from the surface in centimeters. This was derived from a fit to data in Coleman, Hudson, and Plato (1983).
- c. Calculated falloff rate based on the assumption that all of the beta radiation is due to the 3.27-MeV beta ray from Bi-214. The dose rate is assumed to vary with distance as $\exp(-0.0044x)$, where x is distance from the surface in cm. The attenuation factor 0.0044/cm was estimated from the rule of thumb that the half thickness of a beta absorber is one-eighth of the range of the beta rays (Cember 1983, p. 97). For natural uranium ore and byproducts with beta emitters other than Bi-214, the actual falloff with distance would be greater because all other significant beta emissions have lower energies than 3.28 MeV.
- d. Range of 2.28-MeV beta radiation per Cember (1983, p. 99).
- e. No radiation at this distance.
- f. Range of 3.27-MeV beta radiation per Cember (1983, p. 100).

Table A-5. Uranium beta dose reduction factors for apparel.

Item ^a	Fraction of beta dose remaining
Leather, medium weight	0.62
White cotton gloves	0.89
"Tyvek" coveralls	0.98
65% Dacron/35% cotton lab coat	0.91

- a. Selected from Table 6-11 on p. 6-23 of DOE (2000).

**ATTACHMENT A
BETA RADIATION**

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Table A-6. Variation of dose rate with body location for Step III process operations.

Operation	(mR/hr) ^a						Radiation level relative to hands, bare ^c
	Hands, bare	Hands, gloved	Face	Chest	Legs	Feet	
Handling empty trays	4	3	1.5	4	(b)	(b)	
Loading trays (brown)	25	13	2	4.5	4.5	2	
Handling loaded trays(brown)	25	13	5	16	(b)	(b)	
Handling loaded trays (green)	25	16	7.5	25	(b)	(b)	
Unloading operation (green)	25	(b)	7.5	7.5	4	2	
Blending	15	10	7	8.5	12	(b)	
	Radiation level relative to chest ^c						
	Hands, bare		Face	Chest	Legs	Feet	Hands, gloved
Handling empty trays	1.00		0.38	1.00	(b)	(b)	0.75
Loading trays (brown)	5.56		0.44	1.00	1.00	0.44	0.52
Handling loaded trays(brown)	1.56		0.31	1.00	(b)	(b)	0.52
Handling loaded trays (green)	1.00		0.30	1.00	(b)	(b)	0.64
Unloading operation (green)	3.33		1.00	1.00	0.53	0.27	(b)
Blending	1.76		0.82	1.00	1.41	(b)	0.67
Maximum	5.56		1.00	1.00	1.41	0.44	

a. Data from Heatherton (1948h).

b. No data.

c. Results in lower half of the table are based on the data in the upper half.

ATTACHMENT B CODES AND SPECIAL TERMINOLOGY

Special codes and terminology were used in correspondence and documents that related to Linde's work for the MED and AEC in place of common names or to specify special forms of materials with particular characteristics. Over the course of time, some terms might have had multiple meanings. Table B-1 lists apparent definitions deduced during preparation of this document.

Table B-1. Codes and special terminology.

Code or term	Apparent meaning
C-103	UO ₂ from DuPont; a feed material used for Linde Step III
C-306	UO ₂ from Mallinckrodt; a feed material used for Linde Step III
C-316	UO ₂ from Mallinckrodt; a feed material used for Linde Step III
F-29	U ₃ O ₈ made at Linde
K-25	UF ₆ gas containing various concentrations of U-235
K-65	Residues containing Ra and Pb that were byproducts of the ore to UO ₃ conversion process at Mallinckrodt Chemical Works
L-19	A domestic ore processed at Linde; estimated to contain mostly 10% to 16.5% U ₃ O ₈ (Aerospace 1981, Table B-1)
L-30	African pitchblende ore; estimated to contain 8% to 12% U ₃ O ₈ (Aerospace 1981, Table B-1)
L-50	African pitchblende ore; estimated to contain 6.7% U ₃ O ₈ (Aerospace 1981, Table B-1)
Mx, MX	Uranium or U ₃ O ₈
MX-308	U ₃ O ₈ (in ore)
My	Radium
Mz, MZ	Radon
O-71	UF ₄
P-65	UO ₂ produced by Linde Step II; a feed material used for Linde Step III
Product 65	P-65
Q-20	Torbernite ore processed at Linde; estimated to contain 17.7% U ₃ O ₈ (Aerospace 1981, Table B-1)
R-10	African pitchblende ore processed at Linde; estimated to contain 3.5% U ₃ O ₈ (Aerospace 1981, Table B-1)
T	Uranium
Tubealloy dioxide	UO ₂
Tubealloy tetrafluoride	UF ₄
X	Uranium or uranium ore

ATTACHMENT C DATA SOURCES ON URANIUM PROGENY CONCENTRATIONS IN LINDE MATERIALS

calculated value
<MDA, mda shown

SRDB Ref ID	Date	Location	Description	U238	U234	U235	totalU	Th230	Ra226	Th232	Th228	Ac227	Pa231	units	Th230/U	Ra226/U	Th232/U	Ac/U	Pa/U		
16294	1995 bldg 14		dry valve pit (dust)	1038	1068	53.8	2159.8	354.7	15.3	2.3	1.7			pCi/g	0.16	0.01	0.00				
			sump (dust)	1.4	1.7	0.07	3.17	0.72	0.52	0.2	0.22					pCi/g	0.23	0.16	0.06		
			corridor overhead (dust)	369	378.8	11.6	759.4	60.2	0.14	5	0.67					pCi/g	0.08	0.00	0.01		
			corridor wall (terra cotta block)	3.2	3.2	0.14	6.54	1.7	1.4	1.4						pCi/g	0.26	0.21	0.21		
14620	1978 bldg 30		air samples during D&D				1.90E-08	2.10E-09	1.10E-09					pCi/ml	0.11	0.06	0.00				
9009	1981 sediment, onsite and offsite		Ellicott Creek	0.82		0.05	1.69	0.6	0.55	0.7					pCi/g	0.36	0.33	0.41			
			Creek1	0.95		0.05	1.95	0.7	0.7	0.8						pCi/g	0.36	0.36	0.41		
			Twomile Creek - upstream	4.3		0.1	8.7	0.92	0.69	0.01						pCi/g	0.11	0.08	0.00		
			Twomile Creek - linde discharge	0.71		0.06	1.48	0.02	0.52	0.02						pCi/g	0.01	0.35	0.01		
			Twomile Creek - downstream	1.5		0.05	3.05	0.96	0.59	0.48						pCi/g	0.31	0.19	0.16		
			Storm Sewer	6.47		0.19	13.13	1.4	1.35	0.62						pCi/g	0.11	0.10	0.05		
			Storm Sewer	99		4.57	202.57	18	6.93	0.51						pCi/g	0.09	0.03	0.00		
			Storm Sewer	13		0.52	26.52	2	1.59	0.65						pCi/g	0.08	0.06	0.02		
			Storm Sewer	116		4.1	236.1	9.9	0.89	0.34						pCi/g	0.04	0.00	0.00		
			Storm Sewer	4.5		0.17	9.17	0.2	0.64	0.39						pCi/g	0.02	0.07	0.04		
			Sanitary Sewer	362		13	737	1.33	1.94	0.11						pCi/g	0.00	0.00	0.00		
			Sanitary Sewer	0.51		0.05	1.07	0.34	0.38	0.21						pCi/g	0.32	0.36	0.20		
			9026	1990 Linde Soils		area 1 - mean	11.2			22.4	7.8	4.3	1.6					pCi/g	0.35	0.19	0.07
area 2 - mean	12.7						25.4	5.7	3.4	1.4					pCi/g	0.22	0.13	0.06			
area 3 - mean	17.1						34.2	24.4	9.4	1.4					pCi/g	0.71	0.27	0.04			
area 4 - mean	46.8						93.6	30.7	9.8	1.4					pCi/g	0.33	0.10	0.01			
8828	1981 Linde Soil and Sediment		near disposal well - subsurface (loc 11)	24.05		0.84	48.94	5.9	5.53	0.92		14.25	0.73		pCi/g	0.12	0.11	0.02	0.29	0.01	
			test well debris (loc 13)	26.4		1.09	53.89	3.53	0.82	0.51		2.1	0.29			pCi/g	0.07	0.02	0.01	0.04	0.01
			Sanitary Sewer (loc 15)	362		12.93	736.93	1.33	1.14	0.11		5.54	0.95			pCi/g	0.00	0.00	0.00	0.01	0.00
			Storm Sewer (loc 19)	99.2		4.57	202.97	17.7	6.93	0.51		14.29	1.14			pCi/g	0.09	0.03	0.00	0.07	0.01
			Storm Sewer (loc 21)	116		4.1	236.1	3.89	0.89	0.34		3.07	0.39			pCi/g	0.02	0.00	0.00	0.01	0.00

ATTACHMENT D
LINDE URANIUM COWORKER ASSESSMENT FOR NOVEMBER 1947 TO JANUARY 1950
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Due to the limited availability of bioassay data from the Linde site, it was necessary to conduct a coworker study of all the bioassay data for use to determine intake estimates. The data that were used in this study were transcribed directly from hardcopy into worksheets. The data in the worksheets were verified (as indicated below), a statistical analysis was conducted and verified, and an intake assessment was conducted and verified. Each of these processes is further described below. The resultant intake tables are provided in the intake assessment section.

Data Verification

The Linde bioassay data were verified as follows:

1. Data were transcribed directly from source documents to spreadsheets by data entry personnel. A review of the datasets was conducted to determine the datasets in each source document (see Table D-1). The data were present in sampling lots (e.g., a group of samples related by sample date).
2. A single, master data spreadsheet was created by merging spreadsheets from individual source documents.
3. A completeness and accuracy review of 100% of the data was conducted by an individual independent of spreadsheet creation. Any discrepancies in data entry were identified and corrected. Two samples in the December 1950 dataset were excluded from further analysis because they were identified as belonging to employees at the electrometallurgical plant (i.e., not Ceramics Plant employees). One sample in the November 1948 dataset was excluded because it was a duplicate (same name and result).

ATTACHMENT D
LINDE URANIUM COWORKER ASSESSMENT FOR NOVEMBER 1947 TO JANUARY 1950
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Table D-1. Linde data sources in the Site Research Database (SRDB).

Period	Samples (count)	SRDB Ref ID		
		8955	11148	16979
Nov-1947 (11/11–11/12)	73	X		
Jan-1948 (01/04–01/06)	88	X	X	X ^a
Feb-1948 (02/20–02/23)	84	X	X	
June-1948 ^b (06/17–06/19)	69	X	X	
Aug-1948 (08/18)	67	X	X	
Nov-1948 (11/12–11/17)	94	X	X	
Feb-1949 (02/07–02/10)	91	X	X ^c	
Apr-1949 (04/11)	4	X		
Jul-1949 (07/01–07/14)	88	X ^d		
Sep-1949 (09/11–09/12)	2	X		
Oct-1949 (10/20)	1	X		
Dec-1949 (12/30)	10	X		
Jan-1950 (01/23–01/27)	9	X		
	680			

a. Pages 97–98 and 696–697 only.

b. Datasheet in SRDB Ref ID 11148 version has handwritten correction of sampling month (from June to May).

c. Dataset is incomplete.

d. Samples are annotated as “termination”.

4. Dataset completeness was evaluated through a review of available data on the Linde urinalysis program.
 - a. The urine data are from transmittals from the laboratory to Linde. Based on a review of each individual dataset, and after referencing was conducted between datasets (using the sample identifiers that did not appear to vary from dataset to dataset), it appeared that each individual dataset was complete.
 - b. A handwritten listing of Linde urine datasets (ca. 1980) was found in the SRDB (Author unknown undated). Based on this listing, one dataset (October 1, 1948) is currently not available.
 - c. The transmittal letter for the February 1948 urine samples (March 4, 1948), clarifies that Linde was to submit quarterly urine samples (instead of monthly, as was previously understood). The frequency of the available Linde urine data are consistent with this pattern (i.e., monthly sampling up to February 1948 and quarterly thereafter).

With the exception of the October 1948 dataset, all known urine data have been included in this study.

Statistical Analysis

The verified data were analyzed in accordance with the requirements in ORAUT-PROC-0095, *Generating Summary Statistics for Coworker Bioassay Data* (ORAUT 2006).

1. The 73 samples collected in November 1947 that were annotated as preemployment were not used in the coworker analysis because preemployment samples would not relate to exposures on the job.

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2. Seven followup samples (four in April 1949, two in September 1949, and one in October 1949) were excluded from statistical analysis. These followup samples indicated a reduction in urinary excretion in every case. Exclusion of these samples is favorable to claimants.
3. Two samples from December 1949 that were labeled "Area Plant - Electrometallurgical" were excluded from analysis because they were not Ceramics Plant employees.
4. One sample from November 1948 was a duplicate sample entry (typographical error) and therefore was excluded from further data analysis.
5. To perform statistical analysis, samples were grouped based on sampling date. Because most of the data were clustered around sampling campaigns, the midpoint of the sampling interval for each sampling event was generally assigned as the effective bioassay date. The effective bioassay dates are used in the Integrated Modules for Bioassay Analysis (IMBA) software to calculate the intake rates.
6. The uranium mass excretion rates were converted to the uranium activity excretion rates by applying the specific activity of natural uranium (683 pCi/mg) and urination rate of 1.4 L/d.
7. The analytical limit of detection was assumed to be 0.01 mg/L. This value is based on annotations on the urine data transmittal memoranda that accompanied most datasets. Because none of the data were explicitly labeled as <LOD, all nonzero data were included in the data ranking and the curve fitting.
8. A lognormal distribution was assumed for the urinary excretion data, and the 50th- and 84th-percentile uranium excretion rates were calculated using the method in ORAUT-PROC-0095 (ORAUT 2006). These excretion rates are listed in Table D-2.

Table D-2. Uranium urinary excretion data (pCi/d).

Period	Number of samples	Effective bioassay date	50th percentile (pCi/d)	84th percentile (pCi/d)
01/04/48–01/06/48	88	01/05/48	20.4	62.0
02/20/48–02/23/48	84	02/21/48	15.8	47.2
06/17/48–06/19/48	69	06/18/48	9.5	15.9
08/18/48	67	8/18/48	4.9	14.1
11/12/48–11/17/48	93	11/14/48	6.5	26.1
02/07/49–02/10/49	91	02/08/49	2.9	14.9
07/01/49–07/14/49	88	07/07/49	10.9	46.4
12/30/49–01/27/50	17	01/13/50	4.9	15.3
	597			

Intake Assessment

Urine results in Table D-2 were used in the intake assessment. Samples from between December 1949 and January 1950 were not used because the July 1949 dataset was labeled as termination samples for the bulk of the Linde employees. All urinary excretion rates were modeled as normally distributed 24-hour urine samples with a uniform relative error of 30%. The excretion data were modeled with IMBA for multiple chronic intakes of Type M or Type S uranium.

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The intake rates, GSDs, and periods to which they apply are listed in Table D-3 for Type M uranium, and in Table D-4 for Type S uranium.

Table D-3. Chronic intake rates for Type M ²³⁴U.

Start date	End date	50th-percentile value (pCi/d)	84th-percentile value (pCi/d)	GSD
11/01/1947	01/27/1950	74	297	4.0

Table D-4. Chronic intake rates for Type S ²³⁴U.

Start date	End date	50th percentile (pCi/d)	84th percentile (pCi/d)	GSD
11/01/1947	01/27/1950	1,884	8,085	4.3

Plots of expected and observed urinary excretion from these fits are shown in Figures D-1 through D-4. In each plot, the solid line represents a fit of the coworker bioassay data.

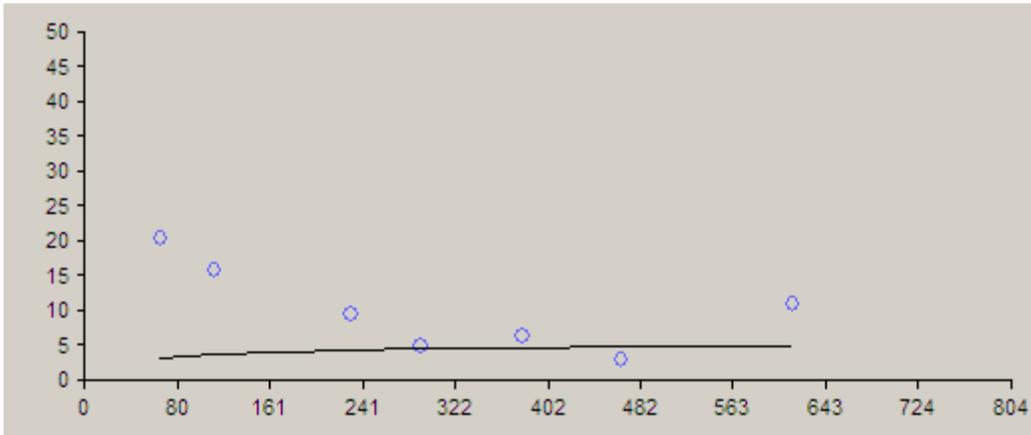


Figure D-1. Type M 50th-percentile value for November 1, 1947, to January 27, 1950.

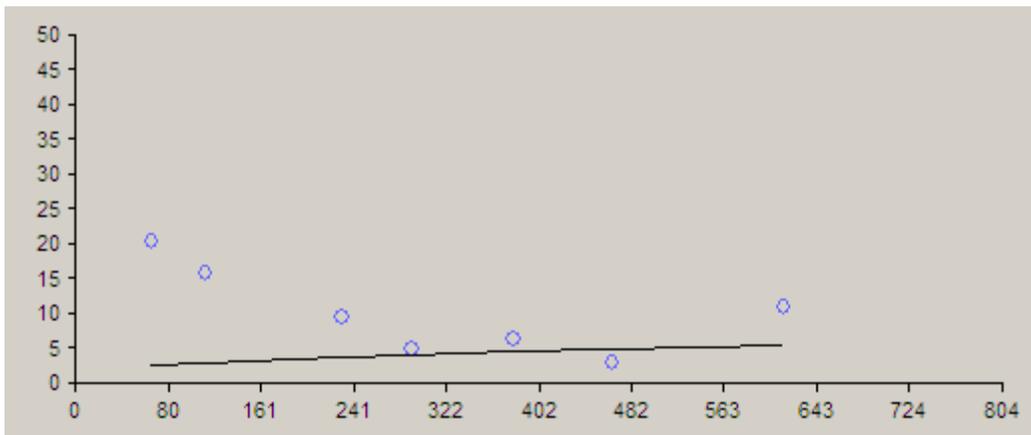


Figure D-2. Type S 50th-percentile value for November 1, 1947, to January 27, 1950.

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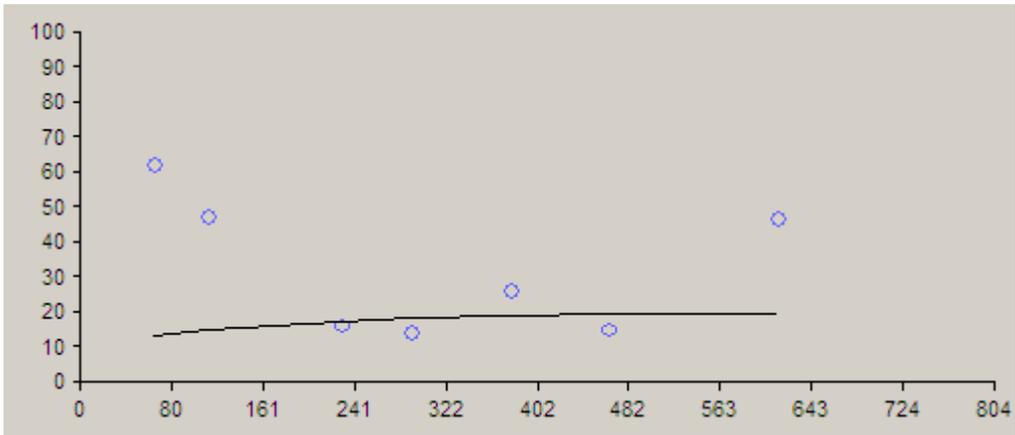


Figure D-3. Type M 84th-percentile value for November 1, 1947, to January 27, 1950.

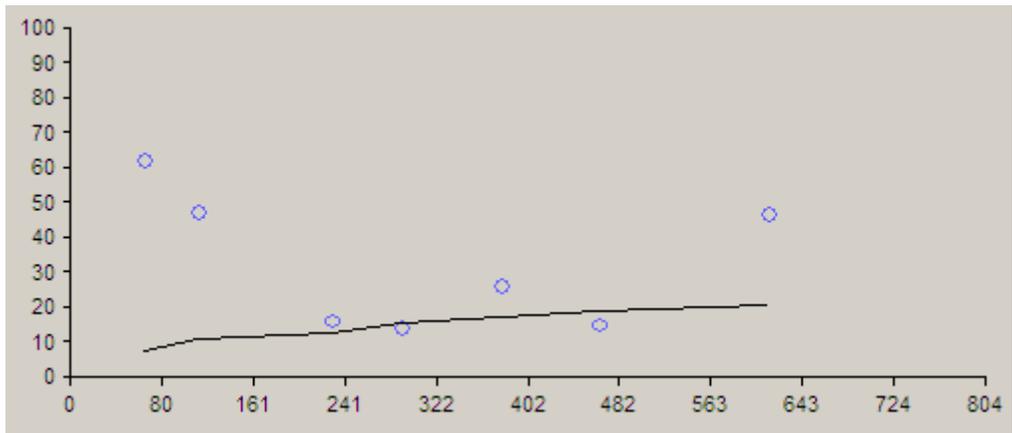


Figure D-4. Type S 84th-percentile value for November 1, 1947, to January 27, 1950.

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Original Issue

During the SC&A-conducted interview in Buffalo, Linde site experts and past workers indicated that there were many thousands of used burlap bags stacked up in the open bay area behind Building 30 (see Attachment 3 of this review report). These bags were used for transporting uranium ore to Linde for processing. After the end of the operation period, the contaminated burlap bags were stored behind Building 30 awaiting disposal. Many Linde workers, operation staff, and administrative personnel sat on these contaminated bags during breaks and lunch periods. This practice continued for many years, exposing many people at close distances to beta and gamma radiation sources left over in the uranium-contaminated burlap bags. The site profile does not estimate the missed beta and gamma doses to workers resulting from sitting on or standing next to those burlap bags. (SC&A 2006)

Subsequent Analysis

During the March 26, 2007, Linde Working Group meeting the burlap bag issue was discussed by members of the working group, NIOSH, and S. Cohen & Associates (SC&A). The following task was defined by the working group (based on SC&A 2006):

NIOSH to investigate details of used burlap bags. Which bags (formerly containing African or domestic ore) were stored at which locations and during which periods of time. This may affect both internal and external exposures. Even though African ores were processed only during the SEC [Special Exposure Cohort] period (pre 10/31/1947), empty bags, that had contained African ore, may have been around longer (i.e., after 1950).

NIOSH to determine whether there was an on-site incinerator to burn used burlap bags and, if so, the possible effects on internal and external exposures.

In November 2007, an analysis of the burlap bag issue was conducted by NIOSH and submitted to the working group along with responses to the other issues that had been identified in the site profile review. Table 5-1 of the response document summarizes the issue and is reproduced below (NIOSH 2007c).

Date	Data Source	Data
Undated	Medical Section, Manhattan District, <i>Data Sheet for Industrial Hazard Rating</i> (MED undated)	<ul style="list-style-type: none"> • Step I material (ore) arrives in burlap bags, covered in paper sacks • Step III material (UO₂) arrives in 75 lb drums
1943–1946	Linde Construction, <i>Operations Report</i> (LAPC 1946c)	<ul style="list-style-type: none"> • Empty bags and drums are held until they can be burned or scrapped • <i>Bags from dry ore are shaken in the bag shaker ... the bags are next taken to the laundry room for washing. All bags are then burned in the incinerator. Ashes from the incinerator are returned to the grinding circuit for processing.</i>

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Date	Data Source	Data
08-25-1943	"Safety Precautions, Ceramics Plant" (Murphy 1945)	<ul style="list-style-type: none"> • <i>Bags in which low-grade ore is received are to be sent back to the original supplier</i> • <i>Bags in which African ore is delivered are to be burned to recover the elements</i>
07-04-1944	"Interview with [Name redacted; Privacy Act Information], a Former Linde Employee," April 10, 1981 (Dupree 1981)	<ul style="list-style-type: none"> • <i>Washing of burlap bags in which the ore was received began</i>
07-15-1944	<i>Step 1 - L-30 Ore</i> (Olevitch 1944)	<ul style="list-style-type: none"> • <i>Empty ore bags contain about ½ lb of ore</i> • <i>Washing burlap bags recovers 70% of material</i> • <i>After washing, the bags are removed, centrifuged, and stored out in the backyard of the plant. To date about 19,000 bags have been washed and stored.</i>
10-10-1944	"Interview with [Name redacted; Privacy Act Information], a Former Linde Employee," April 10, 1981 (Dupree 1981)	<ul style="list-style-type: none"> • <i>Burning of burlap bags in which the ore was received began</i>
10-20-1944	"Visit to the Tonawanda Area, 18 and 19 October 1944" (Tybout 1944a)	<ul style="list-style-type: none"> • <i>The contractor has decided not to use the bag washer for the bags from L-50 (the low grade ore)</i> • <i>The incinerator which will be used for burning the bags was inspected. At the time, it had been in operation only one or two days.</i>
10-??-1944	Interview with [Name redacted; Privacy Act Information], a former Linde employee, April 10, 1981 (Dupree 1981)	<ul style="list-style-type: none"> • <i>The burlap bags had to be disposed of. To control the ore dust that remained in the bags after they were dumped and prevent dust from escaping during their disposal, a series of mechanical devices were installed. First a bag shaker was added to the disposal process to shake out ore dust left behind after dumping. Then a bag washer was installed to wash any material remaining in the bag after it had been shaken. Finally, a bag incinerator was installed to burn the bags after they had been washed. This entire process was completely installed by October, 1944.</i>
02-22-1945	E. L. Van Horn (USACE) to A. R. Holmes (LAPC) (Van Horn 1945)	<ul style="list-style-type: none"> • <i>... It is desired, however, to continue film monitoring on employees engaged in burning L-30 ore bags ...</i>
06-20-1946	"Interview with [Name redacted; Privacy Act Information], a Former Linde Employee," April 10, 1981 (Dupree 1981)	<ul style="list-style-type: none"> • <i>Burning of burlap bags in which the ore was received ends</i>

Just before the January 8 working group meeting, a review of NIOSH (2007c) from SC&A was received (SC&A 2008):

Section 5.0 of the NIOSH response discusses the "burlap bag issue." NIOSH concludes that "Based on the reviewed historical records, and considering the fact that the period during which the burlap bags were staged and burned is within the current SEC period, a revision to the current dose reconstruction methodology is not warranted" (NIOSH 2007[c], Section 5.0). This, however, does not adequately respond

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to the site expert interview assertion that thousands of burlap bags were still stacked behind Building 30 after 1950; as stated in the SC&A site profile review: "During the MED period, they stacked all the contaminated burlap bags in storage area of Building 30. These contaminated burlap bags were kept in there until they were removed to be burned in the incinerator in the late 1950s. Many of the people working in Building 30, including operation personnel, secretaries, and maintenance workers, would sit on those bags resting or eating their lunch. This went on for many years." (SC&A 2006, Attach. 3, p. 112).

During the January 8 working group meeting an attempt was made to resolve the burlap bag issue, considering both NIOSH (2007c) and SC&A (2006). A consensus on the subject could not be reached. The conclusion of the working group was to have a technical conference that focused on the burlap bag issue. SC&A agreed to review the interview notes that were associated with the issue. As a result, a conference call was held on February 13, 2008. The former employee that reported the burlap bag issue was able to participate on this call.

Based on clarification of the burlap bag issue from the former employee who made the original assertion, it was determined that the burlap bags in question were inside Building 30:

... there were two pallets of bags containing some material in Building 30 in the time period around August 1951. He and his friends would get drinks, stand by the pile of bags, and place their cups on the bags. He was told by one co-worker that the bags were left over from the Manhattan project. He was asked about the appearance of the bags and he replied that they looked like large canvas sandbags.

An affidavit that describes the burlap bags was submitted by this former employee along with the Linde SEC Petition Documents that were submitted on March 19, 2008.

Based on this newly clarified description of the burlap bags, NIOSH was tasked with an assessment to compare calculated doses from an assumed pile of bags (two pallets of bags 2 to 3 ft high, for both ore and concentrate) to currently assigned doses.

Comparison of currently assigned dose to potential exposure from ore bags

Currently assigned dose (1950 to 1954)

1.85 R/yr (GM) with GSD of 4.04 from ORAUT-TKBS-0025 (ORAUT 2005c), Table 18.
(note: 95th-percentile value would be 18.5 R/yr).

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Dose assessment for the maximizing case:

Measurements take in 1944 on African ore (Skinner 1944)

Location	Gamma dose rate
Ore sampling room	
15 ore bags in center on ore	0.019 R/hr
1 ft from ore bags	0.0062 R/hr
Ore box car	
Center of car on ore	0.017 R/hr
Ore storage area (pile 4 by 5 by 20 ft)	
Center of 4- by 20-ft face on ore	0.040 R/hr
Center of 4- by 20-ft face on ore	0.026 R/hr
1 ft from 4- by 20-ft face	0.013 R/hr
2 ft from 4- by 20-ft face	0.013 R/hr
3 ft from 4- by 20-ft face	0.010 R/hr
5 ft from 4- by 20-ft face	0.0061 R/hr
10ft from 4- by 20-ft face	0.0028 R/hr

Based on the description of the exposure conditions from the former employee, the following exposure conditions and assumptions can be inferred:

- A dose rate of 0.0062 R/hr based on 1 ft distance from 15 ore bags, and
- An exposure duration of 1 hr/wd, 250 wd/yr.

These result in a total annual exposure of 1.5 R/yr

Summary

Based on the weight of the available evidence (tabulated below), it is unlikely that two pallets of uranium ore (which was last processed at Linde in 1946) would have been in Building 30 in 1951 (5 years after the cessation of processing of uranium ore). The current external exposure model for the period in question incorporates uncertainty in the external dose assignment by application of a lognormal distribution with a GM of 1.85 and a GSD of 4.04. This assumed distribution (with a 95th-percentile value of 18.5 R/yr) accounts for possible deviation of the actual worker exposure of the magnitude that would result from the assumption that two pallets of uranium ore were in Building 30 in 1951.

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Information that contradicts the presence of 2 pallets of uranium ore in Building 30 in 1951	Information that supports the presence of 2 pallets of uranium ore in Building 30 in 1951
<ol style="list-style-type: none"> 1. LAPC documentation outlines the processing of uranium ore including the receipt of uranium ore in bags, handling of the ore bags, and methods that were used to recover material held up in bags after they were dumped (shaking, washing, incineration, and recycling of incinerator ash). 2. LAPC documentation establishes that uranium ore was received in bags and that ore concentrates were received in drums. 3. LAPC documentation establishes end of uranium ore processing as 1946. 4. Affidavit (1981) from a former employee substantiates the description of the handling of the uranium ore bags in the LAPC documentation. 5. Surveys of Building 30 in 1950 and the balance of the site in 1952 did not identify elevated radiation levels consistent with two pallets of uranium ore. 	<ol style="list-style-type: none"> 1. Affidavit (2008) from a former Linde employee identifies the presence of 2 pallets of bagged material in Building 30 in 1951. 2. Affidavit (2008) from a former Linde employee identifies the material as uranium ore based on statement from a coworker.

It should be noted that the uranium intake value in this revision of the site profile (15,200 dpm/d) would bound any internal exposure scenario from two pallets of uranium ore bags in the stated configuration (bagged with plastic lining) and conditions (storage).