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Basis for Development of an Exposure Matrix for the Mallinckrodt Chemical Company St. Louis Downtown Site and the St. Louis Airport Site, St. Louis, Missouri	Revision:	03
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☐ New ☐ Total Rewrite ☒ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
10/24/2003	00	New document to establish the technical basis for the development of a radiation exposure matrix for the Mallinckrodt Chemical Company St. Louis Downtown Site, St. Louis, Missouri. Initiated by Janet L. Westbrook.
03/10/2005	01	Approved Revision 01 initiated to incorporate comments on Sections 7.0 and 8.0; to incorporate additional lately captured information regarding site work and external and radon exposure rates; to incorporate neutron exposure information; to incorporate information about the St. Louis Airport Site (SLAPS); and to provide additional guidance to dose reconstructors. Incorporates formal NIOSH review comments. Section 7.0, regarding external dose, remains on hold. Initiated by Janet L. Westbrook.
06/14/2007	02	Approved Revision 02 initiated to reflect comments of the ABRWH. Constitutes a total rewrite of the document. Modified Purpose and Scope, and Attachment A to incorporate SEC information as instructed by NIOSH. Made minor editorial changes to eliminate readily discernable errors and eliminated extraneous intake tables. Added information to reconstruct doses from available monitoring and coworker data for the period 1949–1962, and to clarify some discrepancies between the early-in-the program draft and current guidance. Deleted Attachment D (which was formerly C). This revision changes the method for assigning uranium, radium and thorium coworker intakes and radon exposures and eliminates the application of equilibrium amounts of uranium progeny intakes to reconstruct dose. Incorporates formal internal and NIOSH review comments. Revised dates for operational period in sections 6 and 7 to end in 1958. Removed references to unmonitored thorium and radium exposures (since reconstruction of such exposures has been determined to be not feasible by the SEC action). Added a section titled “unmonitored raffinate exposures” to cover the period 1948–1958 and inserted the text “reserved” to indicate that reconstruction of internal exposure from such pathways is not covered in this TBD for the time period 1948–1958. This revision results in an increase in assigned dose and a PER is required. Training required: as determined by the Task Manager. Initiated by Cindy W. Bloom and Joseph Guido.

05/25/2009	02 PC-1	Page change initiated to incorporate SEC information on pages 10-13 in Section 1.0 (extension of class to 12/31/1958) as instructed by NIOSH. Updated NIOSH required language on pages 10 and 11 in Section 1.0. Added information on pages 106-108 in Section 6.5. Updated NIOSH reference on pages 106-108, 124, 128 and 216 in Sections 7.1, 7.3, 8.5, 8.6, and Attachment A, respectively. Added reference on page 141 in Reference Section. On pages 158-160, updated NIOSH and ORAUT references in Reference Section. On page 210, updated NIOSH reference in Table A-34. Table A-40 on page 215 was revised to clarify that tabulated intakes represent gross alpha activity and to provide guidance on isotopic mixture to be applied. Incorporates formal internal and NIOSH review comments. Training required: as determined by the Objective Manager. Initiated by Joseph S. Guido. Approval: Richard Merrill Signature on File for 05/21/2009 Joseph S. Guido, Document Owner Signature on File 05/21/2009 John M. Byrne, Objective 1 Manager Signature on File 05/21/2009 Edward F. Maher, Objective 3 Manager Signature on File 05/21/2009 Kate Kimpan, Project Director Signature on File 05/25/2009 James W. Neton, Associate Director for Science
11/22/2010	03	Revision initiated to incorporate SEC-00150 information in Section 1.0 for the St. Louis Airport Storage Site as instructed by NIOSH. Additional changes in document include deletion of Sections 8.4, 8.6, and 8.8 and replacement of the material that is still applicable (considering the SEC determination) along with expanded instruction specific to SLAPS into a new Section, 9.0. In addition, the designation of covered periods noted in Section 1.0 was updated to reflect current program guidance. Incorporates formal internal and NIOSH review comments. Section 7.4 changed to clarify that medical x-ray exposure is not to be assigned at the Mallinckrodt Destrehan Street Plant due to the fact that the examinations were performed offsite. Section 1, 7.0 and 7.1 changed to clarify that external exposure to monitored employees is to be included in dose reconstructions for individuals employed prior to 1949. This exposure was previously excluded from dose reconstruction reports. Training required: as determined by the Objective Manager. Initiated by Joseph S. Guido.

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ACRONYMS AND ABBREVIATIONS

AEC	Atomic Energy Commission
AP	anterior-to-posterior
CER	Center for Epidemiological Research (Oak Ridge Associated Universities)
Ci/L	curies per liter
D&D	decontamination and decommissioning
DCF	dose conversion factor
DWE levels	time-weighted daily average exposure levels
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
FMFL	fluorinated MFL
GSD	geometric standard deviation
HASL	Health and Safety Laboratory (of the Atomic Energy Commission)
HVL	Half-value layer
LOD	limit of detection
lfm	linear feet per minute
MAC	Maximum Allowable Concentration
ME or MEP	Minor Elements Production
MED	Manhattan Engineer District
MFL	MgF_2 liner
MgX	magnesia concentrate feed
MPC	maximum permissible concentration
mR	milliroentgen
mrad	millirad
mrep	millirep
NBS	National Bureau of Standards
NCRP	National Council on Radiation Protection and Measurements
NRC	Nuclear Regulatory Commission
NYOO	New York Operations Office (of the Atomic Energy Commission)
ORGDP	Oak Ridge Gaseous Diffusion Plant
RBE	relative biological effectiveness
RMF	reject MgF_2 material
ROT	rotational
SLAPS or SLAPSS	St. Louis Airport (Storage) Site
SLDS	St. Louis Downtown Site
UNH	uranyl nitrate hexahydrate
VLE	very low enrichment
WL	working level
WLM	working level month

Code terms for the various uranium forms (e.g., TA-7) are given in Table A-5 in Attachment A.

1.0 PURPOSE AND SCOPE

Technical basis documents 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 upon 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 causation[1]] 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 2010a).

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 2010a):

- 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.

The information in Table 1-1 from the DOE Office of Worker Advocacy (DOE 2010) defines the EEIOCPA dose reconstruction periods.

Table 1-1. Information from the DOE Office of Worker Advocacy (DOE 2010) defining the EEIOCPA dose reconstruction periods.

Site:	**Mallinckrodt Chemical Co., Destrehan St. Plant**
Alternate names:	St. Louis Downtown Site, Mallinckrodt Chemical Works, MCW
Location:	St. Louis, Missouri
Covered period:	1942–1962
Remediation period:	1995

Site:	**St. Louis Airport Storage Site (SLAPS)**
Alternate names:	Robertson Airport, Robertson Storage Area
Location:	St. Louis, Missouri
Covered period:	January 3, 1947–1973; 1984–1998

This document provides information for the reconstruction of radiation doses to workers at the Mallinckrodt Chemical Company St. Louis Downtown Site, which refined and processed uranium under contract to the United States government and for the St. Louis Airport Storage Site, which received residues from Mallinckrodt operations from 1946 until 1958, after which it was used until about 1967 for residue storage and disposal.

This document describes exposure conditions in Mallinckrodt Plants 1, 2, 4, 6, 6E, and 7 (including 7E) over the time period of the start of contract operations for the Atomic Energy Commission (and its predecessor agency) through the cessation of these operations, which is different for each plant. The period of such operations began in April 1942. Additionally, exposure due to residual contamination is considered for the period 1959–1962 and exposure due to remediation activities is considered for 1995.

This document also describes exposure conditions for Mallinckrodt workers who performed operations at the St. Louis Airport (Storage) Site (SLAPS or SLAPSS), the waste repository site north of the former St. Louis Municipal Airport in Robertson, Missouri, from 1946 to 1973 and from 1984 through 1998. NIOSH has determined, and the Secretary, Health and Human Services has concurred, that it is not feasible to reconstruct internal radiation dose for individuals who worked at Mallinckrodt prior to 1949 and external dose for individuals for whom external monitoring data is not available (HHS 2005a). For the period 1949–1957 NIOSH has determined, and the Secretary, Health and Human Services has concurred, that it is not feasible to reconstruct internal radiation doses from internal exposures to non-uranium radionuclides (thorium-230, protactinium-231, and actinium-227) for Mallinckrodt raffinate workers, nor is it possible to identify which workers were raffinate workers (HHS 2005b). The period of applicability for this class was extended through December 31, 1958 (HHS 2009).

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 Mallinckrodt dose reconstruction, using whatever information is

available about that member's entire work history. Table 1-2, below provides a summary of the content of dose reconstructions performed for Mallinckrodt workers.

Table 1-2. Summary of Mallinckrodt Dose Reconstruction Components.

1942 – 1948	1949 – 1958	1959 - 1962
External exposure to monitored workers.	Internal exposure to Uranium (all workers) Internal exposure to radium and thorium for monitored workers Internal exposure to radon (all workers, as applicable based on diagnosis) External exposure (all workers)	Internal Exposure (all workers) External Exposure (all workers)

NIOSH has determined, and the Secretary of Health and Human Services has concurred, that it is not feasible to reconstruct internal exposure at the St. Louis Airport Site during the period from January 3, 1947, through November 2, 1971 (HHS 2010). For this period only external dose, occupational medical dose, and internal dose associated with specific bioassay data contained in individual worker files will be estimated. Table 1-3, below provides a summary of the content of dose reconstructions performed for St. Louis Airport workers.

Table 1-3. Summary of St. Louis Airport Dose Reconstruction Components.

January 3, 1947 – November 2, 1971	November 3, 1971 – December 31, 1973	January 1, 1984 – December 31, 1998
Internal exposure for monitored individuals External exposure (all workers)	Radon exposure (all workers, as applicable based on diagnosis) External exposure (all workers). Shallow dose not assigned.	Internal Exposure (all workers) External exposure (all workers).

2.0 INTRODUCTION

The Manhattan Engineer District (MED), the predecessor agency of the Atomic Energy Commission (AEC), asked the Mallinckrodt Chemical Works in April 1942 to begin research on uranium refining and processing operations to lead to large-scale uranium production operations (Fleishman-Hilliard 1967; FUSRAP undated b). The work began immediately and by July 1942 Mallinckrodt was producing almost a ton of UO_2 per day (Fleishman-Hilliard 1967; Mallinckrodt 1994; FUSRAP undated b). Later in 1942, Mallinckrodt started production of UF_4 and in July 1943, it started the first uranium

metal plant (Fleishman-Hilliard 1967; Mallinckrodt 1994). It is estimated that between 1942 and 1957, Mallinckrodt processed more than 50,000 tons of natural uranium products at the St. Louis facilities (FUSRAP 2002).

The first three Mallinckrodt plants (1, 2, and 4) were not built for the purpose of uranium refining but were converted on an urgent basis from other uses and were intended to operate for only six to eight months. Like most of the early MED plants, the early Mallinckrodt facilities were large-scale expansions of laboratory processes and techniques and were designed without pilot plant studies or any special provision for health and safety (AEC 1951b). Also, temporary types of construction methods were used; even Plant 6, which was completed in mid-1946 and did have the benefit of an engineering pilot plant study, was of temporary-type construction because it was to process only high-grade pitchblende and the available supply was thought to be limited (AEC 1951b). The permanent status of the Mallinckrodt site was not established until 1946 (AEC 1951b; Mason 1958a). Engineered and administrative provisions for health and safety were instituted as high exposures were found in the course of monitoring (Hickey and Dupree 1984). A full-scale health program was not authorized until 1947 and did not get under way until 1948, as a joint AEC-Mallinckrodt effort (Mason 1958a). Film badging started only in late 1945 (except possibly for a pilot project starting in mid-1945) and urinalysis in the summer of 1948 (MCW 1950c) (some urinalysis was done earlier, but there was some question about its validity–see Section 5.3.6). Thus there is little data on radioactivity concentrations in air or on internal and external doses prior to the late 1940's.

Although Mallinckrodt had its own industrial hygiene group and did most of its own safety work (Eisenbud 1975; MCW 1955d; AEC 1950a), AEC's Health and Safety Laboratory (HASL) also did periodic air sampling and other surveys for the operating plants. While some records of the Mallinckrodt surveys survive, they essentially cover the same work and time periods as AEC's surveys, except for some special cases. During the early years, film badge servicing, urinalysis, and breath radon analyses were done under the aegis of HASL (AEC-NYOO) (Eisenbud 1975); later, Mallinckrodt took over this work for its own plants and created the corresponding records. Eventually, however, HASL resumed doing the urinalysis and breath radon analysis for a time (MCW 1955d), but eventually Mallinckrodt did its own urinalyses again (ORAU 1983b). It appears that most of the records of this monitoring are available. The external dose records are mostly available from 1946 on, but are missing for the period 1942–1944 and for most of 1945. The internal dose records (as bioassays) are mostly available from 1948 to the end of operations, but are missing for the period 1942–1947. Records for the post-operations decontamination and decommissioning should be found with the Weldon Spring records since film badges were issued from Weldon Spring (MCW 1961b), but to date the Weldon Spring records are only available for individual claims.

The St. Louis Airport Storage Site (SLAPS or SLAPSS) was acquired by AEC in 1946 for use in storing residues arising from pitchblende ore processing (AEC 1959; ORNL 1979). Later, it was also used to store other types of residues and some ore (AEC 1956d; Mallinckrodt 1994). Although MED/AEC operated the site itself from 1946 until July 1953, it appears that Mallinckrodt and perhaps some Ledoux Company workers actually did the work (MCW 1949d; MCW 1949p; ORAU 1989); Mallinckrodt ran the site under contract to AEC from July 1953 to 1958 and possibly until 1962, when control of the site passed to a private concern that was given a license to take over the stored residues (AEC 1959; ORAU 1989; AEC 1972). Thus the film badge records for airport workers from 1946 until at least 1958 should be found among the Mallinckrodt film badge records; film badge records after that may possibly be among the Weldon Spring records.

In this document, the context for interpretation of the existing records is established, along with the basis on which to determine missing doses for periods in which records do not exist.

3.0 HISTORY OF SITE USE

At their height, uranium-refining operations took place in about 60 buildings on the so-called St. Louis Downtown Site (SLDS), of which about 20 were left after decontamination (Applied Nuclear Safety 1986; FUSRAP 2003a). All of these 20 buildings and most of the other 40 buildings are listed in Table A-1 along with their principal uses (see Attachment A for all tables). A summary chronology of the use of the site is shown in Table A-2.

MED was required to store some of the residues produced from the pitchblende ore (AEC 1959) because the ore supplier, the African Metals Company, retained ownership of the radium and valuable metals remaining in the residues. Because of the volume of the residues and the high gamma and radon exposures associated with storage at the Mallinckrodt site, MED acquired a tract of land located in Robertson, Missouri near the St. Louis Municipal Airport (Labert Field) (AEC 1959) to use to store the residues and some of the pitchblende ore (AEC 1959). This storage area was formally called the St. Louis Airport Storage Site (SLAPS or SLAPSS), but in Mallinckrodt and MED/AEC documents it was often referred to simply as "the airport."

3.1 HISTORY OF USE OF THE ST. LOUIS DOWNTOWN SITE (SLDS)

Plants 1 and 2 were already in existence and used for other operations by Mallinckrodt at the time uranium-refining operations started in 1942 (Mason 1977). MED (1944p) states that as of November 1944, MED operations occupied a small part of Plant 1, part of Plant 2, and all of Plant 4.

Laboratory development work started in April 1942 in Plant 1's Building 25 (second floor) and in the alley on the southwest side of the building (Mason 1977). (Mallinckrodt 1994 states that work began in Plant 2 in uranium-refining operations in April 1942, but the Mason 1977 chronology appears to be more plausible.) Additional laboratory and developmental work at the laboratory level to support Plant 2 and Plant 4 took place in Plant 1, specifically the Building 25 laboratory and the alley between Buildings K1E and 25 (Mallinckrodt 1994).

In Plant 1, Building 25 contained the project offices, while Building P contained the engineering office. MED (1944p) states that Building Z contained other offices; Mason (1977) specified that the early uranium project was a semi-works operation for which administrative services were furnished from Mallinckrodt headquarters in Building Z. Building A in Plant 1 was the base for the plant mechanical department, which provided general maintenance services (Mason 1977; MED 1944p). Mason (1977) states that the laboratory in Building 25-2W provided quality control services.

Facilities for batch production were installed in Plant 2's Buildings 50, 51, 51A, and 52 to produce uranium trioxide (UO_3) from ore concentrates (Mason 1977; Hickey and Dupree 1984; Mallinckrodt 1994). The concentrates were "digested" (dissolved) in nitric acid in Building 51 to produce uranyl nitrate (Mason 1977; ORNL 1981; Mallinckrodt 1994; Fleishman-Hilliard 1967). The digested liquid was then transferred to Building 52 to be purified by ether extraction to uranyl nitrate hexahydrate (UNH) (MED 1944p; Mason 1977; ORNL 1981; Mallinckrodt 1994); however, sources such as ORNL (1981) suggest that an area outside of Buildings 51 and 52, referred to as 51X and 52X, was covered with a canopy and used temporarily for extraction. The UNH was converted in Building 51A first to UO_3 and then to UO_2 (Mason 1977; ORNL 1981; Mallinckrodt 1994). The UO_2 was apparently packaged in Building 51A (Mason 1977). By July 1942 Mallinckrodt was producing approximately a ton of uranium oxide (UO_2) per day (Mason 1977; Mallinckrodt 1994).

Part of Building 38 was used as the change house for the uranium project workers (Mason 1977). Buildings 40, 45, 45A, and 47 were used as warehouse buildings for raw, in-process, and finished materials (MED 1944p). Building 50 was also used as a utility area, as a tank storage area for liquids

to be used in Building 51, as a storage area for incoming feed materials and packaged products, and as a mechanical repair area (Mason 1977; Mallinckrodt 1994).

Building 55 contained the "shotgun" laboratory that tested UO_3 samples (MED 1944l; Mason 1977; ORNL 1981) and also operated as a pilot plant from 1943 until some time in 1947. The shotgun laboratory was designated as a special restricted area because of the radium-beryllium (RaBe) source used for the sample testing (Mason 1977).

Work began in 1942 on production of UF_4 by the high-temperature gas-solid reaction of UO_2 with HF; for a short time, one corner of Building 50 (the "sulfur burner room") was used for development work on this process (Mason 1977; ORNL 1981).

Experimental processing of high-grade pitchblende ores began in Plant 1 in about July 1944 (Mason 1977; Mallinckrodt 1994). Because of the high radium content of these ores and the residues resulting from the processing, Mallinckrodt wanted to confine the materials to a limited area and to prevent their spread into other plant areas (Mason 1977). Mallinckrodt therefore instituted strict controls of the developmental work and also decided to do pilot-scale work to obtain design data for eventual construction of a production-level refinery (Mason 1977). The laboratory for the testing of radium extraction methods was set up in Building 25-2 and the pilot plant in Building K-1E (Mallinckrodt 1994; ORNL 1981; Hickey and Dupree 1984 (which states that the pilot plant was in Building 25-2)) and in the alley (Fleishman-Hilliard 1967). The radium-free feed liquor that resulted from the Building K-1E digestion and precipitation processes was conveyed in containers by hand cart to Building 52, where it was first treated in vessels outside the building (presumably in the alley) (Mason 1977). The liquid was then taken into Building 52 for conversion as usual to UO_3 and then to UO_2 (Mason 1977). By the end of 1944, Mallinckrodt had obtained sufficient data to begin the engineering design of a pitchblende ore refinery (Mason 1977). Mason (1977) states that "radium-bearing materials were not processed or stored at any time in the Plant 2 buildings," but consistent with the usage of the term "radium-bearing materials" in various documents from the 1940's and 1950's, it may be the high-radium-level residues that are being referred to. Mason (1977) also states that solid residues from the extraction were drummed, stored temporarily, and transferred from Plant 2 to other government sites for scrap recovery.

In the spring of 1945, an annex to Building 52 (presumably 52A) was added to serve as a pilot plant for a continuous countercurrent ether extraction process to replace the existing batch process (Fleishman-Hilliard 1967). It is not clear whether it is this plant or the Building K-1E plant that is the one referred to as the "Pilot Plant" in early film badge records; perhaps the term included both. Work at Plant 2 continued until 1946, when the plant was closed in preparation for the startup of the newly built Plant 6 (Mason 1958a; Mason 1977; Eisenbud 1975; ORNL 1981; Mallinckrodt 1994). Mason (1977) also states that when Plant 6 started up, all uranium work at Plants 1 and 2 stopped and the buildings were sealed to await further cleanup (but see below).

Plant 1 was not used after about 1945 (ORNL 1981) or early 1946 (Mason 1977); the offices and laboratories apparently moved to Plant 6. In particular, administrative and related services moved from Building Z to Plant 6 at this time; however, the quality control services moved to a laboratory in Building 400 of Plant 4 (Mason 1977). Although as noted above the Plant 2 operating area was said to have been closed in 1946 when production moved to Plant 6, Mason (1958a) states that milling of UO_3 and unloading of (some) pots was not discontinued at Building 51 (Plant 2) until about 1947 and ORAU (1977) states that this building was closed about January 1947. Thus it can conservatively be assumed that Plant 2 was in limited operation through 1946.

From late November 1942 through April 1943, Plant 4, a lumber sash and door works, was hastily converted for uranium processing (AEC 1951b; Mason 1958a) and dubbed "the metal plant" (AEC 1949b; AEC 1951b). It replaced the uranium metal production work done in Building 25-2 (Hickey and

Dupree 1984). Production of uranium tetrafluoride (UF_4) began in Building 400 in April 1943 after the process had been scaled up from the early work in Building 50 of Plant 2 (AEC 1951b; Mason 1977; Fleishman-Hilliard 1967). Production of uranium metal began in Buildings 400 and 401B in July 1943 (AEC 1951b; Mason 1977; Mallinckrodt 1994). Magnesium metal for the process was stored in Building 406, while the residues from the process (e.g., slag) were stored in Building 408 (Mason 1977). The principal production of metal moved from Plant 4 to Plant 6E in 1950 (Mallinckrodt 1994) although some metal was still produced in Plant 4 (AEC 1951b; Hickey and Dupree 1984) and some UF4 was still produced there until perhaps early 1953 (Hickey and Dupree 1984). After the development of a continuous furnace process, UO_2-to-UF_4 production moved to Building 705 of Plant 7 (7N) in late 1951 (overlapping Plant 4's production) (AEC 1951b; Fleishman-Hilliard 1967; Mason 1977 (which says that Plant 4 UF_4 production was completely shut down in 1951); Hickey and Dupree 1984; Mallinckrodt 1994). In about 1950 or 1951 (ORNL 1981 says 1956, but this is evidently incorrect), Plant 4 was refitted as an experimental development and a metallurgical pilot plant processing uranium metal and was then referred to as the "Pilot Plant" (Mason 1977; ORNL 1981). The "dingot" metal production process was developed and conducted at Plant 4 in the mid-1950's (AEC 1956a; Fleishman-Hilliard 1967), along with sporadic ordinary metal "derby" production on a developmental basis. Plant 4 was used until 1956 (Mason 1977; ORNL 1981; Mallinckrodt 1994; FUSRAP 2003c).

Due to the need to increase production and also due to the recognition by MED and Mallinckrodt of significant safety problems with dust and external doses (partly arising from the prospective extensive use of radium-containing pitchblende ore (ORNL 1981; ORAU 1983a; Mallinckrodt 1994)), Plant 6 was built in 1945–46 on a large site fronting on Destrehan Street (Mason 1958a; Fleishman-Hilliard 1967; Mallinckrodt 1994); it began operation in July 1946 and was then referred to as "the refinery" (AEC 1949b; AEC 1951b). Mason (1977) states that the choice of this site was based on proximity, security considerations, and space availability for constructing administrative and other support buildings that would enable the uranium operations to function as an independent unit. Most of the administrative offices, laboratories, and support facilities for the uranium refining operations were in fact located there. In early 1946, the ore-to-UO_2 part of the refining process was moved to Building 104 of Plant 6 from Plant 2 and apparently the laboratory work moved to Building 102 from Plant 1, while the UO_2-to-metal production remained at Plant 4 (FUSRAP 2003c; Hickey and Dupree 1984; AEC 1949b; Mason 1958a). However, some reduction of UO_3 to UO_2 appears to have been done at Plant 4 also, perhaps as part of pilot plant operations, as indicated by Mason (1958) and AEC (1950c). Mason (1977) states that expansion of Plant 6 (new construction and production increases) continued through 1954.

In November 1947, Mallinckrodt cast 100 special billets for use by Hanford in an alpha extrusion experiment (AEC 1949d). These special billets contained higher nickel levels than usual and were prepared as part of the research into green salt production, in the belief that the new continuous green salt production reactor might give a product with higher levels of nickel than usual (AEC 1949f). From late 1947 to early 1948, Mallinckrodt was engaged in producing natural uranium castings for the Schenectady zero power pile (AEC 1949d). Also from late 1947 to early 1948, several tanks and centrifugal filters were added to the digest process line to allow the reprocessing of the radium (K-65) and barium sulfate residues and recovery of 95% of the 2% of the original uranium from the ore that was in these two residues (AEC 1949d; AEC 1948g). The K-65 and barium sulfate residues already stored in the St. Louis area were then returned from storage and processed. Subsequently this so-called C-3 process was used on all the K-65 residues produced and the companion process on all the barium sulfate residues produced (AEC 1949d).

The incoming ore arrived by rail and was stored in Building 110; however, in late 1950 or early 1951 an outdoor onsite ore storage area was added for pitchblende ore (Q-11) (AEC 1950i). Building 104 housed the continuous process equipment, which replaced the batch process equipment that had been used in Plant 2, and processed mostly pitchblende ore (Mallinckrodt 1994). The new refinery

process was designed to include the new operations developed in the laboratory and pilot plant, i.e., to recover radium and raffinates as separate residues and to remove sulfate as a barium sulfate cake (Mason 1977). In 1949, following laboratory and pilot-scale studies, a second digest line was added to Building 104 to process uranium ore (mill) concentrates (Mason 1977; Mallinckrodt 1994). This appears to have included a magnesia concentrate designated MgX or MGX and a calcium uranate concentrate designated CX, both of which were prepared in the Congo from low-grade tailings (AEC 1951b; AEC 1949f). Building 114 was used for temporary storage of residues until they could be transferred elsewhere (Mallinckrodt 1994). Most of the UO_2 produced at Plant 6 was trucked over to Plant 4, with the rest going by rail to Harshaw and Linde for some years (AEC 1949b). Pitchblende ore use was phased out over the period 1952–1954, after which the pitchblende digest line was placed on standby (Mason 1977). Feed concentrates were used exclusively from 1955 through the end of production in 1958 (Hickey and Dupree 1984).

When equipment was added to Plant 7 to allow continuous UO_3-to-UF_4 conversion, Plant 6 continued to produce UO_2 until early 1953 and then began to produce only UO_3 (Hickey and Dupree 1984; Mallinckrodt 1994). Milling of UO_3 at Plant 6, milling of ore at Plant 6, and pre-digestion ore grinding, conducted initially at Plant 4 and later at Plant 6, were discontinued in 1950, mid-1949, and 1955 respectively (Mason 1958a). Pitchblende ore continued to be used as feed until early 1955 (AEC 1959). In 1957, a pilot-scale fluid-bed denitration reactor from Argonne was installed for testing and developmental improvements at the Destrehan site, presumably at Plant 6 (Fleishman-Hilliard 1967).

In 1949 it had become clear to AEC that process improvements to Plants 4 and 6 were not enough to bring about satisfactory control of dust and other hazards (AEC 1949b; AEC 1951b). As Mallinckrodt reminded AEC, Plant 6 had been built as an ordinary processing plant with no special provisions for health hazards because it was not expected to be used more than eight months (AEC 1951b; MCW 1950t). AEC authorized funding for dust control and mechanization improvements, which were installed in 1949–1950 (see Table A-3). Plant 6 was shut down for a time in late 1949–1950 for this purpose. It is not clear what the workers did during the time the plant was shut down, although it seems likely that those who had the necessary skills worked on the installation project.

These improvements were regarded as an interim measure, however (MCW 1950e; AEC 1951b). Mallinckrodt and AEC agreed to build a new pair of plants that were located at the Destrehan Street site (AEC 1949b; Mason 1958a). The first was Plant 6E, the new metal plant, which was constructed from early 1948 to June 1950, began startup operations in June 1950, and went into operation in July 1950 (AEC 1949e; AEC 1951b; Mason 1977). Note that there was a laborers' and hod (a tray, trough or shallow box on a stick used to carry a load of bricks or mortar) carriers' strike from 28 March into early April 1949 that slowed construction of Plant 6E (AEC 1949e; AEC 1949d). Metal production (UF_4-to-U metal) operations at Plant 4 moved to Plant 6E, which was from then on referred to in records as "the metal plant." Metal production took place in Building 116 (Mason 1977; Mallinckrodt 1994). An expansion project was started in March 1951 and finished in about September 1951 (AEC 1951b). Building 116C was built in 1954 to recycle magnesium fluoride slag (Mallinckrodt 1994).

The second new plant was Plant 7, the green salt plant, which was constructed from November 1950 to March 1951 and was turned over to Mallinckrodt for operation in March 1951 (AEC 1951b). Note that AEC (1949b) appears to indicate that Plant 7 operations began in late 1952, while Mason (1958a) indicates a 1948 start date and Mason (1977) indicates a 1951 start date. The confusion may be due to the nature of the new direct or continuous UO_3-to-UF_4 process used at Plant 7 and the apparent use of Plant 4 facilities to test out the process, as a pilot plant, and to work out difficulties even after Plant 7 went into production. The buildings involved at first were Buildings 703 through 708 (Mason 1977). At Plant 7, a continuous process replaced the batch-type process used at Plant 4 and the UO_3-to-UO_2 production process at Plant 6, although UO_2 could still be produced as needed (AEC 1951b; Mason 1977); however, Mallinckrodt (1994) states that it was only later that equipment was added to allow the continuous production of UF_4 from UO_3 directly.

Uranium metal recovery and some storage operations were moved to Plant 7 in late 1951 (AEC 1951a; AEC 1951b; Mallinckrodt 1994) or early 1952 (Mason 1958a). Some reversion of UF_4 to UO_2 or UO_3 was done in 1953 and perhaps into 1954 (MCW 1953c). Building 700 was placed in service in 1954 to serve as a warehouse (Mason 1977). A new wet slag (interim residue) recovery operation was added in late 1955 in Building 701 (Mason 1977; Mallinckrodt 1994); this was apparently what was referred to as Plant 7W and may have been a pilot plant (Hickey and Dupree 1984). Some time in 1954 (Mason 1977) or in the late 1950's (Mallinckrodt 1994) machining of (nuclear) reactor core (elements) was done on a temporary basis in a fabrication facility in Building 700. In 1955, very low enrichment uranium (probably only a small amount) as UF_4 was processed at Plant 7 (AEC 1955d) and in August 1956, about 5.5 kg of 20%-enriched uranium was processed, presumably in Plant 7 (MCW 1956e).

Plant 7E, whose sole building (712) was constructed as a temporary facility in 1954–1955 and which was regarded administratively as part of Plant 7, was used from 1955–1957 to process pitchblende raffinate (solids removed during uranium refining by wet filtration) to produce a concentrated thorium solution (FUSRAP undated b, FUSRAP 2003a; Mason 1977 says from 1955–1956) by an acid digestion process similar to the uranium ore digestion (AEC 1955e). The concentrate was sent to the Mound site for further processing.

A new facility to replace the so-called "Ledoux Laboratory" was completed in November 1952 (MCW 1953a). The purpose of this was to provide improved dust control for the sampling and processing of K-65, the radium-containing solid waste. Further improvements were made in 1953 (MCW 1953a). Other sampling and assay work was done, such as the evaluation of slugs produced by National Lead Company of Ohio from extruded rods that had been manufactured by the Bridgeport Brass Company from dingot billets apparently produced by Mallinckrodt (MCW 1956d).

In 1957 or 1958, all uranium refining operations ceased at all the plants (FUSRAP 2003c; DOE 1981) and the work moved to Fernald and Weldon Spring. Eisenbud (1975) stated that all Plant 6 work was transferred to Weldon Spring in March 1957 (processing steps through UO_3 production, at that time). However, Mason (1958a) stated that some Plant 7 production operations continued up to July 1958, when they were transferred to Weldon Spring; this was probably to use up the store of orange oxide that had already been produced. This is supported by the statement of Mallinckrodt (1994) that the last of the site was put on standby in 1958.

Decontamination and surveys were performed at Plants 1 and 2 in 1948–1950 by Mallinckrodt personnel, applying AEC criteria (ORNL 1981; Mason 1977, which says the work began in 1949); contaminated materials and some contaminated equipment were collected and delivered to AEC for disposal, while the rest of the contaminated equipment was transferred to Plant 6 (Mason 1977). After AEC was satisfied as to the completion status of the decontamination, AEC performed a final survey (Mason 1977), with presumably some touchups by Mallinckrodt and resurveys by AEC. In 1951, AEC released these plants to Mallinckrodt for unrestricted use and no further AEC work was performed there (Mason 1977; DOE 1981). Mallinckrodt (1994) states that further decontamination took place in 1954 and 1970. Some of these buildings were still extant as late as 1990 (Applied Nuclear Safety 1991). Plants 4, 6, 6E, and 7 were surveyed by AEC and Mallinckrodt in 1958–1959 and were decontaminated or taken down in 1959–1961 by Arch Wrecking Company (under contract to AEC), with safety and health coverage by Mallinckrodt (Mason 1977). Mallinckrodt performed a final decontamination survey for AEC during 1960–1961 (Mason 1977). The buildings removed during the takedown included all of the Plant 4 buildings and all wet-process buildings in Plant 6 (ORNL 1981; Mallinckrodt 1994) (see Table A-1 for details). The site was released to Mallinckrodt without restriction in 1962 (ORNL 1981). These decontaminations were done to the AEC standards then in force, i.e., not to background levels (ORNL 1981; DOE undated). The remaining Plants 6, 6E, and 7 buildings were decontaminated to modern standards in the 1990's and demolished in 1997 (FUSRAP 2002).

Note that the term “Destrehan Street site” seems to have been used in documents sometimes in reference to all the Mallinckrodt St. Louis facilities and sometimes just to those on the Destrehan Street site proper. In this technical basis, the former interpretation will be used, i.e., Plants 1, 2, 4, 6, 6E, and 7 will be covered. For clarity in using the references, note that Plant 4 fronted on Broadway Street and although Plants 1 and 2 did not, either Plant 4 or all three plants could be referred to as “the Broadway site.” Thus the “Broadway” and “Destrehan” terms appear to be a loose reference to geographical location and not necessarily to a division of function or operations. Also, as will be explained later, due to a rotation practice, Mallinckrodt workers were apt to have worked in multiple plants over the course of their employment. In distinguishing between these plants and the SLAPS airport site (see Section 3.2), these plants as a group will be referred to in this technical basis document as the Mallinckrodt St. Louis main site.

To summarize, work performed at the Mallinckrodt St. Louis main site on a continuing basis included the following.

1. Production of UO_2 and UO_3 from ore, with some being shipped to Harshaw and other sites and with some natural and low-enrichment UO_3 coming from Hanford and other sites in the 1950’s (DOE 1997; Mallinckrodt 1994; MED 1946a)

2. Production of UF_4, with some being shipped to Harshaw and K-25 (DOE 1997; Mallinckrodt 1994; MED 1946a; FUSRAP undated b)

3. Production of uranium derby metal and vacuum recasting of ingot metal, with the ingots being the final product shipped to other sites (DOE 1997; Mallinckrodt 1994; MED 1946a; FUSRAP undated b)

4. Recovery of scrap uranium metal, some from other sites, such as Hanford (FUSRAP Undated b; DOE 2000; Mallinckrodt 1994)

Other work performed for a limited period or on an occasional or small-batch basis included the following.

1. Production of dingots using a thermite reduction process (Mallinckrodt 1994; Fleishman-Hilliard 1967; AEC 1956a)

2. Machining of metal rods for reactor fuel slugs (Mallinckrodt 1994; FUSRAP undated b)

3. Casting of special billets (ingots) and other special uranium castings (AEC 1949d)

4. Reversion of UF_4 to UO_2 or UO_3 (FUSRAP Undated b, which says UO_2 or U_3O_8; Mallinckrodt 1994; AEC 1954g)

5. Production of UO_2F_2 (FUSRAP undated b)

6. Reprocessing of pitchblende residues to recover uranium (AEC 1949d; AEC 1951b)

7. Recycling of slag for use as liner material in the processing of uranium metal (AEC 1956a; Fleishman-Hilliard 1967)

8. Extraction and concentration of Th-230 from pitchblende raffinate (FUSRAP undated a; FUSRAP undated b; Mallinckrodt 1994; AEC 1955e)

9. Experimental processing of very low enrichment UF_4 (FUSRAP undated b; Mallinckrodt 1994; ORNL 1981) and some 20% uranium metal (MCW 1956e)

10. Production of small research quantities of uranyl nitrate hexahydrate (UNH) [AEC 1951b]; conversion of small research quantities of aqueous uranyl nitrate hexahydrate to UO_3 (DOE 2000)

11. Production of U_3O_8 and UO_2 using an experimental continuous denitration furnace (Mallinckrodt 1994)

12. Experimental extraction of uranium using tributyl phosphate (TBP) to replace ether (Mallinckrodt 1994), apparently in a pilot plant circa 1950–1951

13. Miscellaneous analysis and assay work (e.g., MCW 1956d)

FUSRAP (2003b) states that uranium ore assay was done in the "Ledoux Laboratory" located in Buildings 110A and 111 of Plant 6. However, from MCW (1954a) and other contemporary references, it appears that only the K-65 residue assays were done in the Ledoux Lab, which work had been contracted to Ledoux by African Metals (ORAU 1989a), which retained the rights to the radium in the residue. The Ledoux Laboratory is also mentioned in Mallinckrodt film badge records, so presumably the Ledoux and Co. personnel were badged under Mallinckrodt's aegis.

MED (1944p) stated that non-MED Mallinckrodt employees and employees of the St. Louis Sash & Door Works (the former operator of Plant 4's Building 400 in its pre-MED days) had occasion to enter Buildings 45, 45A, and 47 in Plant 2 and "Building 1" at Plant 4 (presumably Building 400) respectively. These employees were presumably not monitored in any way other than having their access controlled for security reasons.

Mallinckrodt processing of black oxide (pre-milled ore), soda salt (sodium diuranate, or $Na_2U_2O_7$), UO_3 (orange oxide), and UO_2 (brown oxide) was done under AEC/MED Contract W7401-Eng 1; UO_2 and UF_4 (green salt) under Contract W7405-Eng 29, 1st Phase; and UF_4, biscuit metal (uranium derbies), slag processing, ingots (billets), croppings, sawdust processing, and other metal production under Contract W7405-Eng 29, 2nd Phase (MED 1945a; MED 1944p).

Starting in 1952, some recycling of uranium was done by the AEC and its contractors nationwide. Thus the question arises whether this was done at the Mallinckrodt facilities in St. Louis. However, Mallinckrodt (as a company) did not begin to receive recycled uranium until 1962, which was after the St. Louis facilities had been shut down and their work had shifted to Fernald and Weldon Spring (the latter run by Mallinckrodt) (FUSRAP 2003b). Also, ORNL (1981) stated that in its pre-survey review of the site, including interviews with Mallinckrodt old-timers, no indications were found that there had ever been any process conducted under AEC contracts involving the purification or working of Th-232, highly enriched uranium, fission products, or byproduct material. Thus it is assumed that no recycled uranium or any of the materials listed by ORNL (1981) was handled at Mallinckrodt's St. Louis facilities as part of AEC work.

In 1949, AEC requested that Mallinckrodt produce in their AEC-owned facilities 200 pounds of uranium metal for "nonproject and educational uses" (MCW 1949h); however, there is no indication that Mallinckrodt ever did so. Mallinckrodt apparently also carried on some commercial processing of euxenite (an ore) at Plant 5 at some point in the 1950's.

3.2 HISTORY OF USE OF THE ST. LOUIS AIRPORT STORAGE SITE (SLAPS OR SLAPSS)

The main supplier of the pitchblende ore to MED, the African Metals Company, retained ownership of the radium and valuable metals remaining in the residues after the ore was processed (AEC 1959). Thus by contract, MED was required to store the radium-bearing residue (K-65 or gangue lead cake) and the metal-rich barium sulfate cake residue until they could be transferred to African Metals (AEC 1959). From 1942 to 1945, the residues and other solid wastes were stored temporarily at the Mallinckrodt site and then shipped to the Lake Ontario Ordnance Works. Because of the volume of the residues and the high gamma dose rate and radon emanation rate of the K-65 residue, MED obtained consent in March 1946 to use for residue storage purposes a 21.7-acre tract of land located in Robertson, Missouri north of the former St. Louis Municipal Airport (also known as Lambert Field) (AEC 1959). In January 1947, MED obtained title to the property by condemnation (AEC 1959). This storage area was formally called the St. Louis Airport Storage Site (SLAPS or SLAPSS), but in Mallinckrodt and MED/AEC documents it was often referred to simply as "the airport." The SLAPS site was operated by MED/AEC from 1946 until July 1953 (AEC 1959; ORNL 1979), when the operation was turned over to Mallinckrodt (AEC 1959); Mallinckrodt then ran the site under contract to AEC from July 1953 to 1958 and possibly until it was turned over to a private concern that assumed control of it under an AEC license (AEC 1959; ORAU 1989; AEC 1972). Although AEC owned SLAPS, Mallinckrodt workers appeared to have been doing the residue delivery and placement work even in 1946–1953 (MCW 1949d; MCW 1949p).

Initially, it was only the radium-bearing waste residues (K-65), the barium sulfate residues (AJ-4), and the pitchblende raffinates (AM-7 or "airport cake") produced at Mallinckrodt that were stored at SLAPS (Mallinckrodt 1994). Later, SLAPS was also used to store other types of residues and wastes and some ore and to serve as a storage and burial site for contaminated objects and debris (AEC 1959; AEC 1956d; Mallinckrodt 1994; AEC 1948e; AEC 1949m). The ore was stored there as part of AEC's strategic stockpiling program (AEC 1949d). The other types of residues included the residue left after reworking of the AM-7, called AM-9; Colorado (domestic non-pitchblende) ore raffinate; and a residue formed from the precipitate of the first-phase ether extraction columns ("Sperry cake," apparently a synonym for or subset of the AM-7) (AEC 1956e; AEC 1964; Mallinckrodt 1994). Metal scrap, dolomite slag ("C-liner" or "C-oxides"), and tailings of uranium scalping operations from magnesium fluoride slag (the latter two from the derby metal production) were also sent to SLAPS (Mallinckrodt 1994). Some of the debris buried at the site appears to have been from the decontamination and decommissioning of the Plants 1 and 2 area in 1948–1950. From perhaps mid-1948 on, pitchblende ore (Q-11) was stored at SLAPS (MCW 1949p).

In 1948 and 1949, the K-65 residue was brought back from SLAPS in lots to be "reworked" (reprocessed to recover more uranium) (AEC 1959), after which it was sent to the Lake Ontario Ordnance Works (AEC 1959). The drums in which it had been stored were returned to SLAPS for storage. From 1955–1957, most of the AM-7 was brought back from SLAPS to be processed to recover Th-230 as a solution that was sent to Mound; the resulting residue, AM-9, was sent back to SLAPS (AEC 1959). Also in 1955, the tailings (D-701) from the processing of the magnesium fluoride slag produced in the metal plant were stored at the site (AEC 1959) or at SLAPS (AEC 1956d; Mallinckrodt). The barium sulfate cake remained at SLAPS because eventually African Metals relinquished ownership of it (AEC 1959).

In 1952, some of the western part of the SLAPS plot, where contaminated metal and debris were buried (presumably from the decontamination of Plants 1 and 2), was filled in deeply with earth (AEC 1964). In April 1959, a railroad siding and loading facilities were installed (AEC 1959), apparently in preparation for moving out the residues and other material (AEC 1959); the tailings from the magnesium fluoride slag processing were then sent to the Fernald site (AEC 1959). In about 1959–1960, some of the scrap and rubble from the demolition and decontamination of the Mallinckrodt St.

Louis site facilities was buried at the west end of the site (AEC 1972; ORNL 1979). At some point, a building consisting of a changeroom, a shower, and office space was moved to the site (AEC 1959; AEC 1964); it is not clear when this occurred, but since earlier references mention only a truck wash pad as a cleanup area, the building was likely not installed until the burial activities of 1959–1960 took place.

In March 1962, AEC issued an invitation to bid on the residues and on September 1962, AEC issued a license to the successful bidder, a commercial entity, to possess and remove 125,000 tons of uranium and thorium residues stored at SLAPS and at the licensee's processing facility (NRC 2004). Although there was little work by Mallinckrodt or SLAPS employees at the site thereafter, some further history of the site is given below.

The 1962 license was terminated in February 1966. This was possibly due to the licensee's going out of business (AEC 1967). A new license was issued to a new purchaser in 1966. In 1966–1967, this purchaser moved the residues from SLAPS (AEC 1967, FUSRAP 2004a) to a site at Latty Avenue in Hazelwood, Missouri (AEC 1967); this was said to have required ten dump trucks operating for five months to move a total of 100,000 tons of residue (AEC 1967).

AEC apparently proposed to the City of St. Louis that the city take over the site, specifically the city-owned airport management organization. Thus in 1969–1970, under a November 1969 acquisition permit from AEC and with some radiological support from the City of St. Louis Health Department, the St. Louis (Lambert) Airport Authority demolished the structures on the site and excavated some of the contaminated earth (AEC 1969; AEC 1972; ORNL 1979; FUSRAP 2004a). Excavated material, including some residual barium sulfate residues, was trucked to the AEC quarry at Weldon Spring (AEC 1969; AEC 1972), while the demolished structures, including the concrete floors and pads, were buried at the site and clean fill was placed over the entire site (AEC 1972). More fill was placed over several areas following a radiation survey performed in December 1969 to meet the requirements of the permit (ORNL 1979). In November 1971, AEC representatives performed a satisfactory final radiological survey of the site (AEC 1972; ORNL 1979).

In 1973, AEC relinquished ownership of the site to the St. Louis Airport Authority by quit claim deed (FUSRAP 2004a). After that, access was controlled by the St. Louis Airport Authority and casual entry was precluded (ORNL 1979). Over the period from about 1972 through 1978, the site served as an isolation or buffer space on the side of a runway approach at the adjacent airport and it was also used as a dump site for nonradioactive rubble from the airport; the fence remained in place, but the area was not patrolled (AEC 1979). Without maintenance, the site deteriorated, in that erosion occurred and minor contamination was transported to the drainage ditch that surrounded the site outside the fence and to the creek that traversed the lower end of the site (AEC 1979). This was shown in the radiological characterization surveys performed by Oak Ridge National Laboratory (ORNL) for AEC in November 1976 and August 1978 (ORNL 1979; AEC 1979). On the basis of these surveys, it was decided that remedial action was required (AEC 1979; FUSRAP 2004a) and in 1981 the drainage ditches along the north side of the site were designated for remedial action under FUSRAP (2004a).

The residues that had been sold and taken out of the site went to the Latty Avenue (St. Louis) site to await processing by the purchaser; however, the purchaser went bankrupt before processing actually began. Under a Nuclear Regulatory Commission (NRC) license, the Cotter Corporation then dried the residues in a kiln at the Latty Avenue site and sent them off to their Colorado facility. However, the Latty Avenue site was not properly decontaminated before the NRC license was terminated and the site was sold to a private purchaser. After an ORNL survey at the Latty Avenue site, the owner was advised by NRC to stop property development and the NRC asked the Department of Energy (DOE) to allow materials from the future decontamination of the site to be taken to the Weldon Spring Plant (AEC 1979). However, DOE considered the Weldon Spring raffinate pit to be unsuitable for

permanent disposal of these materials. NRC then suggested that the material be returned to SLAPS and DOE agreed, providing that this could be done in an environmentally acceptable manner (AEC 1979).

Eventually, the US Congress, via the Energy and Water Development Appropriations Act of 1984 (Public Law 98-360), directed DOE to reacquire and stabilize the SLAPS site and to use it as a storage and disposal site for the Latty Avenue materials (Bechtel 1987; DOE 1986). Although it postponed acquisition of the site even after being directed to do so by Congress, DOE had begun to have routine monitoring of SLAPS done by Bechtel National Incorporated in 1983 and as of 1987 was planning to dispose of the waste materials from the Hazelwood Interim Storage Site (including the Latty Avenue materials) at SLAPS eventually (Bechtel 1987). In October 1989, the Environmental Protection Agency (EPA) placed SLAPS on the National Priorities List, which meant that the cleanup would proceed according to the guidelines of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (FUSRAP 2004a). DOE then began to work with EPA to determine how to clean up the site and where to put the contaminated soil (FUSRAP 2004a). The two agencies signed an agreement establishing an environmental review process and remediation schedule, with one of the options to be considered being storage of the SLAPS and HISS materials at SLAPS; DOE declined to accept SLAPS back from the City of St. Louis until the CERCLA review process was completed (FUSRAP 2004a).

In 1990, the St. Louis Board of Aldermen approved a plan to transfer SLAPS to DOE on condition that a permanent disposal cell for radioactive wastes would not be constructed on the site (FUSRAP 2004a). In 1994, DOE formulated a remediation plan and presented it to the St. Louis community. The community rejected it because it included a disposal cell at SLAPS, contrary to the terms of transfer enacted by the board of aldermen; the site was therefore never transferred to DOE and it appears unlikely that it will ever be (FUSRAP 2004b). However, as of July 2004, FUSRAP was working to develop a Record of Decision to document the final cleanup remediation plan for the North County sites, including SLAPS–a plan that did not include a disposal cell at SLAPS (FUSRAP 2004b).

4.0 DESCRIPTION OF THE MALLINCKRODT URANIUM REFINING PROCESS, OTHER PROCESSES, AND SLAPS STORAGE AND DISPOSAL ACTIVITIES

It is important to understand the Mallinckrodt uranium refining process in order to understand the radiological hazards, to follow the changes in source terms and exposure potential, and finally to estimate the doses to individual workers. The basic process will be described here. Then particulars will be discussed for three cases: the early wartime period, the late wartime and early postwar period, and the later postwar period. Details regarding the types and quantities of ore, uranium products, and residues are shown in Table A-4; Table A-5 is provided as a reference for technical terms and keywords. An additional table is given within the text of Section 4.4 to illustrate the variety of feed forms that was used in later years.

It is also important to understand the nature of the work performed at SLAPS in order, again, to understand the radiological hazards, to follow the changes in source terms and exposure potential, and finally to estimate the doses to individual workers. The discussion of SLAPS work is included in the discussion of Mallinckrodt-produced residues (Section 4.7 below).

4.1 THE BASIC PROCESS

First the ore was prepared for uranium extraction, as follows. Milled ore, as ore concentrate (“black oxide”), was taken from its storage location(s), thawed if necessary in an enclosed “thaw oven” in the thaw house, and dried. It was then digested in nitric acid in a digestion vessel or tank (MED 1946a; AEC 1949b; AEC 1967; Fleishman-Hilliard 1967). Sulfuric acid was added to the solution in the vessel to precipitate the radium and lead as sulfates (MED 1946a; AEC 1949b; AEC 1951b; AEC

1967; Fleishman-Hilliard 1967). The uranium was left in solution as uranyl nitrate and the precipitate was filtered out (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967) using a string-discharge rotary vacuum filter (AEC 1967) referred to as a Feinc because of the name of its manufacturer (Federal Engineers Incorporated or FE Inc). The filtered solids formed a radium-bearing residue referred to as the K-65 residue (AEC 1949b; AEC 1967) or GLC ("gangue lead cake") (MED 1946a). Next, a slurry of barium carbonate was added to the uranyl nitrate solution to remove the sulfates, when present (MED 1946a; AEC 1949b; AEC 1951b; AEC 1967; Fleishman-Hilliard 1967). To remove the solids, the mixture was run in a continuous solid-bowl centrifuge (also referred to by the name of its manufacturer, Bird) (MED 1946a; AEC 1949b; AEC 1967). The uranium remained in solution as uranyl nitrate and the precipitate formed a barium sulfate cake. The uranyl nitrate solution—the "liquor"—was then boiled to concentrate it (MED 1946a; AEC 1951b). Calcium nitrate was added to the solution to assure nitrate saturation (MED 1946a), then the solution was filtered to remove any solids formed. The acidity of the solution was adjusted as needed by adding acid (AEC 1967; Fleishman-Hilliard 1967).

Second, uranium oxide as UO_3 was produced from the solution, as follows. In the two-step ether extraction process, diethyl ether was added to the solution in extraction columns; the double extraction was to remove the acid-insoluble molybdenum (AEC 1951b). The first step was the acid ether extraction, including ether addition, nitric acid addition, and re-extraction into water (also called a "water wash"), while the second step was a neutral ether extraction followed by re-extraction into water (MED 1946a; AEC 1949b; AEC 1951b; AEC 1967; Fleishman-Hilliard 1967). Eisenbud (1975) stated that in the ether extraction process, the isotopes of thorium and protactinium were left in the "aqueous phase" while the uranium was stripped off by the solvent (ether), so presumably the thorium and protactinium were separated from the uranium in the first step of the ether extraction process, before or as part of the water wash.

After the ether extraction was complete, the uranyl nitrate extract solution was boiled to the molten salt to form uranyl nitrate hexahydrate ("hex liquor" or "OK hex liquor") (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). The molten salt was then directed in batch form to gas-fired denitration "pots" or boildown vessels, which were continuously heated and agitated so as to produce the dissociation of the hexahydrate and the formation of UO_3 (also called orange oxide or QM-2) (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). The UO_3 lumps were often broken up by crude mashing, but there was also a formal double grinding process requiring the material to be moved to the grinding area (MED 1944o).

Third, the UO_3 was placed on thin trays, placed in airtight boxes, and loaded into a batch electric (muffle) furnace to react with dissociated (cracked) ammonia to form UO_2 (also called brown oxide or LF-9), a step that took about 7 hours (MED 1949b; MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). Usually the UO_2 was further processed at Mallinckrodt, but some was shipped to non-Mallinckrodt sites such as Harshaw (DOE 1997).

Fourth, the UO_2 was converted to UF_4, as follows. The UO_2 was removed from the fiber containers and placed into large stainless steel drums for temporary storage (AEC 1949b). As needed, it was removed onto steel (later monel) trays and weighed (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). The trays were then set into airtight graphite or nickel boxes and placed in a hydrofluorination reactor (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). (Note that this was not a nuclear/atomic type of reactor but rather a chemical reaction vessel.) In the reactor, hydrogen fluoride gas (HF) was passed over the UO_2, forming UF_4 (also called green salt or TA-7) and water (MED 1946a; Fleishman-Hilliard 1967). The UF_4 was unloaded and put through a pulverizer or mill and then a blender, followed by packing into metal containers (AEC 1949b). Most of the UF_4 was further processed at Mallinckrodt, but some was regularly shipped to non-Mallinckrodt sites (DOE 1997; AEC 1949b); however, MED (1946) implies that all of the UF_4 produced at Mallinckrodt was also further processed

there. Excess HF was neutralized with lime or potassium hydroxide solution to recover uranium (Mason 1977).

Fourth, the UF_4 was converted to uranium metal, as follows. The UF_4 was blended with magnesium powder and mixed in a tumbler (AEC 1949b; Fleishman-Hilliard 1967; Mason 1977). A special firing container (the "bomb") was lined with a refractory material, variously reported to be lime (1945, per MED 1946a); dolomite (from 1946 on, per FUSRAP undated a, or 1942 on, per Fleishman-Hilliard 1967); or recyclable magnesium fluoride from about 1954 on (FUSRAP undated a; Fleishman-Hilliard 1967). The bomb was "jolted" (shaken) on a mechanical jolter until the liner was packed sufficiently hard. The mixture (the "charge") was then placed in the bomb. After the bomb was sealed, it was placed in a gas-fired furnace and heated until it "fired"; the magnesium reduced the UF_4 to uranium metal in this process (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). The molten mass formed a "derby" or "biscuit" of solidified metal as it cooled (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). (The derby form was also called KB-2 and there were subtypes of derbies called Number 1, Number 2, etc.) After the bomb cooled, the derby was taken out by "breaking out" the bomb shell (Mason 1977) and the slag on the derby was chipped off pneumatically, crushed, and sent to uranium salvage (recovery), first to Vitro and eventually to onsite recovery (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967; Mason 1977).

Finally, the metal derbies were remelted and cast in an induction-heated, high-vacuum furnace (a process called vacuum recasting). In this process, the derbies were placed in a crucible, the crucible was placed over a mold, and the crucible-mold assembly was placed in a quartz shield, sealed, evacuated, and placed into the furnace (MED 1946a; Fleishman-Hilliard 1967). There was a stopper rod at the bottom of the crucible that was removed when the critical temperature was reached, allowing the molten metal to flow into the mold and form a cylindrical ingot or billet (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). (The billet form was also called YM-5.) The billet was then removed from the mold by separating its parts. The porous impurity-heavy top section was cropped off and sent for recovery; the other surfaces were cleaned of liner ("C-liner") slag and other impurities (MED 1946a; AEC 1949b; Fleishman-Hilliard 1967). A sample was taken from the billet by power hacksaw (AEC 1949b) and the billets were sawed to suitable lengths (presumably only when necessary) (Mason 1977). The billets were then packed, stored temporarily in Building 400 (Mason 1977), and shipped to the appropriate non-Mallinckrodt site for further processing (MED 1946a; AEC 1949b; Mason 1977).

The nitric oxides produced as offgasses in the pots were sent to a recovery system (MED 1946a; AEC 1949b; FUSRAP 2003b) where the nitric oxides were converted back to nitric acid. The GLC residue and the barium sulfate cake were usually leached with sodium carbonate to remove the residual uranium (AEC 1967).

The precipitate from the first extraction column was on occasion dewatered using a Sperry filter press, producing a supernate and a batch of cake called Sperry cake (AEC 1967). The supernate from the press and the aqueous uranium tails from the wash were de-etherized and treated with a hydrated lime slurry (AEC 1967). This was passed through a continuous rotary vacuum leaf filter (referred to by the name of its maker, Niagara); the supernate was discharged to the local river and the limed fraction became AM-7, called "airport cake" (AEC 1967), from its being stored for several years at the AEC's SLAPS site that had been an airfield. Note that the Sperry cake appears to be a subset of the AM-7 or perhaps synonymous with it. Also, several other types of cake (e.g., the barium sulfate cake) were also referred to loosely as "airport cake" due to their being sent there for storage.

4.2 THE WARTIME PERIOD (APRIL 1942–APRIL 1945)

In the first months of refining by Mallinckrodt, a different extraction process from the ether extraction was used since the latter had not yet been developed. No information could be found as to the details

of the first process; however, the ether extraction process seems to have been in the process of development at Mallinckrodt from April 1942 on and in use from July 1942 on (DOE 1997; AEC 1967; Fleishman-Hilliard 1967), so the first process could have been used for about three months at most (mid-April to mid-July). The magnesium reduction process for metal production was developed by Iowa State by about mid-July 1943 (DOE 1997) and Mallinckrodt established the first metal plant, Plant 4, during the same month (Fleishman-Hilliard 1967). Mason (1977) stated that there were no wet processes in Plant 4 (ever).

Initially, the work consisted primarily of the production of UO_2 and UO_3 from mined ore marginally milled (FUSRAP undated b); some preliminary milling to "black oxide" (a form of U_3O_8 concentrate) thus had to be done, some of it at Mallinckrodt (DOE 1997). The ore had to be ground to "four mesh" size for optimum digestion as well, if the ore particle size was larger (MCW 1947). Little information is available as to how or where the early milling and grinding operations were performed, but it was apparently in Plant 2 (see Table A-1), later in Plant 4 (AEC 1945f; AEC 1945h; AEC 1945i), and still later in Plant 6 (e.g., MCW 1950e). Some soda salt was also used as feed material (DOE 1997). Note that the radium-lead precipitation step was necessary for the high-radium pitchblende ores, but not necessarily for other types of ore.

Plant 4 began production-level UO_2-to-UF_4 conversion in April 1943 and production-level UF_4-to-metal production in July 1943. The ore$\rightarrow UO_3 \rightarrow UO_2$ conversion continued to be done in Plant 2. MED (1942) stated that the ether extraction was done by a completely enclosed process of "recirculating" and that a solution of purified uranyl nitrate was boiled in large open receptacles to decompose the nitrate and produce the UO_3. The UO_3 was then ground and sifted to yield the appropriate size for "roasting" in a furnace to produce the UO_2.

AEC (AEC 1951b) stated the following. The process of refining pitchblende ore by using nitric acid, including the radium removal technique and acid extraction were developed by Yale University but expanded to production scale by Mallinckrodt during this period; also, double extraction to remove molybdenum when pitchblende ores were processed and the balance of the processing to UO_3 were developed by Mallinckrodt. The UO_2 hydrofluorination process was developed by DuPont and Harshaw, while the process for reduction of UF_4 to uranium metal was developed by Iowa State College at Ames. The research for the continuous UO_3-to-UF_4 process was done by Mallinckrodt.

4.3 THE EARLY POSTWAR PERIOD (MAY 1945–DECEMBER 1949)

As noted above, processing of significant quantities of pitchblende ores began at Mallinckrodt in about May 1945 and accelerated with the start of Plant 6 in 1946.

During and after the war, African and Canadian ores were milled to black oxides elsewhere and at Mallinckrodt (DOE 1997, Mason 1958a); at Mallinckrodt, this moved from Plant 2 (apparently) to Plant 4 (AEC 1945f; AEC 1945h; AEC 1945i) and then to Plant 6 after the latter began operation in 1946. Because of the dust hazards of the pitchblende ore, AEC had Mallinckrodt develop a method to permit automatic unloading and loading of the pitchblende ore in the grinding operation (AEC 1948f). Mason (1958a) gives data showing very high dust levels for ore milling, so the process was apparently not an entirely enclosed one. Ore milling stopped in mid-1949 (Mason 1958a) and after that all ore arrived mill-processed. The ore delivered to Mallinckrodt after that apparently still had to be ground to some extent (e.g., AEC 1947a).

The continuous countercurrent ether extraction process was developed in 1945–1946 and put into production with the start of Plant 6 in 1946 (Fleishman-Hilliard 1967). The sulfur removal (barium sulfate precipitation) step was added when ores containing high levels of sulfur were used. The continuous countercurrent process eliminated the necessity of moving the intermediate materials batchwise from one process location to another as had been necessary at Plants 1 and 2; rather, the

materials passed from vessel to vessel or filter via piping. There was apparently still some possibility of "splatter or slopping over" at some point if the chemical reaction was too violent, but this would not be true of the column extraction process because it was completely enclosed (AEC 1949e). The sulfur removal step was added when ores containing high levels of sulfur were used. However, the removal of products such as UO_3 and UO_2 was usually done by manual scooping and the removal of waste products, such as the filtered-out solid wastes and recovery products, was usually done by manual methods such as scraping.

As noted earlier, Plant 6 was shut down for a time in 1949–1950 for modifications; it seems likely that the end of ore milling coincided with this shutdown. Mechanization improvements during this period decreased the amount of manual and close-in handling of ore and the other uranium forms, but there was still a significant amount, especially with regard to the intermediate solid forms (UO_2, UO_3, and UF_4) produced as particles and chunks of material. Also, during the first year of operation (1946–1947), it had become apparent that not all of the uranium in the pitchblende ore was being dissolved in the nitric acid step, but was remaining in the "K-65" or gangue sludge residue that was to be stored and returned to African Metals Company; a process was developed and installed in 1948–1949 to allow greater capture of the uranium from the ore (see Section 4.7).

It was realized that the UO_2-to-UF_4 production in Plant 4 was particularly problematic from a dust point of view and AEC therefore had Mallinckrodt embark on an experimental program to produce a continuous-process reactor for the production of UF_4 (AEC 1948f).

4.4 THE LATER POSTWAR PERIOD (1950–1958)

Milled ore was sent from Middlesex to Mallinckrodt up to 1955, when the Middlesex work was transferred to the Fernald plant, which thereafter was the sender of milled ore to Mallinckrodt (DOE 1997). An Ore Room and addition were added by 1950 to Plant 6. Early on, there was grinding of ore in a rod mill and opening, dumping, cleaning, and closing of drums (MCW 1950u); later, the duties of the operator included opening (deheading) and cleaning ore drums (AEC 1953). Hence this was not simply a storage area. During 1950, the average concentration of raw materials arriving at Mallinckrodt dropped to less than 50% (as U_3O_8), compared to ~65% during 1947–1949 (AEC 1951b). This was due to a gradual decrease in the content of the pitchblende and to the introduction of the magnesia concentrate MgX, which was produced from low-grade tailings. The new feeds had higher impurity content and the MgX contained 25–30% moisture compared to the normal pitchblende content of less than 3%. In order to maintain the production level, a new extraction column was designed and installed by Mallinckrodt in December 1950 to permit direct solvent extraction of the MgX slurry without prior filtration.

During the period 1950–1951, Plant 6E and Plant 7 went into operation as previously described and a number of further process and equipment changes were made to reduce exposures, principally in the area of dust control and mechanization (see Table A-3). The main reason for the provision of new plant space was to reduce exposures, but it is notable that in each case, production increased markedly after a new plant was added, sometimes to several times the original anticipated capacity (Mason 1958a). Thus the exposure-reduction changes were sometimes successful and sometimes not. In late 1950 or 1951, in order to increase production, Plant 6E was placed in six-day, three-shift operation as quickly as new crews could be trained (AEC 1951b), while Plant 7 was designed to operate on a six-day, three-shift schedule.

AEC (AEC 1951b) stated the following. In 1951, the Plant 4 UO_2-to-UF_4 conversion equipment consisted of six large gas-fired furnaces containing five reactor banks each. The individual reactors were composed of a graphite tray assembly inside of a steel shell. The Plant 4 UF_4-to-biscuit equipment included six individual gas-fired furnaces, and the biscuit-to-ingot conversion equipment included four high-vacuum induction furnaces. The Plant 6E UF_4-to-biscuit equipment included 16

electrically heated induction furnaces and the biscuit-to-ingot equipment included six ultrahigh-vacuum furnaces. In Plant 6E, operations were mostly remotely controlled and/or totally enclosed, for health and safety reasons. In Plant 7, there were three parallel reactor banks, each made up of one UO_3-UO_2 reactor tube and three UO_2-UF_4 reactor tubes, with the four reactors making up the bank operated in series. Each reactor tube was equipped with a ribbon screw that moved the material continuously through the reactor into the feed area for the next tube. A single UO_3-UO_2 tube was installed to provide for the production of UO_2 alone. The later expansion called for additional UO_2-UF_4 tubes to be added.

Some time prior to August 1954, the Ore Room and K-65 sampling operations in Plant 6 appear to have ended, probably due to the end of high-grade ore processing. The Plant 6 pilot plant was constructed in 1949–1951 and began operation at some point during that period (Fleishman-Hilliard 1967); references to it started to appear in AEC air dust study reports by 1953 (AEC 1954c). The purpose of this pilot plant was said to be process and product improvement (Fleishman-Hilliard 1967). An AEC dust exposure report giving time-and-motion information states that a Pilot Plant 6 technician was cleaning old MgF_2 out of a kiln, putting in new MgF_2, and scooping Anaconda feed (sodium diuranate) into a digestion tank (AEC 1956b). Thus it is likely that the pilot plant was working on the development of improved methods for various parts of the refining processes. The research laboratory was constructed and put into operation during the same period as the pilot plant (Fleishman-Hilliard 1967).

The Plant 6E operations became more enclosed and more mechanized over the years. In 1955, the billet (ingot) postprocessing grinding and inspection method in Plant 6E was described as follows (MCW 1955q); it is likely that this was the method used from the start but with the addition, over time, of the grinding enclosure for operation. The operator moved the billet from the water cooling tank into grinding position by means of a remote-controlled hoist. Through canvas gloves installed in the enclosure wall, he ground off the fin (raised line) from the mold joint. Using a remote-controlled piston, he then ejected the billet from the grinding rollers on the scale through a small opening in the enclosure. Using a rag, he wiped off the excess black oxide as he rotated the billet slowly, checking it for defects. He then moved the billet by hoist onto the billet cart to move it to the saw for a sample to be taken.

An alternative method of producing the metal form was developed at Plant 4 in the mid-1950's. This process (AEC 1956a; Fleishman-Hilliard 1967) took the UF_4 to the final cast (ingot/billet) form in one step instead of two, eliminating the need for recasting and the associated impurity contamination. The result was a massive single ingot, called a dingot, weighing about 3,300 pounds. In this process, a bomb was lined at the bottom with MgF_2, a mandrel (mold liner support) was inserted into the bomb, more MgF_2 was poured into the space between the bomb shell (wall) and the mandrel, and the bomb was jolted to pack the liner hard between the mandrel and shell. The UF_4 and MgF_2 were blended and put into a drum, which was then capped and removed to a charging station. The drum was inverted over the station insert collar, the drum cap valve was opened, and the charge was allowed to flow into the bomb. During this step, the operator used a long stainless steel rod to "pole" the charge down into the bomb; the operator also used a mechanical rammer to tamp it down for maximum density. Recycled slag containing MgF_2 and U was added to the top of the charge and tamped. Finally, the exterior of the bomb was vacuumed and a steel lid applied. The bomb was removed by hoist to a "Hevi-duty" furnace, where the thermite (metal-metal reduction reaction) took place.

Because of the size and purity of the dingot, the postcasting processing differed from that of the derby and billet. The bomb was cooled in air, and then transferred to a breakout enclosure where it sat over a downdraft-ventilated floor grill. The bomb was inverted over the grill and the contents jolted out onto the grill. The slag liner was broken with a mechanical sledge hammer and swept onto the grill and down into a hopper. A conveyor took it to a grinder, from which it was discharged into drums and taken for reprocessing (presumably in Plant 6E—see below). The dingot was cleaned with a

pneumatic chipping hammer over the grill and then removed to a machining area, where it was "scalped" (had the outer surface trimmed off) on the top and sides with a vertical turret lathe. If samples were needed, it was then taken to a saw area and sections were cut off with mechanical hacksaws. Finally, the dingot was put into a salt bath and heated for several hours, then put on the bed of a 100-ton forging press that had a mechanical manipulator for positioning. It was pressed into a slab for several minutes, and then returned to the salt bath for about an hour for reheating. This process was repeated four more times, with the piece being rotated on the press between passes. The forged slab was then quenched and taken to storage.

Fleishman-Hilliard (1967) implies that Mallinckrodt also produced extruded billets from these dingots, at least on an experimental basis. Once extruded into a much longer and thinner cylinder, the billet was cut into shorter lengths.

Plant 7 was built not only to increase production of UF_4, but also to take advantage of the new continuous process using a "stirred bed" reactor for producing it (Mallinckrodt 1994, Fleishman-Hilliard 1967). At some point not long after this process went into operation, the process was modified to allow production of UF_4 continuously from a UO_3 feed instead of a UO_2 feed, thus eliminating a transfer step (Mallinckrodt 1994, Fleishman-Hilliard 1967). At this point, UO_3-to-UO_2 production at Plant 6 seems to have ceased or at least to have decreased significantly.

By 1955, Mallinckrodt was using a variety of feed forms from many different sources to produce the various uranium product forms. Table 4-1 (AEC 1955a) illustrates this for a typical period in 1955; figures are in tons.

Table 4-1. Feed forms and quantities (in tons) used for a period in 1955.

	January	February	March	April	
To be produced:					
QM-2	500	465	535	510	
TA-7	280	355	320	320	
TM-5	205	240	270	260	
Shipments to NLO:					
QM-2	235	155	170	170	
YM-5	All finished metal of the metal plant plus all shippable metal from the pilot plant				
TA-7	0	100	100	45	

Feed type	January consumption	January 31 inventory	February receipts	March receipts	April receipts
Q-11	76	8	86	---	---
MgX	26	10	40	64	30
South African	---	---	129	80	90
Portuguese	21	---	40	---	20
Colorado soda salt	46	12	50	50	50
Beaver Lodge	23	31	28	28	28
Vitro	9	---	---	---	---
Colorado black	92	12	50	50	50
Canadian black	43	17	25	25	25
NLO Recycle/Scrap Plant	27	15	20	20	20
MCW	18	---	15	15	15
Miscellaneous	---	---	---	---	---
Dissolver	24	77	20	20	20
Sawdust	5	6	5	5	5

A list of process cells, dust collectors, and tanks appears in reference MCW 1955g.

4.5 OTHER PROCESSES

Some uranium recovery operations consisted of processing solid scrap wastes, such as the portions of billets removed as assay samples, to recover the valuable uranium and thus to maximize the uranium obtained per unit quantity of ore. This was probably done in the early years by digestion of the scrap in nitric acid (FUSRAP 2003a). Sawdust (from the sawing of uranium metal billets) was stored under oil until it could be processed in this way and converted to ingots (Fleishman-Hilliard 1967; MED 1944o; MED 1944p); the sawdust was also recovered by oxidizing it at high temperature to U_3O_8, and then sending it back to Plant 6 as a feed material (AEC 1949g). As mentioned earlier, some uranium was recovered from neutralizing excess HF in the UF_4 production process (Mason 1977).

In early 1954, a slag separation plant was built at Plant 6E, apparently as a six-level wing (116C) on Building 116, to recover most of the uranium content from the MgF_2 slag produced there in the UF_4-to-derby operation (AEC 1959, AEC 1954f). The slag was fed into a jaw crusher on the first level, then the crushed slag was conveyed on a “vibro conveyor” to a bucket elevator and on to a roll mill hopper on the 6th level. From there the slag was gravity-fed via a roll mill feeder into a series of roll mills and screens on the middle levels. Reject material from the last mill screen flowed by gravity feed into a reject hopper and then to a reject drum on the 1st level. Discharge streams from the roll mill and the roll mill screens were fed into a ball mill. The discharge from the ball mill was conveyed by a bucket elevator to a series of air classifiers; after passing through these, the separate product and reject streams flowed by gravity feed to the respective drums on the first level.

In late 1955 or early 1956, operations to process slag began in Building 701 in Plant 7. This building was then called the Slag Separation Plant or the Slag Processing Plant. According to AEC (1956d), the feed material was uranium concentrate from reject MgF_2 material (RMF). The RMF was charged from drums into a skip hoist that discharged into a hopper serving a rod mill. In the mill, the RMF was crushed and water was added to make a slurry. This was passed through a mechanical screen shaker; the part that did not pass through was recycled through the rod mill and the part that did pass went onto three successively smaller-sized Wolfey gravity feed tables. The tables separated the uranium-bearing slurry from the rest of the slurry, with the former being allowed to run off the last table into a screw conveyor. The slurry was then fed into a drum. This drummed material was referred to as "U-Con" or "U-CON." The non-uranium-bearing slurry was pumped to settling tanks and then to a rotary filter; the resulting cake (D-701) was discharged into dumpsters (buggies) and taken to the SLAPS waste storage site.

Little information could be found about shipping, receiving, and storage operations and about the milling of the UO_3, except that it was apparently done in Plant 2 until the work moved to Plant 6 (Mason 1958a). See Sections 5.2.1–5.2.3 for more details. The ore areas and residue storage areas appeared to be separate from the product warehouse areas, however.

Similarly, regarding the reversion of UF_4 to UO_2 or UO_3 (or U_3O_8) there was little information except for a short reference in an AEC Plant 7 air dust study report (AEC 1954g) to the work of a panel board operator's work: the operator was said to vacuum "C-31 material" from a drum into a "reverter." What the C-31 material consisted of was unclear, but often the "C-" designated scrap material or waste material captured in a dust collector. Later such AEC reports also mention that the reverter was being used by this operator (AEC 1955d, AEC 1956b) but not mentioned in an earlier report (AEC 1952a), so presumably this work continued from at least 1953 (the date of the AEC 1954g survey) to the end of Plant 7 operation.

There was no information about processing very low enrichment (VLE) uranium beyond what was given in Section 3.0 above, except for a reference in an AEC air dust study report for Plant 7 in which it was stated that the subject AEC survey covered "health and safety problems existing during production and processing green salt, with the added operation of processing enriched uranium"; the panel board operator was said to include among his observed duties "charging enriched UF_4 into hopper" and "replacing enriched material drum and sample bottle" (AEC 1955e). Since there was no further mention of any of these activities in later such reports, it appears that this operation may have been performed for only a short period of time, e.g., to use up excess UF_4 from another site. There is no indication that Mallinckrodt itself produced the VLE UF_4. In any case, the operations described appear to have been of a routine process nature.

There was no information at all about the production of UO_2F_2 or the processing of (supplied) uranyl nitrate hexahydrate, both of which functions were mentioned by only a single reference source (see the summary list of work in Section 3), with no details given. There was information (AEC 1955d) regarding an experimental process begun in Plant 7 in 1956 in which MgF_2 liner (MFL) was treated to reduce the hydrogen content for use in dingot bombs. This created fluorinated MFL (FMFL, perhaps also called D-30). However, this process appeared not to involve any radioactivity except what would likely have been present in the ambient air due to other processes. Also, Fleishman-Hilliard (1967) commented that the reason for adding a little UO_2F_2 to a bomb was to slow down the process thermally, resulting in a better separation of slag and metal.

An experimental permit was issued in July 1956 that allowed the pickling of 14 tons of high-carbon scrap metal in Plant 6, which was done on 29–30 July 1956 without the health and safety department's knowledge (MCW 1956f). It is not known if any more of this work was done.

Mallinckrodt (1994) estimated that small-volume batch and experimental uranium-related processes constituted less than 0.3% of the total uranium produced. Some of the processes considered in this estimate were the conversion of slightly (very low) enrichment feed materials to metal or uranium nitrate liquor, extraction of Th-230 from pitchblende raffinate, production of U_3O_8 and UO_2 using an experimental continuous denitration furnace, experimental extraction of uranium using tributyl phosphate to replace ether, production of uranium metal dingots, and recycling of slag for use as liner material. This supports an assumption that only a negligible part of total processing activities involved such short-term and usually low-volume processes.

Regarding specific laboratory sampling and assay processes, there is limited information available. This is given in Section 5.2.4.

4.6 ORES AND OTHER FEED FORMS

In the early years, the ore arrived as a milled concentrate from Canada (Mallinckrodt 1994), consisting mostly of black oxide (U_3O_8) (Mallinckrodt 1994; Fleishman-Hilliard 1967); MED (1945) stated that the Eldorado mine site in Port Huron, Canada, was a source of black oxide to Mallinckrodt. These concentrates were produced at offsite uranium mills and were free of radium and its decay products (Mallinckrodt 1994). That is, in the early years, Mallinckrodt did not process the high-radium-containing ore of later years. Although the uranium was mostly supplied to Mallinckrodt in already milled form (as black oxide), some milling and pre-processing of high-grade uranium ore was performed at Mallinckrodt (FUSRAP 2003c).

The Vitro plant in Canonsburg, Pennsylvania produced sodium diuranate ($Na_2U_2O_7$), also called soda salt, some of which was sent to Mallinckrodt for refining to UO_2 and UO_3 (DOE 1997, MED 1945a; MED 1943e); other soda salt may have come from Belgium and Port Hope, Ontario (MED 1943e). This appears to have been digested in the same fashion as the black oxide. Soda salt and other non-ore feeds were referred to as “soluble feed.”

Other wartime ore sources were pitchblende ores from Canada (Radium City in the Great Bear Lake Area and Port Hope in Ontario) (DOE 1997; Eisenbud 1975). Later in the war, domestic ores were used also; the principal Colorado source during the war was not the carnotite ore itself, but tailings from vanadium mining and milling, shipped as a concentrated sludge (Eisenbud 1975).

In about 1944, AEC wanted to increase production of uranium, not only by increasing capacity but by using high-grade pitchblende ores. However, such ores had the disadvantage that they contained a high level of radium as a decay product of the uranium. This entailed significant gamma and airborne exposure hazards. It was because of the limitations of Plant 2 with respect to capacity and hazard that Plant 6 was designed and built (Mallinckrodt 1994). Another consideration was that crude concentrates and pitchblende ores tended to have undesirably high levels of sulfur, which necessitated the extra precipitation step for removal (Fleishman-Hilliard 1967). The high-level ore was used as a principal feed material from May 1945 until early in 1955 (AEC 1956e; AEC 1959), when the plant switched to processing various types of concentrates. However, MED (1943e) remarked in 1943 that there appeared to be more “radiation” in the U_3O_8 being received by Mallinckrodt from Port Hope, suggesting that pitchblende ore concentrates may have been used as feed prior to May 1945. It is known that experimental processing with pitchblende ores was done in 1944 at Plant 1 (Mallinckrodt 1994), so this may explain the 1943 reference.

Most of the high-grade pitchblende ore processed by Mallinckrodt was obtained by AEC as a concentrate from the Belgian Congo in 1944 (AEC 1967), the so-called African ore. There is some disagreement as to how it came to St. Louis. DOE (1997) states that from 1943 on, the receiving and storage facility operated at Middlesex, New Jersey (DOE 1997) assayed, crushed, riffled, and redrummed the ore as it came into the United States, then sent it to the various refineries, including

Mallinckrodt (AEC 1949b, Eisenbud 1975). MED (1945n) states that the African ore came through the Eldorado (Port Huron, Canada) area for processing before being sent on to the US refineries. AEC (1967) states that the concentrate was shipped from the Belgian Congo to St. Louis in 55-gallon drums (but this could mean that it came by way of Middlesex). Whatever the case, it was not likely that significant milling of this ore (as opposed to simply grinding to somewhat smaller size) was done at Mallinckrodt. In any case, it arrived by rail in carload lots and was stored in Building 110, the warehouse (Mason 1977).

After World War II, foreign uranium ore was supplied from the Belgian Congo, Canada, Australia, South Africa, Portugal, and other nations. Besides the foreign ore, domestic carnotite ores began to be mined directly, milled elsewhere, and then sent as ore concentrate (mainly U_3O_8) to Mallinckrodt. Early postwar domestic ore supply areas included Uravan, Durango, Grand Junction, and Naturita, Colorado, and Monticello, Utah (DOE 1997). Once the US began to stimulate domestic mining and milling in 1948, the proportion of domestic ores used appears to have increased; thus the overall concentration of uranium in the ore may have decreased over time. The ore was usually stored in the warehouse or in another dedicated area on site, but presumably because of the volume of the pitchblende ore (Q-11) and its hazards, from about mid-1948 on at least some of it was stored at SLAPS (AEC 1949d) in a dedicated shed or shack (MCW 1949g; AEC 1949d, which states that ten 25-ton lots were shipped to Mallinckrodt in May 1949 and an additional twelve lots were sent to SLAPS).

From 1955 on, ore concentrates were mostly used. This included some Belgian Congo ore tailings concentrates (resulting from the leaching of raw ore during pre-processing in the Belgian Congo in previous years before the ore was shipped as a concentrate) (AEC 1951b). Soda salt appears to have been sent from several sites; a description of some work indicated that Fernald, Durango, and Anaconda diuranate were being handled by a soluble feed operator (AEC 1956b) and as noted Vitro also supplied soda salt until it was shut down.

4.7 RESIDUES AND EFFLUENTS

The radium-bearing pitchblende residues (wastes) were always stored separately from the non-radium-bearing residues and the barium-bearing and other types of cake (AEC 1967); thus the external exposure implications of handling residue waste depended on what kind of waste it was.

From 1942–1945, MED solid wastes were stored temporarily at the Mallinckrodt site and then shipped to the Lake Ontario Ordnance Works in Lewiston, New York (Mallinckrodt 1994). The radium-bearing pitchblende residues (K-65 or gangue lead cake) were shipped by rail to the Middlesex, New Jersey repository for storage for a time, up to 1946 (AEC 1949b). But from the time AEC acquired the SLAPS site in 1946 and up through 1948, all residues produced at Mallinckrodt were stored temporarily in Building 114 of Plant 6 until they were shipped by truck to SLAPS (MCW 1949p; AEC 1967; Mason 1977; Mallinckrodt 1994). From 1948 to at least 1949, the K-65 residues were shipped to Middlesex (AEC 1949b) or to the Lake Ontario Ordnance Works (AEC 1959) after being drawn back from SLAPS and reprocessed. After about 1949, K-65 was shipped to the Lake Ontario Ordnance Works (FUSRAP undated a; AEC 1959; AEC 1949b); although Mallinckrodt (1994) says that these were still sent to SLAPS up to 1956, it was clearly only the other types of residues and wastes that were sent after 1949, not the K-65. Some uranium scrap, including the mainly magnesium fluoride slag immediately above the derby (in the metal reduction step) was sent to the Vitro Manufacturing Company for uranium recovery (AEC 1949b).

Initially, it was only the K-65, the barium sulfate residues (AJ-4 or “airport cake”), and the pitchblende raffinates (AM-7) produced at Mallinckrodt that were stored at SLAPS (Mallinckrodt 1994). The K-65 was trucked in drums (AEC 1947a), while the barium sulfate (AJ-4) and pitchblende raffinate (AM-7) cakes were collected in dumpster-type containers, loaded into AEC dump trucks, and transported on

a daily basis to SLAPS (Mallinckrodt 1994). The K-65 drums were stored in a dedicated shed structure (AEC 1947a), but the other residues were simply dumped on the ground in piles (AEC 1947f; AEC 1947a; AEC 1947e; AEC 1949b) because they were insoluble in water and were thus regarded as fairly immobile (AEC 1947a).

Later, SLAPS was also used to store other types of residues and wastes and some ore and to serve as a storage and burial site for contaminated objects and debris, such as empty drums, Rauschig rings from the ether extraction columns, bituminous floor materials, and some materials from the decontamination and decommissioning of Plants 1 and 2 (AEC 1959; AEC 1956d; Mallinckrodt 1994; AEC 1949m). As noted earlier, the other types of residues included the AM-9 residue left after reworking of the AM-7 to recover thorium; Colorado (domestic carnotite and other low-grade non-pitchblende) ore raffinate (AM-10); and the precipitate residue of the ether extraction columns ("Sperry cake," apparently a subset of the AM-7) (AEC 1956e; AEC 1967; AEC 1964; Mallinckrodt 1994). There were also small amounts of other raffinates present at the SLAPS waste storage site from the processing of lower-grade uranium ores (AEC 1967). The material obtained from processing carnotite and other low-grade domestic ores was kept separate from the K-65 (AEC 1967).

Metal plant waste, such as metal scrap, dolomite slag ("C-liner" or "C-oxides"), and tailings of uranium scalping operations from magnesium fluoride slag were also sent to SLAPS (Mallinckrodt 1994). The C-liner was mainly used and nonrecyclable dolomite liner with less than 2% uranium content (FUSRAP undated b; AEC 1949b) and resulted from the separation of slag in the reduction (bomb) step in the metal plant (first in Plant 4, later Plant 6E). This waste was created until early 1953 when the dolomite liner was replaced by a recycled magnesium fluoride liner (FUSRAP undated b). There was another bomb waste called "C-special" (AEC 1949b), which may be the same as the C-liner slag since it also originated in the bomb furnace. Yet another bomb waste was the recyclable magnesium fluoride slag that remained after "scalping" the uranium content from the magnesium fluoride slag, beginning in 1955; this was called C-701 (FUSRAP undated a).

Within the Mallinckrodt plants, most "product" (UO_3, UO_2, and UF_4) was packaged into 75-lb paper sacks and then into a barrel. There was usually a fine film of uranium material clinging to the sacks, so they were burned in an incinerator and the ashes sent to recovery (MED 1944o). Floor sweepings and spillages, swept into sumps; scrapings off the walls and equipment; and dust collected in collectors, usually by vacuum systems (MED 1944o) were also sent to a recovery system.

Some reprocessing of residues was also done to recover uranium. AEC (1951b) states that following the development and installation of a sodium carbonate/sodium bicarbonate leach process in 1948–1949 to recover more of the uranium, the K-65 produced up to that point was brought out of storage at SLAPS in lots and reprocessed in about 1949 (MCW 1949o and AEC (1959) imply 1948–1949), resulting in a final uranium content in the residue of 0.05%. This was apparently done in the same vessels and in the same general manner as ore would be processed, including heating the K-65 drums in the thawing oven used to thaw ore drums (MCW 1949o). The new residue was sent to the Lake Ontario Ordnance Works (AEC 1959) to await return to African Metals and the corroded drums in which the K-65 had been stored were returned to SLAPS for storage (AEC 1949m). At least some of the barium sulfate cake was reprocessed similarly (AEC 1951b; AEC 1948g); however, the resulting barium sulfate residue was taken back to SLAPS because (eventually) African Metals relinquished ownership of it (AEC 1959). Some of the Sperry Cake, a good source of protactinium-231, was brought back from SLAPS and shipped to Mound, which processed approximately 20 tons (about eighty 55-gallon drums) of it and obtained approximately two grams of protactinium-231 (AEC 1967).

In late 1954 or early 1955, a new subplant, called Plant 7E, was established. This was part of what was referred to as the Minor Elements Production (ME or MEP) facility that did smaller-scale processing and development in Plant 7. The purpose of 7E was to process some of the AM-7

(pitchblende) residues that had been in storage at the SLAPS site (FUSRAP undated a; AEC 1967; FUSRAP undated b). Starting in 1955, the thorium-bearing AM-7 raffinate residue was brought back from storage at SLAPS, stored at Plant 6, and conveyed by dumpster from Plant 6 to Plant 7E as needed (AEC 1955b). The processing was first done on a crash basis in early 1955, apparently on a laboratory level (AEC 1955c; ORAU 1991), to produce a solution containing several hundred grams of thorium. Mallinckrodt later undertook the process on a pilot scale, but insisted on only a limited number of workers and strict safety precautions (ORAU 1991). The resulting residue, AM-9, was sent back to SLAPS (AEC 1959).

AEC (1955b) described the thorium solution extraction process as follows. The AM-7 was first digested in nitric acid in a tank and filtered. The resulting "liquor" was then processed in a TBP (solvent) contactor, forming an aqueous phase and a thorium-bearing TBP phase. The TBP phase was treated with hydrofluoric acid, leaving another aqueous phase, a stripped TBP phase, and thorium fluoride (apparently in solution). The thorium fluoride was sent to the Hot Lab in Plant 6, where it was treated with aluminum nitrate ($Al(NO_3)_3$) and a pentaether-ether mixture, forming thorium nitrate ($Th(NO_3)_4$) and impurities. The thorium nitrate was stripped from the impurities, yielding the solution that was sent to Mound. The various waste streams were treated in several ways (e.g., the aqueous fractions were treated with lime). This left various cake, slurry, and water filtrate forms; the first two types were sent to storage and the latter to the sewer. The main residual cake, called AM-9, was sent back to storage at SLAPS. From the beginning of 1955 into 1957, a total of 350 tons of the AM-7 was processed (AEC 1959; AEC 1967). ORAU (1991) says the processing was performed in 1958). Note that the Th-230 was also called "ionium" and was referred to that way in Mallinckrodt records.

As noted earlier, significant earthmoving operations to cover buried contaminated items were done in 1952 (AEC 1964); the tailings from the magnesium fluoride slag processing were sent to the Fernald site in 1959 (AEC 1959); and in 1959–1960, some of the scrap and rubble from the demolition and decontamination of the Mallinckrodt St. Louis site facilities was buried at the site (AEC 1972; ORNL 1979). There were separate sets of sewers running from Plants 1 and 2, Plant 4, and Plants 6, 6E, and 7 out to the streets, under the streets, and out to the Mississippi River (Mallinckrodt 1994). In 1949, about 3 million gallons a day of liquid effluent classed as alkaline filtrate was being sent to the Mississippi River out a drain pipe, presumably a sewer; this was mostly cooling water, but some was process waste containing up to 12 pounds per day of uranium (AEC 1949b). A small additional amount of acid waste flowed to the Mississippi via an acid sewer (AEC 1949b); Mason (1977) states that excess HF (from UF_4 production) was neutralized with lime or potassium hydroxide and sent to process sewers, so it is unclear what the acid referred to by AEC (1949b) might have been. Mallinckrodt (1994) stated that a 1956 description of Plant 6/6E/7 operations showed that 12,000 gallons per day of raffinate filtrate from the Plant 6 pitchblende extraction was being discharged to the sewer. These lines were apparently underground for the most part, but it is possible that some of them were aboveground where they ran inside the site (see the Table A-1 Notes column).

5.0 RADIOLOGICAL CHARACTERISTICS, CONDITIONS, CONSIDERATIONS, AND AVAILABLE DATA

As AEC (1950a) observed, radiation measurements or evaluations of dust exposure for the purpose of dose determination were not made in the Mallinckrodt plants in the first few years of operations because it was expected that the processing of uranium ores and compounds would involve little risk of radiation injury. This was because of the low specific activity of uranium and because of what was thought at the time to be the temporary nature of the work. Thus only a few instantaneous measurements were made and time-weighting was generally not considered. However, when AEC's New York Operations Office (NYOO), which oversaw the Mallinckrodt work, evaluated the potential hazards (which at this time included those of radium-bearing pitchblende ores), they determined them

to be “considerable” with respect to the long term (AEC 1950a). NYOO and Mallinckrodt began a program of workplace and personnel monitoring.

MED and Mallinckrodt had already begun to issue film badges in 1946 (AEC 1950a), with apparently a small-scale effort begun in late 1945. To this was added breath radon determinations in 1945 and a formal dust measurement program in 1948 (AEC 1950a). Although urinalysis for uranium was done as a “screening experiment” in acute and chronic exposures as early as 1944 (MED 1944j), a routine urinalysis program appears to have begun in 1947 or possibly 1948 (MCW 1950c) (see Section 5.3.6).

Some extrapolation of existing data to cover unmonitored periods is necessary, as AEC itself tried to do (AEC 1950a). The sections below provide information as to the available data and other information to address dose reconstruction.

AEC thought that as a result of improvements planned for 1949 and early 1950, there would be no whole-body radiation exposures greater than 300 mrep/week in Plant 6 and the dust concentrations would be reduced to the AEC’s “preferred level” of 50 µg/m^3, or 70 dpm/m^3 (AEC 1949b). AEC also expected that construction of a new metal plant (Plant 6E), in which UF_4 would be reduced to metal as was currently done at Plant 4, would produce satisfactory (occupational) environmental conditions (AEC 1949b). It was also expected that in 1951, the new UO_2-to-UF_4 plant (Plant 7) would further reduce exposures (AEC 1949b). However, with the increase in production, these goals were not met in all cases, although there were some successes and doses and air concentrations did decrease overall. The effects of the various plant changes and improvements were reflected in the airborne and external exposure levels, as shown in the text and tables below.

An AEC effort in evaluating dose to workers is documented in AEC 1950a, which is a report of an attempt by AEC in late 1949 to estimate the cumulative exposures of Mallinckrodt workers at Plants 4 and 6 who were working at any time between July 1942 and 1 October 1949 and who had more than six months of exposure to radioactive materials. The base data came mostly from Mallinckrodt through its health physics staff, who did some calculations and sent them to AEC (e.g., MCW 1950c). This study is important because it was apparently AEC’s first large-scale study of chronic exposure to all types of workers; ORAU (1977) commented that this was the best information available about individual employment dates, jobs, and dust concentration during the period since more than 90% of all full-time uranium workers were included; also, the exposures were chronic and potentially sizeable—production was in thousands of tons per year and the Mallinckrodt main facilities were “factories, not laboratories” (ORAU 1977). Of the 650 workers included in the study, 99 were working in Plant 4, 294 were working in Plant 6, and about 250 had previously terminated (ORAU 1977).

However, the potential usefulness of this data is lessened by the fact that the Plant 4 work records were somewhat deficient and Mallinckrodt was thus not able to evaluate past dust exposures for workers who had terminated employment or who had transferred out of the AEC project work prior to October 1949 (MCW 1950c). Also, some of the estimates were difficult for Mallinckrodt to do because the particular type of work was variable (e.g., maintenance work) (MCW 1950c). Mallinckrodt used the data of 1948 to calculate exposures prior to 1948 although they thought that many of the exposures were likely somewhat higher (MCW 1950c). Finally, since reported dust concentrations were based on a gross alpha measurement rather than on a chemical (element-specific) basis, the reported concentrations and the doses calculated from them might not always indicate a strictly uranium exposure; it was known that some workers, such as those working with K-65 residue, were exposed to radium dust (beyond that normally present in uranium dust as per uranium-radium parent-daughter ratio) (MCW 1950c). Still, correlation of the urinary uranium concentrations with calculated dust exposures was considered to be good for Plant 6, although poor for Plant 4 (MCW 1950c).

AEC's estimates for the dose to the lung were based on air samples of alpha-emitting dusts (translated to a daily weighted average exposure level); to the bone, on breath radon analysis (to determine the fixed radium burden); and to various organs, on film badge data (AEC 1950a). ORAU (1977) stated that there was a Mallinckrodt lifetime tolerance dose exposure level, but did not state what the level was; however, it did report that by October 1949, 52 employees had accumulated 100% of this level, with 45 exceeding 100% of it and 10 exceeding 200% of it.

Plant 6 was the most hazardous area in terms of dust levels, radon levels, and external gamma dose. Both Mallinckrodt and AEC made periodic studies of the various areas and continuous incremental improvements were made over the years of operation. An AEC consultant noted in 1949 that film badge records were well kept and the external exposures could be seen to correlate with the amount of radium in the plant (in ores and residues); despite problems with airborne radioactivity, progress had been made in reducing external dose and airborne dust levels (AEC 1949k). However, in October 1955, a Mallinckrodt health and safety official was asking an operations manager what had happened to Plant 6, listing in detail the many areas that were dirty and had leaking or nonfunctional equipment and the many questionable practices and violations of requirements (e.g., doors left open and respirators not being worn) that were resulting in unnecessary exposures to workers, particularly dust exposures (MCW 1955d). This official stated that many of these items had been pointed out repeatedly, to no avail. Thus although the various hazards were progressively identified and addressed over the course of the years of operation and exposure levels did go down significantly, in the last few years some hazards were allowed to continue for extended periods before being addressed and some exposures were seen to go up. Even so, it appears that some studies and improvements were made very late in the life of the plant (e.g., the cleanup following the January 1957 study of radon and gamma levels in the Cloth Storage Room (MCW 1957)). Because of this somewhat up and down safety history, it is important to consider what was going on at the plants in any given year in order to assess the dose to an individual.

5.1 UNITS, LIMITS, AND RECOMMENDATIONS

The external exposure (dose) units used by MED/AEC during most of the relevant period were milliroentgen (mR) for gamma doses and millirep for beta doses, with the rep being equal to 0.93 rad; the abbreviations in the film badge and other records were mr and mrep respectively. Air exposures were expressed as disintegrations per minute per cubic meter sampled or inhaled (dpm/m^3), while radon exposures were usually given in units of 10×10^{-10} Ci/L. AEC also expressed exposures in terms of "tolerance" levels set on the basis of assumed safe levels; a tolerance level was equal to a given external dose level in mR per week or mrep per week, or radioactive air concentration in dpm/m^3, etc., but the given values changed with time as MED/AEC set the safe levels lower and lower. The tolerance was regarded as a recommendation rather than a rigid limit, but AEC pressed the contractors to get and keep exposures to below the tolerance level. The units and the tolerances are further explained below.

In the early days of the war, MED decided that its tolerance levels of external exposure for uranium processing would be 0.1 R per eight-hour day or 0.6 R per week for gammas and 0.5 R per eight-hour day or 3.5 R per week for betas (MED 1943c, MED 1945b). This was based on the findings of the University of Chicago that the gamma dose rate from an infinite plane source (a 2π geometry) of uranium metal was 0.04 R per eight-hour day and for a room of uranium metal (a 4π geometry) it was 0.09 R per eight-hour day (MED 1943c). Later in the war, the limits were set at 700 mR per week to the whole body and 3,500 mrep per week to the hands (MED 1945b, AEC 1949b; AEC 1950b). MED (1945b) stated that the entire dose for one week of either type of radiation could be received in one day or less; AEC (1950b) stated that the limit was 700 mrep per week "each of beta and gamma," as accepted by the University of Rochester in processing film badges (i.e., Rochester did not flag reported doses as above tolerance if the weekly beta and gamma doses were each below 700 mrep).

MCW (MCW 1950f) states that the tolerance level was 12.5 mR/hr, i.e., the hourly average for the 0.1R per eight-hour day; presumably this was according to AEC usage as well.

At some point, when NYOO had assumed the job of reading the film badges, the tolerance level appeared to have been lowered again to 500 mrep per week, which Mallinckrodt continued to interpret as applying to either beta or gamma but not to the total (AEC 1950b). However, Mallinckrodt used a control level of 150 mrep per week, called the "preferred level" in its 1946–1952 film badge records. The number that was compared to this level was the sum of the gamma dose in mR (i.e., mr in the records) and the beta dose in mrep, as registered by the film badge, apparently with no adjustment of the mrep by the factor of 0.93. In 1947, the basic dose limit was said to be 0.1 rep/day and the relative biological effectiveness (RBE) for alphas to be 10 (Hursh 1975); probably this was true earlier as well.

In anticipation of the lowering of the radiological dose standards (recommended limits) by the national expert committees such as the National Council on Radiation Protection and Measurements (NCRP), AEC began making changes in the plants in about 1948 to meet new "maximum permissible levels" of 300 mR/week for whole body irradiation and 1,500 mrep/week for beta radiation to the hands (AEC 1949b). An AEC internal memo dated January 1949 (AEC 1949c) states that the Plant 6E design by Singmaster & Breyer was intended to meet the following AEC-specified criteria: whole-body beta dose less than 250 mrep per week (based on an maximum permissible (tolerance) level of 500 mrep per week) and beta dose to the hand less than 500 mrep/week (based on a maximum permissible level of 1,500 mrep per week). It was noted that AEC considered these criteria to be the minimum requirements and did not include any factors of safety beyond the "acceptable" (i.e., tolerance levels). New shielding added in 1948–1949 was designed on the basis of 50 mR per day of gamma radiation (MCW 1950e; AEC 1947b).

In August 1949, AEC established and circulated to its contractor personnel a tolerance level of 300 mrep per week, which was to be taken as the total gamma plus beta dose to the whole body. However, Mallinckrodt misunderstood that the 300 mrep limit was to be applied to the total of beta and gamma and interpreted it as the limit for either beta or gamma (AEC 1950b). Finally, in January 1950 AEC made it clear to Mallinckrodt that the limit applied to the total beta plus gamma (AEC 1950b).

In a 1950 letter to AEC, Mallinckrodt summarized AEC's tolerance levels in the postwar era, as given in Table 5-1 (MCW 1950t). Mallinckrodt (MCW 1950l) suggested that AEC use absolute units rather than tolerance units to report exposures because the tolerance values were apt to change with time and this could lead to confusion in interpreting older records.

Table 5-1. AEC tolerance levels in the postwar years.

Date	Beta tolerance level, mrep/week	Gamma tolerance level, mR/week	Total beta + gamma tolerance level, mrep/week
Before June 1948	700	700	1,400
June 1948–August 1949	500	500	1,000
August 1949–January 1950	300	300	600
January 1950 on	---	---	300

In mid-1950, AEC agreed to allow Mallinckrodt to interpret the 300 mrep total gamma plus beta whole-body limit as being taken as the average weekly dose over a three-month period, thus allowing the 300 mrep to be exceeded in some weeks (AEC 1950e); this was apparently based on the fact that Mallinckrodt was already using a system of personnel rotation to reduce doses (MCW 1949p; AEC 1950b). However, AEC at the same time suggested that 150 mrep per week be taken as a recommended limit for most purposes and that a weekly dose of 600 mrep be exceeded only in exceptional cases. It should be noted that in 1953, a design contractor was stating that the design criteria for ventilation and dust control equipment his company had put in at Mallinckrodt and Harshaw

included a maximum weekly exposure of 300 mR of gamma radiation, with actual design predicated on half that to allow for a safety factor in unusual circumstances (Miller 1953). Subsequently, Mallinckrodt gave as the "tolerance cumulative dose" limits in use in 1955 as beta, 500 mrep per week, whole or part body; gamma, 300 mR per week, whole or part body; sum of beta and gamma, 500 mrep per week, whole or part body; and 1,500 mrep per week, extremity (MCW 1955).

During the early days of wartime uranium processing, AEC/MED's acceptable levels of exposure for the uranium processing plants for dust in air were 500 μg/m^3 for insoluble uranium salts and 150 μg/m^3 for soluble salts (AEC 1949b). In 1944 MED determined that a standard was needed for uranium dusts and adopted the air maximum permissible concentration (MPC) level for lead, 150 μg/m^3, as the interim standard (Hursh 1975).

In 1949, a University of Rochester scientific group suggested an air MPC of 50 μg/m^3 for soluble uranium forms based on (chemical) injury to the kidney and an air MPC for insoluble forms based on radiation injury to the lung (Hursh 1975). In 1953 the NCRP recommended in National Bureau of Standards Handbook 52 (quoted in Hursh 1975) a limit of 73 μg/m^3 for both soluble and insoluble forms; it was adopted. These were occupational standards that correspond to a 40-hour week (the number of hours that Hursh (1975) uses in conversions in his discussion of the history of standards).

By 1949, AEC had set a "preferred level" (also referred to as a tolerance level) of 50 μg/m^3 for uranium dust, assuming a routine exposure of 8 hours a day, 6 days a week (AEC 1949b). This was taken to be equivalent to 70 dpm/m^3 for alpha and was based on animal studies (Hursh 1975). Attachment B gives the basis for this figure. This was later referred to as the Maximum Allowable Concentration (MAC) and was still in use as of 1953 (Miller 1953). In early 1955, AEC appears to have adopted a MAC of 100 dpm/m^3 for alpha, as AEC (1955e) stated in an air dust study report. In a 1958 report, AEC gave the limit for natural uranium, either soluble or insoluble, in air as 5×10^{-11} μCi/ml for 40 hours/wk (i.e., occupational) and 1.7×10^{-12} μCi/ml for continuous occupancy (AEC 1958, Table I). In 1949 the AEC also recommended against respirator use except in emergency situations (AEC 1949b), suggesting that before the relevant period of Mallinckrodt work, extensive use of respirators was still tolerated as a means of minimizing exposure.

However, note that in a 1958 paper by an AEC-NYOO safety official, while the wartime MAC was given as 500 μg/m^3, agreeing with the information above, the "present MAC" (i.e., in 1958) was said to be 110 dpm/m^3 instead of the 70 dpm/m^3 of other references (Breslin 1958).

The "generally accepted level" for radium fixed in the body (as a body burden) was taken to be 0.1 μCi (MED 1946c). In the highest concentrations handled by Mallinckrodt (i.e., of the pitchblende ores), 0.1 μCi corresponded to about 0.5 g of ore (MED 1946c). Since the radium was present in insoluble or only slightly soluble form, the original MED value for allowable dust concentrations of ore was 150 μg/m^3 (MED 1946c) (as mentioned above). When the tolerance for other kinds of dust was raised to 500 μg/m^3, MED apparently did not mean for the ore and radium-bearing waste dust tolerance level to rise to 500 μg/m^3 as well, but Mallinckrodt apparently assumed so, based on the statement in MED (1946b) that the maximum allowable concentration for chronic exposure for U_3O_8, UO_2, and UF_4 had been raised from 150 μg/m^3 to 500 μg/m^3, effective June 1945. Thus in late 1946, a Mallinckrodt manager told MED that they were using 150 μg/m^3 as the tolerance level for (apparently unground) ore dust, but 500 μg/m^3 for U_3O_8, UO_3, UO_2, and UF_4; MED (1946c) soon told them to return to using 150 μg/m^3 for uranium compounds and "5 x 10^{-11} grams radium per cubic meter [units approximately equivalent to μCi per cubic centimeter]" for ore residues with the uranium removed (for Ra-226 50 picogram/m^3 is equal to about 110 dpm/m^3). As noted above, the uranium tolerance level was reduced to 50 μg/m^3, equivalent to 70 dpm/m^3, by 1949; 70 dpm/m^3 is also the figure given as the tolerance level for the radium-bearing residue in 1953 (MCW 1953b).

There was a separate tolerance level of 40 μg/m^3 set for the "shotgun" residue dust (i.e., for sampling and work done in the shotgun laboratory), according to MED (1945d); this applied only if the concentration of the Th-234 and Pa-234 decay products (called TI1 and TI2 in the reference) had not been increased by concentration to more than 400 times the equilibrium value (presumably secular equilibrium).

Prior to 1941, there was no standard for occupational radon exposure. In 1941, the United States Advisory Committee on X-Ray and Radium Protection recommended 10^{-11} Ci/L (curies per liter) as the acceptable occupational radon level, based on a 40-hour work week (Akerblom 1999). (This would be 10 picocuries/liter in the units most used today.) This standard was published as a handbook by the National Bureau of Standards (NBS 1941). According to Raabe (2002), the standard was for ventilated rooms in which work was done with radium (e.g., luminous dial painting) and did not include consideration of radon daughter products. An AEC report (AEC 1949b) stated explicitly that the acceptable radon level for "environmental" air (room or outside air breathed by occupational workers) in AEC-sponsored facilities was taken to be 10^{-10} Ci/L, i.e., ten times higher than the NBS standard; the report refers to this level as the "maximum permissible concentration" (page 14) and also as the "preferred level" (page 20). However, a value of 1 x 10^{-12} Ci/L was also mentioned as the tolerance level in 1950 (AEC 1950k). A ventilation design contractor stated in 1953 that the radon design criteria limit for work for Mallinckrodt and Harshaw was 10^{-8} Ci/m^3 of air, or 10^{-11} Ci/L of air (Miller 1953). Thus it is favorable to claimants to assume that the standard that was applied during most of the period in which Mallinckrodt uranium refining took place was 10^{-10} Ci/L (100 pCi/L) and that this applied to radon only and not to the daughters.

Regarding effluents, AEC proceeded on the basis that it was acceptable for liquid and solid effluents to have concentrations up to one order of magnitude greater than natural background (AEC 1949b). AEC "recommend[ed] that neighborhood air levels for these radioactive materials [containing uranium and radium] should not exceed 1% of the levels used within the plants" (AEC 1949b). No information is available as to Mallinckrodt's approach to effluent control, e.g., whether it followed the AEC recommendation.

For workers employed in years during which no (radiological) urinalysis was done, AEC (1950a) prepared a cumulative exposure estimate study of Mallinckrodt workers who had been employed between July 1942 and October 1949. AEC's estimates for the dose to the lung were based on air samples of alpha-emitting dusts (translated to a daily weighted average exposure level); dose to the bone was based on breath radon analysis (to determine the fixed radium burden); and dose to various organs was base on film badge data. Because in dose reconstruction different assumptions are made than AEC made and thus these calculations will have to be redone, their results are not repeated here. It should be noted that workers were not identified by name or work category in the AEC report but the tabulations that produced the bottom-line figures for the report may be available by worker name in dose reconstruction project files.

Also with regard to the AEC report, it should be noted that the calculations of lung dose did not include a gamma contribution because AEC deemed it negligible compared to the dose from airborne particle inhalation; that AEC did not include radon dose because they could not estimate an average concentration and they assumed that dose from airborne particle inhalation would dominate; that AEC assumed all the uranium to behave like UO_2 in the lung; and that AEC assumed that biological equilibrium existed since the start of employment. AEC did include the external dose in the bone dose calculation. It should also be noted that AEC thought that the exposures in the unmonitored years were "at least as severe as they were found to be at the time of our initial studies" (in early 1947). They stated that conditions probably were not more favorable and may have been "moderately" more severe. Thus they thought that their extrapolations could possibly be somewhat nonconservative.

5.2 RADIOACTIVITY CONTENT AND HANDLING OF THE ORE, URANIUM PRODUCTS, AND RESIDUES

5.2.1 Ores and Other Feeds and the Initial Process Steps

The origin of the ores is important in considering source terms at Mallinckrodt facilities because the content of uranium in the ores was greatly variable. Pitchblende ores contained high levels of radium-226 and other radiologically significant daughter products, while other ores and feed materials typically did not. Ra-226 (in equilibrium with its daughter products) constitutes a significant gamma source and thus produced most of the external whole-body dose received by the Mallinckrodt workers, while Th-234 and Pa-234, both beta emitters, produced most of the extremity dose. In addition, radon and radioactive dusts were released in storage and processing, resulting in internal dose due to inhalation, with the radon releases again being highly correlated to the radium content. Since the concentration of radium and other daughters present in the ore, processed uranium, and processing residue at any given time depended most strongly on the concentration of uranium in the ore, on a per-ton-of-ore-processed basis (ignoring process differences), the various doses received depended on where the ore originated.

Pitchblende ores from the Belgian Congo (the so-called “Congo ore” or African ore), supplied by the Belgium-based African Metals Company, had average concentrations of 25% (Eisenbud 1975) or 30% (Mason 1977) uranium by weight, up to a maximum of 65–70% (DOE 1997; Dupree-Ellis et al. 2000). Other early ore sources were pitchblende ores from Canada (Radium City in the Great Bear Lake Area and Port Hope in Ontario) (DOE 1997), containing uranium concentrations of about 10% (Eisenbud 1975). Later in the war, domestic ores were used also. The wartime domestic supplies were actually tailings from vanadium mining and milling (Eisenbud 1975); although the original ore had uranium concentrations of less than 1%, the tailings were shipped as a 20% sludge concentrate (Eisenbud 1975). (Note that there is some confusion among the various references with regard to ore specifications, in that some give the percentage as applying to uranium alone and some as applying to U_3O_8. Since the percentage is by weight and the uranium is by far the larger weight constituent of U_3O_8, the differences are not significant.)

Ores from the Belgian Congo had average concentrations of up to 100 milligrams of Ra-226 per ton of ore (Dupree-Ellis et al. 2000; Eisenbud 1975), possibly up to 135 milligrams per ton (AEC 1949b). (Mason (1977) gives 300 milligrams per ton, but this appears to be in error.) Thus there could be a significant dose rate from the ore when it was in drums or when it was being loaded into other containers and hoppers. As previously noted, the ore was dried before use; this was a necessary condition for optimal processing, but the dust levels created during drying and later handling were high. A 1947 study done for AEC by the University of Rochester evaluated the relative amounts of uranium and radium in ore (see Section 5.3.1). The radon in the Belgian Congo ore was also significant because it built up over time in containers and enclosed spaces. When drums, enclosed storage areas, the thaw house, etc., were opened, a worker could be enveloped in the escaping radon. Table A-4 gives more information about the quantities and radiological characteristics of the ore.

As stated earlier, most of the pitchblende processed by Mallinckrodt was obtained as a concentrate from the Belgian Congo by AEC in 1944 and was shipped to St. Louis in 55-gallon drums from whatever North American receiving point was distributing it at a given time. After the war, feed materials were usually packed into 30- or 55- gallon steel drums at the mills and shipped by rail in full carload lots (Mason 1958a). It can be inferred from Mason (1958a) that a rough conversion is about 15,000 tons of uranium ore per 100,000 drums, so that each ton represented about 7 drums to be dumped, sampled, and processed.

In 1942, there was some contact (i.e., it was open to the air and potentially could be touched) with non-pitchblende uranium in the form of U_3O_8 when it was mixed with nitric acid for digestion (MED 1942). As noted earlier in Section 3.1, the pilot plant operations in Building K-1E yielded a liquor that was conveyed by hand cart to vessels outside Building 52 and as suggested by Mason (1977), the further transfers also appear to have involved some closeup, manual handling. But when the pitchblende ore began to be used, contact was reduced as much as possible. To minimize personnel exposure, the ore (storage) room (addition) was divided by brick piers into corridors, with each corridor being wide enough to hold four drums of ore side by side, with a layer of four more drums stacked on top of them (MED 1946c). It was thought that this design would eliminate the need for workers to pass between or close to stacks of ore during the ore storage and transfer operations. However, due to the blocking of some corridors and the filling of others because of the volume of ore drums, it was after all necessary for workers to pass (close) by the ore drums stored in the partly filled corridors (MED 1946c). As of at least 1947, barrel handling of ore barrels was done with a forktruck, thus eliminating nearly all of the necessity of manual handling of the barrels (AEC 1947a).

In 1948–1949, ventilation and remote control systems were installed in the Ore Room and its addition. This helped to reduce the radon concentrations in the operating areas, except for a point in the Ore Room at the junction of the two conveyor systems: radon levels were found to be high and to remain high for nearly half an hour after pitchblende drums were opened (MCW 1949m). Operators were not supposed to be near the drums after they were opened, but operators sometimes still had to enter the Ore Room or the conveyor alleys while drums were standing open on the conveyor because of operating difficulties. These difficulties included the need to make frequent visual inspections of the flow through the Syntron feeder mechanism into the rod mill, incorrect placement of a drum on the conveyor, failure of conveyor stops, and the jamming of some fiber (cardboard) drums on the conveyor. In the case of the second and third items, the operator had to crawl into the conveyor alley to remedy the problem and in the case of the fourth item, had to go into the Ore Room to remove the open drum manually.

In February 1950, a study was done of gamma and radon exposure to three workers conducting a special pitchblende ore inventory (MCW 1950g). This included moving 1.5 lots (probably a total of 9 drums) by forktruck, weighing the ore drums, checking the numbers, and counting all the ore drums present (not just the checked drums). They received gamma doses of 45–75 mR, compared to the then-tolerance dose of 60 mR per day. Radon exposures averaged 1.02×10^{-10} Ci/L, which was higher than normal because the ventilation system was operated in a special mode to facilitate radon sampling for the study. It was concluded that these exposures were acceptable if the special inventory was done monthly, but if more extensive inventories were done, rotation of personnel and extra planning would be necessary.

In 1950, it was observed during a study that it was very dusty in the Ore Room proper and that while the rod mill (grinder) was running it was necessary for the operator to enter once for 1.5 minutes to go to the top of the skip hoist and dislodge the ore stuck in the supply drum; this was done using a hammer (AEC 1949e). Other than that, the operator's time in the Ore Room was spent opening, dumping, cleaning, and closing the drums, with the average number handled being 22 per shift over about four days (MCW 1950u). In 1954, it was noted that operators were still being forced to enter the Ore Room frequently, due to the ineffective drum-handling system: drums would hang up on the conveyor and have to be pushed free manually (MCW 1954c). Also, large drums had to be removed from the skip hoist by hand because the system could not handle large drums (MCW 1954c).

Contamination control instructions were not always enforced in these known dusty operations. For example, in 1954 operators in the Ore Room were observed to be loosening lids on the ore drums on the conveyor before moving the drums to the skip hoist, which allowed dust to come out under the lids as the drums were moved; similarly, these operators took drums from the skip hoist and placed them on pallets with the lids positioned only loosely and without the clamps being fastened on (MCW

1954c). Drums of ore were also observed to be sitting in the Scale House without lids on, with the lids and clamps being put on in the open area of the Scale House or even outside and not on the conveyor as procedure required (MCW 1954c). The reason for the irregularities with the drum lids and clamps was that by this time many of the drums, having been used and re-used, were old and slightly out of true, so that the lids had to be beaten on and the clamps were fastened on only with great difficulty (MCW 1954c). When the feeder (conveying) screws that removed the ore from the hopper became blocked, ore had to be scooped from the hopper by hand; it was noted at least once in 1954 that this was done without respirators (MCW 1954c). The dust released was not confined to the ore area, since the doors to the Ore Room and Ore Room addition were often left open through negligence or for convenience (MCW 1954c).

Similar issues arose in the MgX area, used from 1949 on. Various memos and an August 1953 report (MCW 1953d) expressed concern about the MgX area, in particular about the inadequate design and maintenance of the conveying facilities that created dust levels in the breathing zone and general area up to 300–350 dpm per m^3. This report noted that the drum washer was not working properly, so that there were high levels of dust when the workers hammered the ring clamps onto the drum; the airflow into the exhaust on the operator's platform was so inadequate that dust often came out of the opening when the operator released the mechanical "grab"; the operator had to go to the top frequently to push the feed material down the hopper into the screw feeder with a paddle, with dust coming out of the hopper opening as he did so. Also, the housing was warped, the gasket was loose, and there were broken windows in the drum washer housing (MCW 1953d). The problems had still not been solved in 1954, when leakage was observed coming from the feed hopper to the tanks at the feeder screw housing because of flanges that were not securely fastened and loose packing at the screw shaft; the tops of the digestion tanks were thus covered with this dust (MCW 1954c).

In 1947, apparently after some months of experience in working with the high-level pitchblende ores, Mallinckrodt wanted to install steel shielding around several of the digestion tanks along the catwalks (platforms) and around the Feinc press filters that produced the K-65 waste (AEC 1949f). However, AEC rejected shielding around Tank M-14 because sludge was shoveled into the tank from the platform and the shielding would impede the shoveling (AEC 1949f). AEC apparently rejected all of the extra shielding eventually (MCW 1947). Mallinckrodt protested, stating that they had agreed to fewer provisions for health protection than they thought advisable in the design of Plant 6, on condition that the provisions would be added "if trouble later developed"; the difficulty was that after the plant was built and high-level pitchblende ores were being handled, AEC and Mallinckrodt disagreed as to what constituted "trouble developing" (MCW 1947). Thus although some shielding appears to have been added in 1948–1949 (AEC 1949b, MCW 1950e), notably for the ore grinding and C-3 filtration operations, the relatively high dose rates from the digestion tanks and the Feinc "bowls" were a continuing personnel protection problem at Mallinckrodt. This was noted on an inspection of the Mallinckrodt facilities by an AEC consultant, who stated that shielding was reaching a practical limit because with the tanks and vessels being shielded, the existing piping had become an important source of dose and the piping was not easily shielded (AEC 1949k). Further, rearranging the piping was not an option because the pitch and length of the sections was important to the process (AEC 1949k).

Dust and radon could be a continuing problem even in some of the "wet" areas. It is known that one reason for the spread of dust and radon was that doors to the cells containing the process equipment were often left open through negligence or for convenience; as late as 1954, a Mallinckrodt internal safety report gave as examples the leach and wash (Oliver) cells, the Feinc cells, and the M-14 cells (MCW 1954c). Tank lids were also left open unnecessarily, most notably the centrifuges, which were sometimes opened on one shift for cloth changing and not closed until the next shift (MCW 1954c); this allowed K-65 residue to dry out and drift out of the centrifuge and onto its outer surfaces and the floor. Also, as equipment became worn, there could be substantial leakage out various openings. In

the case of the centrifuges, leakage was observed around the shaft, plow, and scoop openings at the top; this leakage was often allowed to collect and dry out (MCW 1954c).

From about mid–1948 on, at least some pitchblende ore (Q-11) was stored at SLAPS (AEC 1948e, MCW 1949p). Apparently at least one forktruck driver (to move the drums) and one truck driver were required; possibly a sampling worker was needed at times. Guards were said to have been "maintained" at the site from 1946 to 1951 (AEC 1959), apparently constantly; after that, it appears that guards were present only for routine patrols and actual worker entry into the site for deliveries or removals of ore. It is not clear whether the storage workers and guards were always Mallinckrodt employees or not; e.g., Mason (1977) states the raffinate cake and barium sulfate cake collected in dumpsters in Plant 6 were taken away in dump trucks "which AEC operated." However, Mallinckrodt warehouse workers and guards appeared to have been doing the residue delivery and placement work even in 1946–1953 (MCW 1949d; MCW 1949p), when AEC was running the site. There are notations of "airport" in urinalysis and film badge records, so it may be possible to determine from such records whether and when a particular individual did work at the site.

Material was taken between the main Mallinckrodt site and SLAPS by truck (Mallinckrodt 1994; AEC 1947a; MCW 1949p), so it can be inferred that ore drums were received by rail at Mallinckrodt and then trucked to SLAPS. The ore drums were stored on a concrete pad next to the K-65 shed (the pad also formed the floor of the shed) (AEC 1948j). Mallinckrodt (MCW 1949p) restricted the time that warehouse workers spent at SLAPS because of the hazards from the K-65 drums and because of other ore work at the main Mallinckrodt site, such as unloading ore drums from railcars. The task of obtaining ore drums from the airport pad involved three trips per week (MCW 1949p) from Plant 6 (where the warehouse and yard workers were based) to SLAPS; apparently at least one forktruck driver (to move the drums) and one truck driver were required. Because of the proximity to the K-65 storage in the enclosed shed, it appears that the K-65, with its much higher content of Ra-226 than the ore, may have contributed non-negligibly to the exposure of the ore workers.

It should be noted that in the later years, many booths or walk-in areas were called "enclosures." These were generally not entered bodily by the operator, unless there was a malfunction of the equipment; rather, he inserted his arms into such enclosures through openings or used remotely operated devices to perform work within the enclosure. Some "stations" were actually enclosures such as this, some were hoods, and some were semi-enclosed booths.

5.2.2 Uranium Products

Once the Ra-226 was removed following the digestion step and the vessel(s) had been vented, the gamma dose rates were much lower and the radon (which arose from the radium) was no longer an issue in processing (except for the radium-bearing residue). Radium and radon would again build up to significant levels from the uranium parent, but this took more time than the apparent typical digestion-to-shipout time at Mallinckrodt. The principal hazard was thus the uranium-bearing dust.

The main hazard after the radium-bearing residue was removed was dust, since a fraction of the uranium salts and oxides tended to aerosolize when dry and when handled. Initially, somewhat crude precautions were taken to control dust during handling and there was extensive manual handling of uranium salts and oxides in the dry form (Eisenbud 1975); in 1942, it was noted that contact could be made with UO_3 when removing it from the open receptacles (boilers) to transfer it to the furnaces, and with UO_2 when packing it. For example, in Plant 6 (and presumably in its predecessor Plants 1 and 2), the UO_3 dry powder was unloaded from the reaction pots by hand-scooping (Mason 1958a), i.e., manually using handheld scoops. The UO_3 was scooped into a drum through a grated funnel that had a vacuum connection on it to draw the UO_3 dust out of the drum (MCW 1956c) (the vacuum connection was probably in use only from the late 1940's on). The large pieces caught in the grated funnel were broken up by hand, which was always recognized as being a particularly dusty step and a

principal reason why respirators were supposed to be worn during the operation. In 1954, there was a temporary top that was supposed to be used during the filling of the UO_3 drums to keep the dust down, but since it did not allow the operator to see when the drum was full, it was usually left off (MCW 1954c). The dust on the outside of the drums was supposed to be vacuumed off, but the operators often used a rag to do it (MCW 1954c), which meant that much of the dust went into the air and onto the floor or the conveyor. When the dust collection bag for the UO_3 area was changed, a spool piece was supposed to be installed in the ductwork, presumably to allow for an alternate suction source to keep the dust from coming out, but this was not done even through many bag changes (MCW 1954c).

The drums of UO_3 were taken to the loading area and trays were filled with the material. After being weighed, the trays of UO_3 were placed into the furnaces to be reduced to UO_2 (Mason 1958a). The trays of UO_2 were then unloaded by hand into drums for transport to other areas or sites. This was described in Rochester 1948b as follows. In the tumbling area, the newly formed and cooled UO_2 was placed in tumbling drums and rotated on a tumbler to break up clumps; the drums were taken to the skip hoist, where the tumbling drums were opened and transferred to the hopper of the Fiberpack loader; at the Fiberpack loader, a vibrating chute fed the material into 75-lb containers and the containers were sealed on a roller conveyor; and from the UO_2 production area, the UO_2 containers were trucked to the warehouse for storage.

The major handling improvement of 1949, the installation of pneumatic unloading and conveying systems, was supposed to have eliminated all hand-scooping of UO_2 and UO_3. However, AEC inspectors repeatedly noted hand-scooping going on until the end of operations at the plant, often due to the failure of equipment such as the vacuum-type UO_3 "gulpers" (AEC 1954d; AEC 1956b). A 1956 Mallinckrodt report (MCW 1956c) explained why: when the pneumatic system was not operational and the UO_3 was ready to be unloaded from the pots, the unloading could not be postponed because acid would condense in the ducts and run into the pot, ruining the batch of UO_3. So it was recommended that while the pneumatic system was out of order, the exposure be reduced somewhat by collecting the large pieces caught in the funnel grate and waiting until the pneumatic system was back in order before breaking up the large pieces (MCW 1956c).

UO_2 produced at Plant 6 was trucked over to Plant 4 in small fiber containers (AEC 1949b); no information is given as to how this affected containment of the dust. In Plant 4, there was again extensive hand-scooping and other manual handling of the uranium materials (UO_2, UF_4, and uranium metal) (Mason 1958a). AEC (1947a) states that the UO_2 was hand-scooped into trays and leveled off with a stick; the gloved hand thus came into direct contact with the material. Manual handling was reduced by mechanization in 1948 and 1949, but even so dust levels were considered too high (Mason 1958a). AEC agreed to have Mallinckrodt construct Plants 6E and 7 to replace Plant 4 and part of Plant 6. These plants were even more mechanized and were said to require little (if any) manual handling (Mason 1958a); however, as various AEC air dust study reports indicate (e.g., AEC 1954g; AEC 1955d), this was not always so. AEC (1955e) even reported in 1955 that a Plant 7 operator used a piece of cardboard in lieu of a conventional metal scoop to make up UF_4 weight (in loading a container), with the operator's (presumably gloved) fingers dipping into the material frequently.

In 1955, a new derby "pickling" facility went into operation in Plant 6. The derbies made in Plant 6E were transported to this facility to be pickled—i.e., cleaned in a dilute acid bath—and then returned to Plant 6E in baskets of eight or metal boxes of twelve (AEC 1955e, MCW 1955p). Prior to being processed in the recast step, the derbies were dried with a flame in a hood, if necessary (AEC 1955e). Some chipping in the chipping enclosure was still necessary (AEC 1955e) because during the drying (whether by air or flame), the surface of the derby would oxidize to black oxide (U_3O_8). Thus the dust in the chipping operation was at least partly U_3O_8. Although the use of the flame for drying was supposed to be discontinued (MCW 1955o), it appears that it did continue (MCW 1955p).

The billet (ingot) was initially low in beta activity because during the melting in the vacuum furnace (i.e., in vacuo), the dross and slag floated to the top of the crucible and the beta-emitting UX1 and UX2 (Th-234 and Pa-234) sublimed and cooled on the underside of the furnace lid (Mason 1977). The dross from the crucibles and the other furnace residues was packaged separately from the slag and the billet (Mason 1977). However, as the billet aged, the UX1 and UX2 started to build up again.

In November 1953, a study was done of Plant 4 recast operation to determine the cause of high film badge readings (MCW 1953e); although Plant 6E made most of the metal, some metal was still produced on a pilot or experimental basis in Plant 4. The following dose-producing practices were found. The furnace jack was warped, so the operator had to enter the furnace enclosure to guide the jack with his foot each time the furnace was loaded. After unloading the furnace, the operator had to weigh the crucible and put it into a drum by hand. The crucible dose rate varied with the number of times used and the type of metal; the crucible in the study read almost 400 mrep/hr (beta plus gamma) before it was loaded because it had been used before (and would read more after the recast was done). Aged metal billets were stored on the floor beside the operator's desk and were left there until the lead operator or the engineer examined and approved them, a period of one to three days. The operator spent four to six hours sawing "betatron slices" (samples to be sent to Granite City Steel (aka General Steel Castings) in Granite City, Illinois for testing) because the shape of the slices required the operator to spend several minutes setting the metal on the saw. The slices were stored on a table in a storeroom until enough had accumulated for shipment, a period of three to four weeks. When enough slices had accumulated, the operator would examine each closely to determine the weight and lot number stamped on it, which took a total of 30 to 45 minutes.

Besides these practices, MCW (1953e) noted that in their one run per shift, the same two Plant 4 recast operators had to load the crucibles, clean the furnace, saw the metal, degrease the metal (by hand until some time in late 1953), and load the betatron slices. There was no mechanical method to move the crucible from the furnace to the scale, so one of the operators had to climb physically into the furnace bottom and attach a chain to the billet, remove the fire brick from the billet, remove the empty crucible, and weigh the crucible. Meanwhile, at Plant 6E there were separate groups for each step, i.e., saw operators, furnace operators, crucible loaders, and cage men (who ran the degreasing machine). At Plant 6E, after the metal was sawed, it was kept covered and was stored away from contact with workers. Also, the metal at Plant 6E read fairly low compared to the aged Plant 4 metal. Thus as MCW (1953e) pointed out, the hazards faced by the Plant 4 recast workers were not being considered to the same degree as the Plant 6E recast workers. It is not clear whether the subsequent film badge readings went down because changes were made or because the type of operation was reduced or discontinued, but it appears that the handling of the crucible was minimized thereafter.

5.2.3 Residues and Other Wastes and Reprocessing

Because of the chemical processing, various residues and wastes had content that was concentrated or depleted in particular radionuclides, depending on where in the process the wastes were formed. Details are given in Table A-4 and in the text for specific radionuclides. In general, it can be stated that the waste was disposed of promptly because otherwise storage space would have been exhausted. Thus once the waste was taken out of the process equipment or area, exposure to the waste was limited to the radioactivity existing in it at the time it was created or collected, with the exceptions of the K-65 drums that might be stored until they were transported to SLAPS, the slag that was recycled in the later years, the low-level solid wastes (such as rags) that might be accumulated prior to incineration; and the residues brought back from SLAPS for reprocessing. In the case of the K-65 drums, the exposure would be to radon emanating from the drums and to the gamma radiation from the radium; in the case of the slag, the exposure would be to dust and mostly beta radiation; in the case of the low-level solid wastes, which were probably kept in dumpsters or similar large bin-type containers, the exposure would be dust and external radiation; and in the case of the reprocessable residues (e.g., the AM-7), the exposure would be to dust and external radiation. It does not appear

that any of the wastes had sufficient time before disposal to build up daughters much beyond what was already in the waste, except to some extent the residues brought back from SLAPS.

The residues dumped on the ground or stored in drums at SLAPS are a special case, since they sat there for a number of years, but only a few workers entered the storage area intermittently. In the case of the residues dumped on the ground, the exposure would be to dust and to some degree from external radiation and in the case of the drummed K-65 residue, it would be to radon and gamma radiation.

A condition placed on the ores from the Belgian Congo by African Metals was that the Ra-226, the Ra-226 daughters, and the lead and precious metals be extracted, stored, and returned to African Metals (AEC 1967; AEC 1949b). Thus the Mallinckrodt process included steps to extract these materials as a separate residue from the bulk of the ore residue; this was the radium- and lead-bearing K-65 residue, also called gangue lead cake or GLC. K-65 and other wastes were trucked to SLAPS but sent by train to sites outside Mallinckrodt. Radiation levels from the K-65-containing railcars and trucks exceeded those permitted under the regulations of the day, so shipments had to be made under special permits granted by the Interstate Commerce Commission (forerunner of the Department of Transportation) (AEC 1949b).

A 1947 dust study done for AEC by the University of Rochester evaluated the relative amounts of uranium and radium in the K-65 residue (see Section 5.3.1). It was reported in February 1948 that the K-65 contained about 600 mg of radium per ton and about 0.2% uranium; at that time it was being sent to the Lake Ontario Ordnance Works at an estimated rate of 6,000–12,000 pounds per day (AEC 1949m). AEC (1949b) stated that as much as 100 grams of Ra-226 contained in the K-65 residues was produced per month at the Mallinckrodt facilities. This was in fact the quantity produced in December 1948 (AEC 1949b). It was reported that 200 grams had been transported at one time to Middlesex (AEC 1949b), meaning that up to this quantity had been in storage at the Mallinckrodt site or at SLAPS and had had to be loaded for transport at one time.

In addition to the K-65 residues, there were other solid and liquid residues and wastes, as reported in February 1949 (AEC 1949m). The other two major solid refinery residues were the barium sulfate or AJ-4 residues and the pitchblende raffinate or AM-7 residues. The barium sulfate contained about 4 x 10^{-9} grams of radium per gram of residue and about 0.1% uranium; because of the low radioactivity content, it was being dumped on the ground at SLAPS at the rate of about 6,800 pounds per day. The AM-7 consisted of various metal hydroxides with about 0.1% uranium; it too was dumped on the ground at SLAPS at an estimated rate of 23,000 pounds per day. The liquid wastes (from the refinery processes) contained about 0.002% uranium; they were discharged through a sewer to the Mississippi River at an estimated rate of 3,000 gallons per day, with about 12 pounds per day of it being uranium. Miscellaneous waste byproducts of the UF_4 production process were sent to Vitro for recovery of uranium, but in relatively insignificant quantities, while the slag from the uranium metal production process contained about 0.3% uranium and was stored at the airport. All of the various processes generated contaminated scrap metal, with the most problematic, in terms of quantity and degree of contamination, being Raschig rings from extraction columns, corroded drums in which K-65 had been stored before reprocessing, and floor materials (such as bituminous floor coverings being replaced).

The K-65 residues were stored in drums. Some of the waste sent to SLAPS was said to have been hand-packed by Mallinckrodt workers into barrels (drums) (Eisenbud 1975). A concrete-lined pit ("the swimming pool") was constructed to store the drums in, but was never used "due to health reasons" (i.e., the dose rates and perhaps the radon concentrating in the pit would be at excessively high levels) (AEC 1959) and because the corrosion of the K-65 drums would have made retrieval from a pit difficult (MCW 1949g). However, AEC (1959) stated that the pit was used to store tailings from the slag reprocessing operation from 1955 on. The same storage design and precautions as for the ore

were followed for the radium-containing waste (MED 1946c), except that the drums may have been kept in the open until the storage shed was built in about August 1947 (AEC 1947a). (See also Section 5.2.1 above.) Shield walls were included in this to divide it into smaller areas (AEC 1947a). Workers who performed operations where the K-65 and ore were stored at the Mallinckrodt main St. Louis site and at SLAPS (i.e., the warehouse/yard workers) were placed on a rigid time schedule to keep them from exceeding the tolerance dose (MCW 1949g; MCW 1949s; MCW 1949p; MCW 1950v). For example, MCW (1949s) states that a warehouse worker (including forktruck drivers) could, in one week, unload one ore car and make one trip to SLAPS involving K-65 handling and other duties within 50 feet of the K-65/ore pad or he could work loading one railcar with K-65 drums and make one trip to SLAPS ditto; an additional restriction was that no more than 2 hours per week could be spent at SLAPS, with only one hour per day actually working at the pad. As Mallinckrodt and AEC recognized (MCW 1949g), prior to the reprocessing of the K-65, corrosion of the drums was a severe problem: although the K-65 was insoluble, stream pollution at SLAPS was a possibility, but repackaging the K-65 would involve significant worker dose. MCW (1949g) suggested that some of the "sand" (inferentially, the AM-7 residue, as furnace sand with the radioactivity deposited on it) was being put into the K-65 drums, presumably to lower the dose rate from individual drums.

Concern was also expressed in 1949 about the bulldozer and crane operators working at the fresh and aged raffinate (AM-7) heaps at SLAPS (MCW 1949g). This was studied and it was found that the beta dose rate at the cab of a bulldozer pushed all the way into a heap of raffinate was considerably below tolerance. Since the bulldozer operator averaged less than 8 hours per week on the raffinate heap work, this operator's exposure was a small fraction of tolerance. These workers were thus not issued film badges.

As noted in Section 4.7, most or all of the K-65 was brought back in drums from SLAPS and reprocessed starting in early 1948. In January 1949, the gamma dose to the hands of operators opening drums of return K-65 was studied by placing film badges on their wrists (MCW 1949e). See Section 5.4.1 for results. No correction of the high hand dose situation was made, however, because the K-65 drum opening was done over a limited period of time (i.e., once all the K-65 stored at SLAPS had been brought back and reprocessed, the operation was over) and it was not realized how high the doses were until the study was done late in the reprocessing campaign (MCW 1949e).

The K-65 waste residues included not only the residues themselves, but also the used cloths from the Feinc press filters; drum disposal was the only solution for disposal of the cloths, since (1) they were impregnated with the radium-lead salt sludge and thus would not burn and (2) they were made of plastic fibers and thus would not dissolve in acid (AEC 1949f). It was reported that three used filter cloths, stored in two 55-gallon drums, produced 30 times the tolerance level dose rate at contact with the drums (AEC 1949f). Thus the cloths and the operations associated with them were of major concern with respect to external exposures in Plant 6.

In 1949, a study was done of the beta and gamma exposures associated with preparing, repairing, cleaning, and changing Feinc filter cloths by the cloth operators (MCW 1951g). Due to a reduction in the external dose tolerance levels by AEC, it had been recommended that an additional (third) worker be added to the rotation schedule for this job. Major revisions as a result of the 1949 study were that a basket was provided for carrying the used cloths, the filters were partly cleaned by the area operator before the cloth operator began work, and a fourth worker was to be added to the rotation schedule in May 1950. However, the cloth operators did not like to use the basket because it was hard to haul it up the stairways of the filter platforms and they still had to spend some time cleaning the filter. Also, during the summer of 1950 several dozen workers were transferred from Plant 6 to Plant 1 (see Section 5.0) and this disruption of operations and the need to retrain new workers delayed the assignment of new people to the rotation, which was not done until November 1950. This also increased the two principal cloth operators' doses significantly over the other cloth operators' doses.

As a result, it was agreed in 1950 that the area operators would better clean the filters and blankets in preparation for the cloth operators' work, the cloth change interval would be increased from two days to three, and a fifth worker would be added to the rotation (MCW 1951g; MCW 1951a). In January 1951, a new study was done of beta and gamma exposures associated with preparing, repairing, cleaning, and changing filter cloths (MCW 1951a); this included cloths for the Feinc, C-3, and Recovery filters. Dose rates measured with instruments were combined with time measurements to estimate doses; the gamma doses were said to agree well with film badge readings but not the beta doses, due to the technical difficulties of field measurements of beta radiation. These results were said to be comparable to those found in the 1949 study, although some of the tasks the cloth operators were doing in 1949 had been given to the area operators to do (MCW 1951a), but clearly the weekly doses had increased at the time of the 1951 study. Also, the operators were still not using the basket provided because of its bulkiness. But waiting in the cell for work to start and other work practices that increased the "close to Feinc" (distance of less than three feet) time had been changed and the cloth change interval was increased from two days to three (MCW 1951a), so the doses were expected to decrease.

There were varying quantities of miscellaneous waste arising from various sources. For example, rags and paper with small amounts of uranium forms and residues were created from cleaning and wiping procedures, such as the black oxide from wiping derbies, billets, and mold strips and the residue from wiping the outsides of drums before transport. Other types of contaminated materials included packaging, sweeping compound, old uniforms and gloves, and like items that were used in the process areas or were in contact with radioactive matter. All of these types of materials could be burned in an incinerator outside Building 115 at Plant 6 or outside Building 403 in Plant 4 (Mallinckrodt 1994) and the ash could be processed or sent elsewhere for recovery. The filter cloths were also incinerated (MCW 1951a), at least during some periods of operation.

Dust from the various processes was collected mostly in bag-type filters, although some was collected with a rotoclone (a water spray type of collector) and run into a recovery tank (MED 1944o). Dumping these filters, i.e., dumping the bags of dust into drums, was recognized as a high-dust operation (e.g., AEC 1954a, AEC 1954d, AEC 1954c). Mallinckrodt estimated that bags were changed about every six weeks for the Plant 6 Pot Room dust collector and that it took 1.5–2 hours per bag change, for a downtime percentage of 0.4% (MCW 1955r). Occasionally a bag would break, obviously resulting in even higher dust levels. For these reasons, respirators were supposed to be worn but were not always (e.g., AEC 1954e). There was also a possibility of increased external dose from dealing with the collectors. For example, in 1956 a maintenance worker received an external dose higher than usual, as shown by his film badge reading; this was found to be mostly due to the eight hours he spent repairing one of the Hoffman collectors that served the recast (YM-5 or billet) area (MCW 1956j). This collector handled the beta-active black oxide that resulted from the recast activities (MCW 1956j).

Dust was a problem even with empty drums. Mallinckrodt reported to AEC in 1950 that used K-65 drums being returned to Mallinckrodt in ATMX railcars did not always have lids and were not always cleaned (MCW 1950n). This resulted in dispersal of the residual dust throughout the car during shipment, to such an extent that Mallinckrodt collected 100 pounds of it in one railcar after it was unloaded; there was contamination of the receiving dock as well. Dust concentrations in the railcar in excess of 250 times tolerance (i.e., more than 17,500 dpm/m^3) were found in the general area of the railcar and about 27 times tolerance in the worker's breathing zone, but the radon concentrations did not exceed 20% of tolerance and the gamma radiation did not exceed 15% of tolerance. AEC appears to have resolved this by directing the drum sender (presumably Lake Ontario Ordnance Works) to correct the situation.

It was noted in January 1955 that for a considerable period, radon concentrations of 1–8 × 10^{-10} Ci/L had been detected in the Plant 6 Cloth Storage Room (MCW 1955j). After much detective work, it

was found that the wall near the M-50 (tank) sump was saturated with "material" that had come from the sump and from the Wash Oliver cell (presumably by liquid leakage and/or by deposition via air currents). Holes in the wall and ceiling of the Cloth Storage Room created a draft from the sump area across the accumulated material and up into the upper area of the room. This situation appears to have been remedied once discovered. However, in December 1956, the Cloth Storage Room was again studied because of the wide variation in the radon readings taken during weekly checks; over 1 August to 31 December 1956, the 18 weekly measurements of radon level varied from less than 1.0 x 10^{-12} Ci/L (i.e., nondetectable by Mallinckrodt methods) to 1.11 x 10^{-10} Ci/L, with the average being 0.5 x 10^{-10} Ci/L and the median being 0.265 10^{-10} Ci/L (MCW 1957). It was found that there were two major radium-containing deposits in the floor and a wall of the room. While the highest gamma reading was only 2 mR/hour, in accessible areas, it was thought that the reading would be higher in the nonaccessible areas behind equipment. Thus the migration of material from adjacent areas appears to have been a continuing phenomenon.

It was recognized that radon levels at the K-65 and ore storage area at SLAPS were high also; along with the gamma problem, the radon problem necessitated restrictions on the time a worker could spend there (MCW 1949g). Mallinckrodt was supposed to be taking radon samples at SLAPS, but after one set had been taken someone mistakenly stopped taking them (AEC 1949j). An AEC safety representative then averaged the sixty-plus samples taken up to then to produce results that could be graphed so as to see the rough falloff with distance (AEC 1949j).

The ore drum thawing and drying oven—apparently a large walk-in room with steam coils for heating—was used to thaw the K-65 drums before processing and even for temporary storage of dozens of these drums (MCW 1949o). Not only did radon emanate from the drums during heating, but because the drums were apparently opened for the heating, K-65 had been spilled onto the coils and was contributing radon on a continuing basis. This could not all be cleaned off by a vacuum cleaner. High radon levels were seen outside the oven during the heating, so a fan and stack were installed in the back of the thawing oven to draw away the radon from the drums during thawing (MCW 1949o). However, this produced no improvement. It was discovered when the heating coils were turned off, even when the fan was on, air was drawn in under the oven door and forced out over the top of the door, where it eddied in front of the oven before being drawn in again under the door. This phenomenon kept radon concentrations up inside and outside the oven. Although the time spent by workers in the oven was short and their daily weighted exposure was below the radon tolerance level, it was believed that it was not safe to operate at tolerance levels for extended periods (MCW 1949o). Thus the thawing oven ventilation had to be revised and the coils taken apart for cleaning.

As noted earlier, in 1955–1957 Mallinckrodt processed AM-7 residues (see Table A-4) and produced 3,600 gallons of a concentrated thorium nitrate solution that was sent to Mound (AEC 1967; DOE 2002). AEC (1967) states that Mound purified and concentrated approximately a kilogram of thorium-230 from this material, but DOE (2002) states that although 500 grams were produced and an additional 500 grams ordered, the latter were apparently never produced. The favorable to claimant assumption will be made that the entire 1 kg was produced. Thus assuming a high separation percentage, in the original 350 tons of AM-7 during processing there were approximately the one kilogram of Th-230, about 10.4 kilograms of total thorium, and 0.15 kilogram of uranium. This is consistent with the report by Figgins et al. (1962) that in the solution there were 29 ppm of Th-232 and 3.8 ppm of Th-230, i.e., 11.6% (weight) Th-230 by isotope.

When AEC asked Mallinckrodt to establish a pilot plant to process more of the thorium-bearing residue, Mallinckrodt refused, on the basis that the health hazards of thorium were not well understood (AEC 1955c). One concern was that because the process involved only solutions (i.e., the liquid form), exposures would mainly arise from accidental releases or leaks, which would not be easily detectable by ordinary industrial hygiene measures; hence Mallinckrodt wanted some way to detect exposure via urinary or other biological measurements (AEC 1955c). AEC agreed to study the

biological half-life of thorium in the lung and bone following inhalation of thorium fluoride and nitrate salts; they were also to study the urinary clearance rate (AEC 1955c). Mallinckrodt approached the Los Alamos site because it would be receiving the thorium, but could elicit only the information that thorium could be considered equivalent to plutonium on a curie basis (ORAU 1991). AEC agreed that the pilot plant would be built and operated as if it were to process plutonium (AEC 1955c) and the pilot plant began operation at MEP on 25 February 1956 (ORAU 1991). Because the health hazards were on a "speculative level," Mallinckrodt restricted the number of workers on the project and took strict precautions as to handling, contamination control, and access (ORAU 1991). However, there does not appear to be any information available as to how the urinalyses were analyzed.

The "breathing zone" operations in the thorium processing were the removal of the raffinate cake (formed in the processing) in dumpsters and the opening of the contactor tank to adjust the concentration of the process material and to add laboratory waste materials (AEC 1955d). While AEC (1955d) found that exposures of the Plant 7E workers were always below the MAC (note that since gross alpha was measured, the thorium and its alpha-emitting daughters were in fact measured in air sampling), it was also pointed out that the pilot plant was then in the startup phase of operations and that thus the 1955 air survey was possibly not representative of mature operating conditions (AEC 1955d).

It is not clear how long it had been since the first residue sent in 1946 to the SLAPS waste storage site had been produced in the refining process. That is, this type of residue had been produced since ether extraction started in July 1942, but it is not clear whether the residues produced between 1942 and 1946 were all stored at Mallinckrodt and then shipped to SLAPS, or whether some of the older residues had been shipped elsewhere. Assuming that the waste was all produced in 1942 and sat in containers for 15 years, until 1957; this will maximize the radium and radon content. As Table A-6 shows, although the Th-230 and Th-232 daughters would have had some time to build up, only the Th-232 daughters would be nearing equilibrium with the parent. The maximum Ra-226 content over the 2.25 possible years of processing (i.e., the 15-year maximum) was 0.158 mCi (ignoring decay of Ra-226) and the maximum Rn-222 content was 0.158 mCi.

Regarding the protactinium processing of residues, there is no suggestion in any reference that the Sperry cake used had been processed in any way at the St. Louis downtown site; the waste appears to have been shipped out to Mound directly from SLAPS. Thus, it will be considered that there are no radiological implications of protactinium processing associated with the Mallinckrodt downtown site.

AEC (1960) states that the SLAPS waste, also called the airport residue, was evaluated for sale or disposal in about 1960 and was sampled even before that. The pitchblende (K-65) residues were auger-sampled in June 1953; barium sulfate cake, Colorado raffinates (from domestic ores), and miscellaneous ores were also considered. See Table A-4 for quantitative information.

It is not clear whether the storage workers and guards were always Mallinckrodt employees or not, but Mallinckrodt workers appeared to have been doing the residue delivery and placement work even in 1946–1953 (MCW 1949d; MCW 1949p) and there are mentions of "airport" in urinalysis records. ORAU (1989) suggests that Ledoux Company laboratory workers also worked there, probably doing sampling. Material was taken to and from the Mallinckrodt St. Louis site by truck (Mallinckrodt 1994; AEC 1947a; MCW 1949p). Guards were maintained at the site from 1946 to 1951 (AEC 1959); after that, it appears that guards were present only for routine patrols and actual worker entry into the site.

At the time that SLAPS decontamination was being planned in about 1964, the residues still stored on the site were the pitchblende raffinate (AM-7), Colorado ore residues, leached and unleached barium sulfate cakes (AJ-4), miscellaneous residues (but not K-65), and the C-oxides (AEC 1964). The C-oxides were then being shipped to Fernald for reprocessing and the rest were to be offered for sale. In addition, there were several hundred tons of contaminated metal and debris at the site (AEC 1964).

5.2.4 Sampling and Laboratory Activities for All Forms

As noted earlier, other feeds besides ore were used from the mid-1950's on. The drums of these alternative feeds were usually sampled (e.g., for oil analysis) in the Plant 6 warehouse by either Analytical Laboratory workers (MCW 1956h) or warehouse workers. The process as performed by the laboratory workers was described in December 1956 as follows (MCW 1956h). Three drums were opened and a small amount was scooped out of each and put into a bottle, which was labeled and taken to the laboratory. Air samples of this activity were taken with the warehouse exhaust fan running and the large doors (panels) to the outside open. Air movement was found to be almost nil and the dust created by the sampling lingered in the air for an extended period. The average airborne level during sampling was 18,000 alpha dpm per cubic meter. A recheck of sampling was done under the same conditions but from the residue drum where the samples taken at the origination point were put after analysis there; this drum held the samples from the entire lot shipped and so could be assumed to be representative of the lot. Readings during the residue drum sampling showed an average level of 8,530 dpm per cubic meter. Using the all-purpose hood in the Old Boiler House showed levels of 3,460 and 584 dpm per cubic meter respectively for the two types of drums. Since the residue drum was at most half full and was a single dust source, it was clearly preferable to sample that way. It is not clear whether the change to sampling the residue drum and using the Old Boiler House hood was made, but it is likely that it was.

In 1955 feed material had come from or was expected to come from Beaver Lodge, South Africa, and Portugal (the latter as a concentrate) (MCW 1955m). A problem identified with this material was that it contained scrap iron, cake materials, and large pieces of uranium. Obtaining a representative sample of the feed would thus require preliminary separation of the extraneous material. It was necessary to process this feed and more like it at the rate of 200 drums per day, hence construction of a suitably ventilated sampling station was not an option in the short term. It appears that at least in the short term Mallinckrodt sampled these drums with an auger in the ventilated sampling bays of the Plant 6 warehouse.

In the early days of the project, the shotgun laboratory in Building 55 of Plant 2 used a 100-mg RaBe source to test UO_3 samples using neutron absorption techniques; hence it had to be designated as a special restricted area for access control purposes (Mason 1977). It appears that the RaBe source was not used after some early point, since (MED 1944m) and other documents state that such samples were prepared at Mallinckrodt and then sent elsewhere for analysis. It may therefore be assumed that use of the RaBe source for this purpose had ended by September 1944 (the date of MED 1944m).

MED (1944m) stated that UO_2 shotgun samples (possibly the reference meant UO_3) were prepared by dissolving 25 lbs of UO_2 in acid and extracting uranium nitrate hexahydrate in a four-step ether process; the remaining water layer, which also contained nearly all of the Th-234 and Pa-234 (UX1 and UX2), was run through a separating funnel, then evaporated to dryness in a dish, first by the chemist using a handheld blast burner, then in a muffle furnace. The sample remaining, which averaged 3–5 grams, was ground by hand in a mortar and poured into a bottle. The accumulation of sample bottles, usually three to twelve per day, was sent away daily for analysis. In 1954, the shotgun samples were made up in the Dry Material Sample Room (or Powder Sample Room), apparently because of equipment availability, but the work was performed by the Shotgun Sample Lab personnel and not the Dry Material Sample Room personnel (MCW 1954b). There was also a Metal Sample Room (MCW 1954b), presumably for assaying the finished metal forms.

Prior to August 1955, an average of two Mallinckrodt UO_3 samples were run daily in the Shotgun Laboratory and film badge readings were under the applicable limits (MCW 1955e); usually only one worker was needed for this. However, from August 1955 into October 1955, a campaign was performed to run UO_3 samples from other sites as well; these other-site samples constituted more

than half of the total and were mostly from Fernald but also from Beaver Lodge, Port Hope, "Canada," and "Pilot Plant" (apparently not a Mallinckrodt pilot plant). The workload increased by a factor of three and temporary workers were hired for a few months to do the work. With one Mallinckrodt worker and one temporary per shift to do two Mallinckrodt samples and four other-site samples per day, film badge readings went up significantly—one badge read 5,810 mrep in one week in August and another read 2,040 mrep in September, mostly beta. The hot plate hood, the muffle furnace, and the evaporating dish in the cooling and scrapedown hood were found to be contaminated with material producing mostly beta radiation, while a can of pellets under the sample press was giving off a significant gamma dose rate.

The situation was studied (MCW 1955e). It was found that there was no significant radiation reading in the laboratory assay of UO_3 until the laboratory crucible containing the sample was placed on the hot plate; as the sample was evaporated, the reading rose rapidly. The source of the radiation was the dried residues on the crucible. For the Mallinckrodt-produced samples, the average reading of 10 samples was 1,500 mrep/hour at 1" above the top of the crucible and 1,000 mrep/hour at 2"; the respective averages for the four "Pilot Plant" samples checked were 1,800 and 1,200 and for the ten Fernald samples they were >12,500 and 12,000 mrep/hour respectively. (Apparently the maximum that the Zeus instrument could read was 12, 500 mrep/hour, so the Fernald 1" readings were undoubtedly much higher.) A film badge set at 2 feet over the scale on the main work bench and about 5 feet from the boildown and crucible cooling hoods for a week read 1,000 mrep beta and 50 mR gamma. A time-and-motion study showed that a laboratory worker handled the sample in some way for a total of 11 minutes after boildown, i.e., after significant readings could be expected to appear.

The Shotgun Laboratory was decontaminated by the Mallinckrodt decontamination group, with the contaminated items either cleaned or disposed of; a Lucite shield was provided to put in front of the crucibles during cooling and a steel box was provided to put the crucibles in during cooling and storage (MCW 1955e). Respirators were required to be worn during the scraping, grinding, and palletizing of the samples. A film badge placed in the same area as the first one had been read 1,500 mrep/hour beta and 95 mR/hour gamma after two weeks, indicating that the cleanup and other corrective measures had been only partly successful.

K-65 sludge was sampled to determine its radium content 24 hours after it was produced, put into metal drums and stored in an adjacent warehouse (AEC 1949f). The sampling appears to have been done in the warehouse by the warehouse workers in the early years, but in a sampling room in the Scalehouse in later years; the assay was done in the Ledoux Lab by Ledoux company workers (MCW 1954a, ORAU 1989a).

In March 1955, a survey of the Scalehouse Sampling Room was made to evaluate dust, radon, and external exposure hazards from sampling K-65 drums (MCW 1955n). At this time, drums of K-65 were sampled once a day. Approximately 24 drums were moved, four at a time on a pallet, by forktruck from the storage bay to one of the K-65 sampling bays. Two samples were taken from each drum using a thief sampler inserted by means of the sampling holes (as described above); after the sample was deposited in a pan, the thief was cleaned by scraping it and knocking it against the sample rack, putting dust into the air. The pans of material were accumulated inside the sampling area until all the drums had been sampled, after which the pans were taken into the Scalehouse area and put on a rack to await transport to the Ledoux Laboratory. The operator then cleaned the floor of the sample room. It was found that during the 80 minutes of the sampling work period, the total external exposure to an operator from sampling a lot of 24 drums was 3.4 mR gamma and 3.8 mrep beta; the average total beta-gamma dose rate was 5.5 mrep/hour, the peak radon level was less than 0.5×10^{-10} Ci/L and the average was less than 0.25×10^{-10} Ci/L; and the average dust level was 1,870 dpm per cubic meter, with both the general area and the operator breathing zone concentration during the actual sampling being about 2,300 dpm per cubic meter. It was also found that air was frequently

forced into the Sampling Room through the sampling holes in the floor, especially with a north or west wind. This air carried with it dust from its passage across the stored drums of K-65 and thus contributed strongly to the dust concentration in the room despite the nominal adequate exhaust flow, which was exhausted at floor level to draw down the dust from the sampling pans. It was recommended that respirators be worn, which apparently was not being done previously.

In 1953, the Ledoux Lab technician spent three whole days and two half days in the Ledoux Lab and two half days in the shotgun (assay) lab (MCW 1953b). At this time, the K-65 (radium-bearing) residue testing work in the Ledoux Lab consisted of compositing residue, drying it in an oven, blending it in a blender, redrying it in a dry box, mixing it in a tumbler, and then presumably testing it. The sources of dust in this operation were identified as using the grinding hood, when dumping pans of K-65 for grinding; weighing out (since there was some spillage and some need to scrape off the bottoms of the pans); cutting the sample (ground K-65 was cut through a riffle); screening (on the "Ro-tap"); and using the jaw crusher (for AM-7 residue only), for which there was no hood (MCW 1954a). The sink used for washing pans had no sump, so the wash water went to the sewage; splashing from the sink was viewed as a source of the contamination on the floor (MCW 1954a). At one point, the exhaust fan door was locked closed until the chain assembly could be repaired, hence ventilation was impaired (MCW 1954a). The cabinets' interiors were found to be very dusty and the hood bases and walls, which were made of transite, had visible signs of absorbing K-65 (MCW 1954a). There was an associated Furnace Room, presumably for drying, in which respirator wearing was recommended (MCW 1953b) and the K-65 was said to be weighed on a pan on a scale "through the hole in the Furnace Room wall" (MCW 1953b). However, the heat from the ovens (furnaces) created enough draft to draw the radon up out of the lab and out over the roof (MCW 1954a). All of this information suggests a significant amount of manual handling of the residue and uncertain control of contamination, even after a new laboratory was built in 1952 and improvements were made in 1953 (MCW 1953a).

When the "U-Con" process was set up to recover uranium as a slurry from reject MgF_2 material, the U-Con began to be sampled in the Slag Separation area of Plant 7 and the samples processed in a minimal preliminary fashion in the Analytical and LeDoux Laboratories (MCW 1955L). Four samples per day were taken and transported together in open stainless steel pans in a coaster wagon to the Shotgun Laboratory. They were processed in a hood with a left-right sliding panel, the purpose of which was to keep dust out of the laboratory technician's breathing area. The technician reached around the panel and used a small hand scoop to remove some of the U-Con and place it in a grinder in the hood. After the sample was ground the grinder pan was emptied back into the sample pan. Then the sliding panel was moved to allow the dust in the grinder to be brushed out into the grinder pan. Finally the panel was slid back and the grinder pan was re-emptied back into the sample pan and the sample pan was removed from the hood. The grinding and grinder brushing took a total of 8.7 minutes and was repeated for each of the four samples per day. With preparation work, the technician thus spent about an hour per day in the Shotgun Laboratory. A dust study showed the average breathing zone concentration to be 20 dpm per cubic meter and the general area concentration to be 23 dpm per cubic meter over the entire four-sample operation, indicating that the open pans were more of a problem than the grinding itself, because of the hood.

A check of the Shotgun grinding hood was also performed. This showed that the flow volume was 234 cubic feet per minute and the air velocity averaged 75 linear feet per minute over the face of the hood (MCW 1955L), only somewhat under the 100 linear feet per minute that might be typical of such a hood today.

5.2.5 Safety, Health, Decontamination, and Laundry Facilities

A respirator decontamination facility was added, presumably in Plant 6, in April 1950 (MCW 1950e). It is unclear where this was done previously.

Although most contaminated equipment could be repaired in situ or in the Mallinckrodt repair shop, which was not dedicated to AEC work but served the entire Mallinckrodt general site, some equipment had to be sent out to other companies' facilities for repair (AEC 1948h). AEC approved this practice based on its requirement that all items should be decontaminated if possible to "zero wipe" (i.e., no detectable removable contamination) and on the assumption that any resulting contamination on floors and machines would not be significant. AEC also stated that air samples should be taken of representative repair operations in the Mallinckrodt shop and that areas immediately adjacent to the Mallinckrodt shop should be monitored for contamination in order to verify that surface contamination was not being tracked out (AEC 1948h); it is not clear if this was done or not.

MED (1942) stated that both contaminated and clean clothing were laundered on the premises, in separate laundries; however, AEC (1947a) stated that contaminated protective clothing from all areas was sent to public laundries, contrary to other AEC sites' practice. Use of public laundries appears to have ceased at AEC direction (as suggested by AEC 1947b). An onsite laundry with "clean side, dirty side" flow was installed some time prior to April 1950 (MCW 1950e).

5.3 INTERNAL DOSE CONSIDERATIONS

The primary route of internal exposure was via inhalation of airborne particulates, although radon was a considerable problem in some areas. It was noted in December 1942 (MED 1942) that the primary precautions taken against radiological hazards were against inhalation of the dust. The wet operations did not generate as significant a level of airborne particulates as the dry operations (Mason 1958a). Thus the operations that were likely to produce airborne particulates were those in which the uranium-containing material was dry or was heated, although airborne contamination could occur even when the material was not open to the room air because some of the equipment leaked (Caplan and Mason 1952). Material that had settled on the floor and other surfaces could also be resuspended in the course of operations.

A number of parameters related to internal exposures were measured, but very little internal data is reported in units of dose. Measurements of airborne concentrations were used as indicators of potential exposures and of the need for changes in processes and equipment (as suggested by AEC 1950a). Uranium urinalysis appears to have been performed as a means of retroactively checking for acute exposures or for the onset of damage due to chronic exposure, rather than a dose measurement per se, although some dose calculations were apparently done by AEC for study or verification purposes. In addition, as discussed below, the particle size and solubility of the various uranium forms were still being investigated experimentally by researchers. This technical basis document presents potential internal exposure information in terms of airborne concentration data (and the derived inhaled amounts) and surrogate urinalysis results.

5.3.1 Particle Size, Solubility, and Composition Considerations; Air Sampling Methods

A discussion of the thinking of the time regarding particle size and solubility is included in the discussion below in case questions arise regarding typical operations or regarding notes in the urinalysis and other records.

The uranium refining operations at Mallinckrodt produced nominally insoluble uranium compounds, e.g., UO_2, UF_4, and uranium metal (Lippmann 1958, regarding solubility); no patently soluble forms, such as UF_6, appear to have been produced. However, as some of the literature in the years between 1958 and about 1975 showed, some supposedly insoluble particles produced in these operations seemed to behave like soluble particles (e.g., Lippmann 1958, Heatherton 1975, Archer et al. 1975). More recently, ICRP 71 (ICRP 1995a) states that studies of UF_4 show behavior consistent with Type F in some cases and Type M in other cases, while ICRP 68 (ICRP 1995b) recommends Type M for UF_4. Yet autopsy data from deceased workers showed a far lower concentration of uranium and thorium in

lung and other tissues than would have been expected based on the average airborne concentrations inhaled. This led Eisenbud (1975) and others to postulate that the particle behavior formulation at the time was incorrect: they conjectured that due to the high density of the uranium and daughters, particles of respirable diameter behaved like lighter particles of much larger diameters.

A study of air dust particle sizes in the UO_3-to-UO_2 area was done in 1948 for AEC by the University of Rochester (1948b). Both filter paper dust samples and cascade impactor samples were taken at the tumbling area (where the newly formed and cooled UO_2 was place in tumbling drums and rotated on a tumbler to break up clumps); at the skip hoist (where the tumbling drums were opened and transferred to the hopper of the Fiberpack loader); at the Fiberpack loader (where a vibrating chute fed the material into 75-lb containers and the containers sealed on a roller conveyor); and at the warehouse (where the UO_2 containers were stored). The sampling rate of the cascade impactor was 14 liters per minute; it is unclear what the filter paper sampling rate was. All samples were analyzed for uranium by the fluorometric method and the results were found to be well within the accuracy range of the method. Particle size distributions showed normal curves and to be in excellent agreement with the theoretical curves. The results are shown in Table A-7.

Also shown in Table A-7 are some measurements reported by Sanders (1975). Sanders (1975) also provides a useful general observation that foundry operations (those in which uranium oxides are produced) have the highest percentage of airborne particles in the lower lung-inhalation range, while reduction operations (UF_4 to metal) have the smallest percentage.

Eisenbud (1958) reported that "It has been shown that in these [uranium processing] plants the mass median diameter was about 2 μ [microns]." But he also noted that while the peak for alveolar retention is 1–2 μ for dust of unit density (i.e., 1 g/cm^3), uranium oxide dust has a density of 9 or 10 g/cc, so that a 1–2 μ particle would behave as though it were a 3–6 μ particle of unit density. An AEC report on uranium mills stated that ore concentrates (the form that arrived at uranium refineries such as Mallinckrodt) had a "mass medium [sic] size" of 2.5 μ (AEC 1958). Some uranium refinery workers were said to have been exposed to UO_3 dust with a mass median diameter of 2 μ; however, with a density for U compounds in the range of 9–10 g/cm^3, the effective aerodynamic diameter was much larger than 2 μ, possibly in the range of 5–6 μ (Eisenbud 1975).

Schwendiman et al. (1975) cited the results of a study by Lippmann and Harris regarding the application of size-selective samplers in the uranium industry. Lippmann and Harris performed a sampling survey of six different uranium processing plants. They used a two-stage setup: following a cyclone separator, the first stage collected 100% of particles ≥ 10 μm aerodynamic equivalent diameter (AED), 75% of those = 5 μm, 50% = 3.5 μm, 25% = 2.5 μm, and 0% of those ≤ 2 μm, while the second stage, a filter, collected the rest of the particles. They found that less than 15% of the airborne material collected on the second (the respirable-particle) filter. Schwendiman et al. (1975) noted that this agreed fairly well with the ICRP assumption of a size distribution such that 25% deposits in the lower respiratory passages and, for insoluble compounds, only half of the 25% (or 12.5%) would be retained with biological half-life of 120 days: only 10% of the samples in the study had more than 25% collected on the second filter. Categories studied included U_3O_8, UO_3, UO_2, ore concentrate, and mixed scrap.

Because of the lack of specific information regarding all types of particle sizes at the Mallinckrodt plants and how the information would apply to each worker's breathing zone over time, the ICRP 66 default deposition parameters (ICRP 1994) should be used to estimate internal doses for Mallinckrodt workers.

Regarding the isotopic and chemical composition of the airborne dusts, there is only a little Mallinckrodt-specific information. In 1947 AEC had the ore and residue dust studied by the University of Rochester, which investigated the uranium and radium content of filter paper after use in air

sampling (Rochester 1948a); it was stressed in the University of Rochester's report on the results that the samples were taken not to determine health hazards directly (i.e., by inferring the air concentration from worker positions) but rather to obtain a heavy concentration of each material so as to compare the relative concentrations in the dust. Thus each concentration was taken at the maximum emission point (in fact the centrifuge was partially opened for the sample-taking), without reference to actual worker position or breathing zone. The precision of the measurements was said to be better than +/- 10% and each figure in University of Rochester's report represented at least three analyses. The U:Ra activity ratio was approximately 2 in the ore; 0.02 in the gangue (GLC or K-65) residue from the Scalehouse and 0.3 to 0.4 in the Centrifuge area where the liquid and solid residue (Ra-bearing) fractions were separated, indicating removal of most of the uranium from the K-65. The U:Ra ratio of 2 indicates that U-238, U-234 and Ra-226 were approximately in equilibrium in the ore.

Observations at a large uranium processing mill (probably Anaconda) showed that although the potential for dust creation in the dry processing steps was clear, the wet processing steps, such as grinding, leaching, separation, and precipitation could create aerosols by agitation or by transfer of solutions and slurries (Wilde 1975). Even so, in the wet processing areas airborne uranium was never a major problem, i.e., local hooding and exhaust ventilation were not required in order to keep the dust concentration below allowable levels. The physical characteristics of the airborne particulates in the dry and the wet areas were thought to be similar; thus it was assumed that nearly all of the mass of the particle was siliceous material, clay, or a mixture of the two. The mass of the particles was found to be less than one percent of the total mass. From specific nuclide analyses done over several years, they concluded that secular equilibrium existed at least through Ra-226 in the ore at the time of mining. Specific nuclide analyses of particles taken in various areas of the mill showed that the U-238:Th-230:Ra-226 ratio was 1:1:0.3 and was fairly constant regardless of the source of the aerosol or dust. But in the yellowcake section of the mill, where the ore had been processed to become mostly U_3O_8, the ratio was 1:0.01:0.001, indicating that the Th-230 and Ra-226 concentrations were reduced in the processing (Wilde 1975). However, as discussed in the paragraph above, at least the one study of what was probably Belgian Congo ore at Mallinckrodt indicated secular equilibrium with Ra-226.

AEC began taking air dust samples for particulate alpha emitters in 1943 and Mallinckrodt appears to have been taking dust samples and sending them to NYOO for evaluation from about 1943 on (MED 1944j). The various AEC air dust study reports state that an established AEC protocol was followed, but the documentation of the protocol is lacking. However, some information is known about Mallinckrodt's and AEC's methods. MED (1943d) stated that the sample rate for measurements in the second quarter of 1943 was 3 ft^3/min, with either 30 or 120 ft^3 sampled, depending on the area. Mallinckrodt (MCW 1946g) stated that dust was measured with a "precipitron and ion-meter." For the data reported by MCW (1949d), dust samples were collected on 1⅛" Whatman #41 filter paper disks, using a modified Fischer pump, at 0.5 ft^3/min, over a period of 45 seconds to 30 minutes depending on conditions and job time. The disks were counted on a parallel plate alpha counter such that statistical variations would be no more than +/-10% at the 0.9 confidence level. It was stated that a few of the low-level samples might have errors of +/-20%. Data from 1946 lectures by A. A. Jarrett of Clinton Laboratories were used in the error calculations. AEC (1949g) also states that Mallinckrodt was using a flow rate of 0.5 ft^3/min, with a Fisher and Porter rotometer. AEC (1950a) stated that it was using 1⅛" Whatman filter paper disks and a handheld air sampler with a collection rate of 15–20 linear feet per minute (lfm) to take its samples at Mallinckrodt.

From reports of sampling at other sites and from unspecific mentions in papers and reports about Mallinckrodt, it appears that typical practice was for the air to be drawn through filter paper (usually Whatman #41) and counted on an alpha scintillation counter (e.g., the laundry samples of Utnage 1958b). AEC in-plant air sampling was done by collection on Whatman #41 filter paper and counting of total alphas; a correction for self-absorption in the filter paper was applied (Eisenbud 1975). The results were reported as alpha dpm/m^3 (Eisenbud 1975). The AEC, in sampling stack and environs

air at various sites including Mallinckrodt, used Whatman #41 filter discs with "standard sampling equipment and techniques normally employed by HASL" and counted them on scintillation counters (Weinstein 1958). In 1958 at the Oak Ridge Gaseous Diffusion Plant, the Whatman #41 paper was used with fixed counting equipment, for a counting and collection efficiency of 30% (Becher 1958). Since the methods of the time seem to have been fairly uniform (with HASL setting the standard), it is assumed that the AEC and Mallinckrodt measurement techniques were consistent with these references.

In 1948, some samples on filter paper were taken at Mallinckrodt, conveyed by an AEC inspector to Clinton Laboratories in Oak Ridge to be counted for alpha and beta-gamma activity, and then returned by the inspector to Mallinckrodt to be counted for alpha activity there, apparently as a comparison test (AEC 1948a). The samples were taken in the ore milling area, where ore drums were opened and the ore was ground to the desired consistency for later digestion; thus it can be inferred that the samples showed uranium in equilibrium with its daughters down to radon (as suggested by the results of Rochester 1948a – see table above). The counting equipment was said to be a parallel plate counter at Mallinckrodt, but was unspecified for Oak Ridge. For both the Oak Ridge and Mallinckrodt alpha counting conditions (with identical geometries), the absorption loss was assumed to be 30% and the geometry factor to be 52% (with the extra 2% above the 50% being ascribed to backscatter of the alpha particles). For the Oak Ridge beta-gamma counting conditions, the absorption loss was assumed to be 30% and the geometry factor to be 10%; the beta-gamma counting apparatus at Mallinckrodt was being repaired, so no beta-gamma measurements were made there. The (alpha?) background at Oak Ridge was 4 cpm, while the background at Mallinckrodt was 20 cpm. The conversion factor for alpha was given as 2.75 dpm per cpm and for beta-gamma as 14.3 dpm per cpm. (Although these figures were backward in the text of the reference, the data sheets show the correct correspondence.) In 1949, Mallinckrodt (MCW 1950g) stated that it was assuming the counter geometry to be 52% and the filter paper absorption to be 30%.

AEC (AEC 1948a) noted that the samples taken could not be read at Mallinckrodt for several days after they were brought back from Oak Ridge because the parallel plate apparatus and the counting room had to be decontaminated and the background reduced from 110 cpm to 20 cpm. The agreement for the alpha samples was fairly good, in general mostly within 25% and in many cases much better. For a subsequent set of samples counted at Mallinckrodt (with the background now down to 6 cpm), the same AEC inspector reported (AEC 1948b) that the formula used to convert from alpha cpm to microcuries per cubic meter was as follows, with the 0.3 and the 0.52 being the absorption and geometry factors respectively and the 0.5 being the intake rate of the sampling pump:

$$\#\ \mu Ci/m^3 = \frac{\#\ c/min \times 35.3\ (ft^3/m^3) \times sampling\ time\ (min)}{(1 - 0.3) \times .52\ (c/d) \times 3.7 \times 10^{10}\ (d/sec/Ci) \times 60\ (sec/min) \times 0.5\ (ft^3/min) \times 1 \times 10^{-6}\ (Ci/\mu Ci)}$$

A report issued about the same time by AEC to Mallinckrodt gives the results of dust samples taken in an unspecified Mallinckrodt location and counted apparently at NYOO (AEC 1949i). Counts are given in dpm per cubic meter, with alpha counts given for all samples and both alpha and beta-gamma counts given for about half the samples. These latter show alpha-to-beta-gamma ratios ranging from 0.98 to 6.44, with most values in the range 2.5–3.4.

John Harley, former director of HASL, told an epidemiological studies group (ORAU 1983b) that the equipment used to do the air dust surveys was not very good. He said that HASL had confidence in readings greater than or equal to 25 ug/m^3, but in the range of 10 ug/m^3, the results were thought to be "shaky." He added that although most of the production sites did not do breathing zone sampling (only general air sampling) and some even resisted it, Mallinckrodt did do breathing zone sampling (e.g., MCW 1949d).

The AEC's HASL staff was committed to the time-weighted average as being most representative of total exposure. As Glauberman and Harris (1958) put it, "HASL has found from experience that the multiple-sample time-weighted average exposure procedure is the most accurate... The GA [general area] sample normally will tend to underestimate an operator's exposure and the BZ [breathing zone] sample to overestimate it, but by time-weighting the average concentrations for both types of samples an operator's exposure may be closely evaluated... [this method] yields reasonably reproducible results." In this technical basis document, time-weighted averages will be preferred to static measurements or short-term maxima as being representative of worker exposures. AEC was also interested in the feasibility of using the levels of urinary excretion of uranium as a control metric in production and processing facilities (AEC 1949d); to do this, it was necessary to correlate the urinary measurements with the dust exposures, which could not be done if only general, instantaneous dust levels were used. The time-weighted averages for Mallinckrodt are documented in a series of AEC air dust study reports (e.g., AEC 1954b) and in some Mallinckrodt reports (e.g., MCW 1949d).

5.3.2 Airborne Dust Levels

Eisenbud (1975) stated that "above all other types of exposure, it was the airborne alpha-emitting dust that was the cause of greatest concern." This was particularly true in the sampling and crushing of ore and in the mechanical and manual handling of dry uranium salts and oxides (Eisenbud 1975). Dupree-Ellis et al. (2000) stated that daily average uranium dust concentrations of up to 100–200 times the maximum allowable concentration of 50 µg/m^3 were measured in poorly ventilated processing areas. An industry-wide survey showed the average concentration to be 5,000 dpm/m^3, which an AEC-HASL official stated was "a conservative estimate of the levels that existed from 1942 to 1948" (Harris 1958).

Mason (1958a) stated that while no regular dust sampling program was in effect at Mallinckrodt during 1943–1947, enough samples were collected to show that concentrations were high by 1958 standards, that concentrations of 50 to 100 times the MAC level of 70 dpm/m^3 were not uncommon, and that some operations produced concentrations up to 1,000 MAC for a few minutes at a time. AEC also stated many employees were exposed to elevated dust levels for years (AEC 1949b); AEC estimated that the inhalation of many Plant 4 operators involved in UF_4 production was 27 grams or more of uranium, as compared to what it termed a "life tolerance" of 6 grams, and that an additional two years of exposure would add about 2 more grams (MCW 1949b).

The high levels were of concern to both MED and Mallinckrodt. MED (1944h), in transmitting to Mallinckrodt the results of dust samples taken in June 1944 in the bomb and furnace areas, noted that the results were high and that either ventilation in those areas should be improved or respirator use should be required. Mallinckrodt too was concerned by the high levels, for example the fact that dust concentrations around the various crushing, grinding, and packaging operations consistently exceeded the tolerance levels by a factor of 1–300 (MED 1944k). As a result, Mallinckrodt hired a consulting engineering firm to put together a re-design proposal for dust control (MED 1944k).

MED (1944n) stated the following. In September 1944, MED and Mallinckrodt representatives met to discuss proposals for ventilation improvements in the green salt and metal production areas. It was decided that the ventilation in the green salt furnace room did not need improvement because there were 30 air changes per hour and because the "smell of HF [hydrogen fluoride] was faint." But on the other hand, the green salt unloading, grinding, milling, and blending operations were so dusty that it was decided to do them henceforth under hoods in a continuous sequence, instead of as separate operations, and the blending would be done mechanically instead of manually. Also, the bomb loading, jolting, unloading, and charge blending and the biscuit chipping, all of which were carried out in close proximity, would be provided with separate, localized ventilation. Finally, the green salt blending operation would be redesigned to use a tumbler-type mixer instead of manual mixing, after which time the blender table would no longer be used. Thus in about 1944–1946, significant

incremental improvements in dust control were made that reduced initial production-level dust concentrations in the green salt area.

Respirators were said to be required "for practically all plant operations" in 1946–1948 (Mason 1958a) but respirators were not used consistently (see Section 5.3.3 below).

Major improvements in dust control and ventilation were made at Mallinckrodt in 1949 under the new AEC health program, such as the installation of pneumatic unloading and conveying equipment in Plant 6 process areas that eliminated most hand-scooping and thus that mode of exposure to dust (Mason 1958a). However, while there was a marked reduction in dust levels, the improvement was not what had been hoped for in some areas, especially with respect to the handling of the UO_3 (Mason 1958a). In 1950, for example, it was reported that the air supply system in the Ore Room was such that there was a significant outward flow through the drum opening/closing area shield (MCW 1950u); in 1953, an AEC inspector reported that there were many small openings between the operating area and the drum storage "alleys" in the Ore Room addition; as a result, winds blew into the area and upset the ventilation air balance, causing dust to be blown into the operators' area (AEC 1953). Even the most modern plant, Plant 7, had dust problems: in 1954 an AEC inspector noted that there was a fine film of UO_3 on supposedly clean drums and that as cans of UF_4 were transferred from a hooded enclosure to a conveyor, a green dust cloud could be seen to escape from under the lid of nearly every can (AEC 1954f).

Similarly, in 1948–1950, tighter administrative controls were instituted and much of the manual handling of UO_2, UF_4, and uranium metal in Plant 4 was eliminated, but dust concentrations did not get down to satisfactory levels (Mason 1958a). Even the building of the new Plant 6E and Plant 7 did not completely eliminate the problem: the uranium was never contained well enough that it ceased to create airborne levels of concern in the plant air and in the (multi-building) plants in general (Mason 1958a). A Mallinckrodt official remarked that it had been a constant battle to keep airborne levels at 1 MAC or less (Mason 1958a). An AEC safety official speaking of workers at all the AEC uranium-refining plants (Breslin 1958) reported that even in 1951 approximately half of the workers were exposed to average concentrations above the MAC then in force (which he said was 110 dpm/m^3, although AEC (1954f) indicates that it was 70 dpm/m^3 until at least the end of 1954). He also stated that in 1956, 6% still were above the MAC; the percentages for those exposed to average concentrations greater than 1,800 dpm/m^3 were 4% and 1% respectively. Finally, he noted that while airborne control in these plants was largely achieved by 1955, there had been a retrogression resulting from a large increase in production volume.

Tables A-8 and A-9 give a trend overview of airborne uranium concentrations measured over the years at Plants 4, 6, 6E, and 7 (Mason 1958a). The concentrations are given as multiples of the "preferred level" at the time of measurement (1948), i.e., multiples of 70 dpm alpha per m^3. It appears from the reference that they represent typical or representative concentrations rather than maxima. In AEC's measurements, they did not separate the uranium and radium components of the alpha activity, i.e., they counted gross alpha (AEC 1950a). This was Mallinckrodt's practice as well (MCW 1950c; MCW 1955d); also, beta-gamma activity analysis was not routinely done (MCW 1955d). Thus Tables A-8 through A-16 must be assumed to be gross alpha measurements. There were no continuous air monitors at the Mallinckrodt site, at first because there was no commercial monitor available (MCW 1950e) and later because the results were thought to be of doubtful value (MCW 1955d).

Table A-10 presents some early air sampling data taken by MED. The samples represent single point measurements and no correction was applied for exposure time. Thus unless some assumptions are made as to time spent in the given area performing the given operation, only a bounding or conservative dose calculation can be performed with this data. However, there are some after-

operation or "not in operation" measurements among the data that could help to characterize an average level, if needed.

In this technical basis document, AEC's data are used preferentially because AEC set the standard of measurement for the uranium processing sites and because AEC's figures for the most exposed workers are typically higher than Mallinckrodt's. Thus using AEC's numbers is favorable to claimants, in general. The AEC data are mostly from a series of dust studies that AEC did on a nearly annual basis from about 1948 on. This is presented, with a few additions from Mallinckrodt reports to fill gaps, in comparative form in Table A-11 and in comprehensive form in Tables A-12 through A-16.

Table A-11 presents the results of airborne dust surveys made in Plant 4 by, respectively, AEC-NYOO's Medical Division in May 1948 and Mallinckrodt safety officials in September–October 1948. These results are given as time-weighted daily average radioactivity (particulate) concentrations (called DWE levels by AEC) in air by plant. Table A-11 shows that AEC and Mallinckrodt's data were in general agreement (AEC (1949b) termed it "excellent agreement"), although there were some differences. Mallinckrodt (MCW 1949d) stated that while the Mallinckrodt and AEC results did differ significantly in some instances, it was thought that none of the differences was highly significant except in the case of the office workers; Mallinckrodt (MCW 1949d) also noted that the (overall) lower results of the Mallinckrodt studies were due to Mallinckrodt's taking more control samples and counting low-activity samples for longer times to reduce statistical error.

One notable difference is for "Cage handling," where the AEC-measured level is given as 2.7 times the tolerance level and the Mallinckrodt-measured level is given as 52 times tolerance, or 189 and 3,640 dpm/m3 respectively. The ratio of these two values is about 20. In the original report in which AEC reported its values (AEC 1848l), the job description and summary listing of job categories and DWEs does not include a mention of the cage handling function; there is only a mention of the "Saw man" as taking billets to the cage area. However, in the original report in which Mallinckrodt reported its values and where the comparison table (assembled by Mallinckrodt) first appears (MCW 1949c), there is a category called "Cage man." Thus it appears that the job category of cage man did not exist until mid-1948 or after, i.e., after the AEC study was made. Mallinckrodt seems to have put together an estimate for the "Cage handling" category from the AEC data as some sort of composite of the values for two or more of the other categories, probably including the slag handler (1.6 times the tolerance level). However, given the general functions of the cage man as later described in other dust studies, the cage man's exposure was more likely to be similar to that of the saw man (15.8 times tolerance according to AEC) and the chipper (26.8 times tolerance according to AEC).

Further, an inspection of the detailed job sheet for "Cage man" in the Mallinckrodt report shows that about two-thirds of his dust exposure was due to a single activity, "Dumping D-7" (MCW 1949c). What D-7 was is not defined in any available Mallinckrodt document but it appears to be a form of slag dust.

Dumping D-7 is again mentioned in the Mallinckrodt dust study done in December 1949, but the average levels reported here were reduced by a factor of about 1,000 from those of the earlier Mallinckrodt study. This reduction is most likely attributable to administrative measures taken in 1949 to reduce dust levels in the highest-level activities, but it could also have been due to malfunction of the sampling apparatus in the earlier study, as explained below.

Also, the high value listed in the 1948 Mallinckrodt study (MCW 1949c) for "Dumping D-7" appears to have not been included in the calculation of the DWE by Mallinckrodt. This may have been due to a belief that the sampler malfunctioned in taking that sample. It should be noted that the average level in the next highest area of Plant 4 as measured in this study was less than half this value and that the known highly dusty operations reported on by Mallinckrodt (MCW 1949d) for Plant 6 for October to November 1948, such as ore room, pot room work, and UO_2 handling activities, typically had highest

sample levels that were lower by 50% or more than the MCW (1949c) "Dumping D-7" value. (The pot room and UO_2 handling had only single samples.) Because Mallinckrodt did not include this value in the calculation of the average, probably because they thought it suspect, it is possible that the other D-7 measurements apparently taken at the same time may also have been higher than the true values. Thus the value for "Cage handling" attributed to AEC by Mallinckrodt may in fact be more correct.

Thus the AEC-Mallinckrodt discrepancy in the "Cage handling" category may be due to the job's being new with the Mallinckrodt study, to a mis-estimation of the cage man's exposure from the AEC data, or to a malfunction of the sampler.

An additional note about the dust levels measured in 1948–1949 and their applicability to previous years is in order. It is clear from the inclusion in Table 1 of Mason (1958a) of 1946 through 1950 figures (repeated in this technical basis document as Table A-8) that 1946 and 1947 data were available that Mason thought appropriate for comparison to 1948, 1949, and 1950 data, or at least that Mason believed (by his repetition or plateauing of the same values throughout 1946–1948) that the 1948 data were representative of the 1946 and 1947 operations as well. This can be inferred for Plant 4 as well from Table 2 of Mason (1958a) (repeated in this technical basis document as Table A-8). Thus although the report argues from the paper's Table 1 that significant improvements were made by late 1948 through 1950 that reduced dust levels considerably, this is irrelevant to a significant conclusion that can be drawn from Mason's tables: that the 1948 data was representative of the 1946–1947 data.

This is also borne out by other information from Mason (1958a). This paper states that the dust concentrations "in some operations" in 1942–1943 "were considerably higher than present standards." However, the paper was likely written in 1958 (the conference at which the paper was given took place in October 1958), so the "present standards" were those of the late 1950s. Mason might arguably have made the same comment about 1946 through 1948, since he also stated of the 1946 through 1948 operations in Plant 6 that "during initial operations dust control was minimal, and it can be seen that air concentrations were high during the period 1946 through 1948, when respirators were required for practically all plant operations." While Mason stated that the new health program was authorized in 1947 and got under way in 1948, he also said that one of the first projects of the new Mallinckrodt Health Department was "a thorough analysis of the dust data already accumulated and the immediate collection of additional data to enable an estimation of dust exposure already received by operation and maintenance personnel." Thus even in 1948, apparently no immediate engineered improvements were undertaken. Mason went on to say that only in 1949, under the new health program, "immediate steps were taken to install good ventilation and dust control and to initiate process improvements." This implies that the point at which dust levels began to go down significantly in Plant 6 was in 1949, as is also shown from Mason's (1958a) Table 1. Regarding Plant 4, Mason stated that mechanization was installed in 1948 and 1949, but since he gave the same figures for 1943 through 1947 as for 1948, it must be concluded that either he considered the 1948 values to bound the 1943 through 1947 ones or the values he used for 1943 through 1948 (from whichever year) corresponded to those that were representative of the entire period.

Mason (1958a) referred to his Tables 3 and 4, showing Plants 7 and 6E values respectively (repeated in this technical basis document as Table A-9), as showing an improvement of "a factor of 60 compared to 1943 figures and by a factor of 8 compared to 1950 figures" for Plant 7 versus Plant 6 and a reduction factor "of about 20 compared to 1943 figures and 8 compared to 1950 figures" for Plant 6E versus Plant 4. These explicit comparisons too suggest that Mason had information as to the early (1943) dust levels and that his tables reflect that. Mason also plotted his data from 1943 on, again typically showing a plateau for the years 1943–1947.

Mason (1958a) noted that "no regular dust sampling program was in effect during 1943 through 1947, but sufficient samples were collected to show that airborne uranium concentrations were high by present standards; concentration of 50 to 100 times the present MAC [70 dpm/m3] were not uncommon, and some operations produced concentrations up to 1,000 MAC for a few minutes." However, such levels were also measured in the later dust studies, e.g., near the end of the paper, Mason commented that it was "evident that personnel did work in fairly high concentrations in the early days of the operation, and that the exposures received depended partly on the effectiveness of the respirator program." However, he appears to consider the early days to be 1942 through 1947 or (by his tables) 1942 through 1948.

This does not mean that the dust exposures in about 1949 through 1951 were not also high (above the preferred level), although not usually as high as in 1948, as was shown by the following table of data. Some dust sample measurement data from 1948 and 1950, in multiples of the preferred level (PL), which was the same as the MAC, are shown in Table 5-2.

In 1948 there were areas where the exposures were indeed "50 to 100 times the present MAC [i.e., 50–100 times the preferred level of 70 dpm/m^3, or 3,500–7,000 dpm/m^3]" and that some operations, e.g., the ore room drum cleaning, clearly did produce concentrations up to 1,000 MAC (70,000

Table 5-2. Some dust sample measurement data from 1948 and 1950, in multiples of the preferred level (PL).

Survey date	**May 1948**	**Nov 1948**	**Jul–Aug1950**
Survey performed by	AEC	Mall	Both
General information about the studies			
Number of workers in areas studied	170	279	406
Percent at less than the PL[a]	31	43	61
Percent at 1–3 PL	20	32	31
Percent at 3–5 PL	23	3	5
Percent at 5–10 PL	13	13	0.7
Percent at 10–15 PL	2	0	0
Percent over 15 PL	12	9	2.5
General Categories (in multiples of the PL)			
Average exposure	53	12	2.1
High exposure	660	195	20[b]
Ore Room operations	71	195	4.9
Digest/Feinc/feed makeup/C-3, centrifuge operations	3.4–12	9.8	1.1–2.2
Pot Room operations	460	111	4.8
Raffinate and recovery operations	5.2	3.9	1.8–2.3
Rockwell (brown) furnace operator	350	76/45	20/3.1
Brown oxide packer	560	161	5.2
Warehouse worker	3		1.4
General maintenance and mechanics	1.8		1.3
Boiler House		0.63	0.62
Digest pilot plant	3.5	1.3	1.5
Experimental continuous furnace (pilot plant)	Not in operation yet	Not in operation yet	122
Ledoux Lab K-65 sampler		30	20
Shotgun Lab		0.34	3.4
Production offices		1.4	0.2
MCW offices	0.7	0.08	0.013
AEC offices	0.5	0.11	0.013
Guards	1.1		0.5
Health office	0.2	0.1	0.16
Other Information			

Survey date	May 1948	Nov 1948	Jul–Aug1950
Ore Room: cleaning ore drums, dpm/m^3	Range 1,710–127,000, avg 64,400, for 30 min	---	Range 253–496, avg 374, for 64 min
Ore Room: general air, operating, dpm/m^3	Range 275–8,920, avg 2,590, for 125 min	---	Range 700–5,750, avg 1,954, for 20 min

Figures are from AEC (1948l), MCW (1949d), and AEC (1950o). Dashes in the table above indicate the range given in AEC (1950o), while slashes indicate two types of workers of the same title, e.g., day shift versus night shift workers.

a. The PL is the preferred level, equal to 70 dpm/m^3. All dust sample measurements are in multiples of the preferred level (PL, or 70 dpm/m3), except as indicated.

b. This figure does not include the exposure of Experimental Continuous Furnace workers (122 PL), although these exposures were included in the calculation of the percent over 15 PL.

dpm/m^3) for periods of minutes at a time. Thus it appears that the 1948 figures do fit Mason's description of what "high" was.

Some comparisons were made between spot dust levels measured in 1943–1946 (Table A-10) and the corresponding ones measured from 1947 on, with the point being to verify that for the presumably peak or near-peak points of individual operations, the 1943–1946 dust levels were generally no greater and were usually less than they were later, after Plant 6 was in full operation. This too supports the conclusion that the 1948 figures, prior to installation of significant upgrades in Plant 6, would bound the experience in the earlier years.

Data similar to that in the table above can be shown to exist for Plant 4 (i.e., for 1948 and before), so that the "50–100 times" quotation appears to apply for Plant 4 as well. Also, in AEC (1949c), a memorandum from early 1949, an AEC official summarized the hazards in Plant 4, which he said were to be solved by the completed designs for Plant 6E, including dust levels of up to 186 times the preferred level. This suggests that the 1948 figures for Plant 4 are also indicative of the exposure levels of earlier years. The spot dust levels for the early years, when compared to those of about 1947–1948, also appear to show that the 1947–1948 levels bound the early years.

It can be concluded that Mason (1958a) and the references supporting the table above show that the 1948 figures did bound or were representative of the figures of the earlier years. Comparisons with the data from earlier years are consistent with this conclusion.

Some detailed information is available about the particular case of the laundry workers circa 1958, when the laundry had operated for at least ten years (Utnage 1958b), as shown in Table A-17; some information about the laundry was also found in the various AEC dust study reports.

Information from other sites is helpful in deducing what would be typical at Mallinckrodt. In an AEC report in 1958, the breathing zone concentrations in the final ore concentrates packaging areas of over a dozen mills were evaluated; the concentrations ranged from 0.01 to 5.5 pCi/L, with a median of about 0.15 and a mean of 0.91 (AEC 1958, Table V). These figures suggest levels that might be encountered by Mallinckrodt workers unloading the packages (drums) at the beginning of the refining process. See also Section 5.3.5 below regarding resuspension of surface contamination. Resuspension contributions are assumed to be included in all data cited in this technical basis document since dust levels were typically measured while work was taking place.

No information is available regarding dust exposures at SLAPS. This was likely due to low radioactive dust levels in this open area (i.e., most of the dust collected would have been nonradioactive even in the dump pile areas, except possibly when the dumping was actually taking place) and to the contained nature of the K-65 residue. Because the SLAPS workers likely were subject to higher dust levels in their regular work at the main St. Louis site (e.g., in the warehouse or loading the dumpsters with barium sulfate residues or doing guard rounds in the plant), their dust exposures are based on their main St. Louis site plant exposure and thus are expected to be conservative.

The reported air concentrations generally pertain to those workers directly and continuously involved in uranium refining work. However, Breslin (1958) defined "auxiliary workers" as workers "not directly connected with production but located in or near production buildings, [including] chemists, engineers, office workers, garage mechanics, outside maintenance personnel, and the like," noting that some of these had occasion to visit production areas in the course of their work while others did not. Even with the limited access, in 1948 about 13% of the auxiliary workers studied were exposed to average concentrations above the MAC (110 dpm/m^3 at that time) and more than 1% to concentrations greater than 440 dpm/m^3 (Breslin 1958). By 1954, none of these auxiliary workers were exposed to average concentrations above the MAC (Breslin 1958), although some of the process workers still were. These statements are illustrated by the data given in the various AEC dust study reports.

The case of the maintenance and craft worker requires special consideration. Area mechanics were assumed to be dedicated to the particular process area or plant, with their work time being mostly spent in and around process areas, and thus their daily weighted average inhalation exposures should be considered to be representative of their residence time in the process areas. Similarly, their radon exposures can be taken to be those of their process areas. However, it is more difficult to determine inhalation and radon exposures for maintenance and craft workers who spent part of their time in their shop areas, where contaminated equipment might be brought to them to work on at irregular intervals, and part of their time working on equipment in process areas. As Hickey and Dupree (1984) pointed out, Mallinckrodt Uranium Division maintenance and craft workers were not usually assigned to a particular process (with the exception of area mechanics, which Hickey and Dupree do not note) but served the entire division. Not only Breslin (1958, quoted above) but also MCW (1950c) pointed out the variability of exposure of these workers as compared to the process area workers.

AEC and Mallinckrodt dust studies from 1948 on, list at least some maintenance workers besides area mechanics as a category and tabulate the time spent in various activities and areas in some detail (e.g., MCW 1949c; MCW 1949d). However, AEC (1954b) and MCW (1949d) stated that the studies they described used only general area samples to estimate the exposures of maintenance workers and not breathing zone samples while they were performing specific operations (unlike the case with the process workers). MCW (1950c) made a similar point with regard to the AEC-directed back-calculation of dust exposures to Plant 4 employees in 1949. Although it is not possible to determine what the temporarily elevated levels in the shops and the resulting somewhat higher exposures were, it can be concluded from the data in the various dust studies that the shop area dust levels were lower than the process area levels, usually decidedly so, and that thus the most significant contribution to the exposures of these workers most likely came from their time spent in process areas. It is assumed that from 1948 on, this time is factored into the exposures of these workers (as part of the daily weighted averaging calculation, Attachment C shows an example of this calculation).

Relatively high potential for dust exposure applied not only to those actually present in the dusty buildings and to some extent to those working elsewhere in the plants, but even to those outside the plants. For example, a Mallinckrodt safety official remarked that one reason to revise the ventilation in about 1952 had been that a study of plant effluents showed that "large bursts of dust found their way outside of the plant immediately after filter cleaning" (Harris and Mason 1953). Mason (1958a) also suggests that co-located (nearby but uninvolved) workers were exposed to elevated airborne levels.

In later years, Mallinckrodt was supposed to sample stacks at least once a year, but it was not being done (MCW 1955d). Weinstein (1958) reported on an air sampling study that AEC-HASL did of stack and environs (outside) air at various sites, including Mallinckrodt, in November 1949. They did not take any stack samples at Mallinckrodt, but Weinstein indicated that previous data implied a probable average rate of emission of uranium from the Mallinckrodt stack(s) of about 0.011 g/sec, with a flow rate of about 20,000 cfm. About 52 tons of uranium as metal was estimated to have been discharged in the stack effluents since the beginning of operation. While nearly every reported (outside)

concentration at Mallinckrodt was below maximum permissible levels, it was observed that "1,000 feet would circumscribe the MAC" level (out from the plants), i.e., within a few hundred feet of the plant(s) the MAC might be exceeded. The MAC given in the version of 10 CFR 20 in force at the time was 1.7 × 10^{-12} µCi/ml air for continuous exposure, or 2.5 µg/m^3, which presumably was the "public" MAC and not the occupational MAC. This would help explain the somewhat elevated weighted average concentrations even for workers who did not enter production areas.

Table A-18 lists job titles obtained from AEC and Mallinckrodt reports and from film badge and urinalysis records; in addition, it gives a geometry factor set appropriate for each job title (for later use as described in Section 7), which have likely been superseded by project guidance. Because the tables include information of interest for comparisons, they have been retained.

Table A-18 was prepared to be used with Tables A-19 through A-22 and later tables to help determine the exposure to an individual worker when bioassay data for the worker was missing or was conflicting and when comparable worker bioassay data (see Section 6) was insufficient. Tables A-19 through A-22 were derived from condensing information in Tables A-12 through A-16 and from other sources; the data they contain thus represents average daily weighted air concentrations in nearly all cases. Additional data for individual sampling and laboratory operations is given in Section 5.2.4. All of the data in the tables mentioned are based on a natural uranium mixture, with the exception of thorium processing, as discussed below.

The process, in which AM-7 residue was converted into a concentrated thorium nitrate solution, as explained in Section 4.7, is a special case. No information was found regarding the particle size of this residue, its tendency to be aerosolized, etc. However, the digestion and extraction process appears to be similar to the basic uranium ore digestion and extraction process and so it presents no novel operational or processing features. The processing appears to have been entirely of liquids (AEC 1955c). Besides the AEC-measured data given in Table A-16, there are some data from the Mound end of the processing (Mound 1956): the maximum and average air concentrations in the ionium (Th-230) "high-risk" part of the Mound processing area were 48.1 x10^{-10} and 16.3 × 10^{-10} µCi/cm^3 respectively. In the exhaust line of the hood in which the work was done the maximum and average concentrations were 384.9 × 10^{-10} and 38.8 × 10^{-10} µCi/cm^3 respectively. It is not known whether the work at Mallinckrodt was done in a hood and since the nature of the Mound work was further acid digestion and extraction (DOE 2002), the Mallinckrodt exposures were potentially higher.

Also, it must be noted that the concentrations reported by Mound (1956) were of ionium, i.e., Th-230, not of total thorium. Thus the associated source term must include the Th-232 known to have been in the solution as well. From Section 5.2.3, there was 11.6% Th-230 weight in the original residue, hence the Th-230/Th-232 mass ratio will be assumed to be 0.116/0.884, or 0.131. This gives a Th-232 source to be added to the Th-230 source term (see Table A-6). Although the internal dose per curie intake is generally somewhat higher for Th-232 than that for Th-230, the specific activity (Ci per g) of Th-230 is over 10^5 times that of Th-232.

5.3.3 Respirator Use

An undated MED reference that is assumed to be of 1942–1944 vintage (MED undated a) stated that respirator use was mandatory when the process required use; MED (1942) and MED (undated a) stated that this was especially necessary for the UO_3 and ore grinding and sifting operations respectively. An MED reference from May 1945 shows layouts indicating the areas of required respirator wear (MED 1945n). A Mallinckrodt manager stated in 1946 (MCW 1946g) that although dust levels had been high, exposures were being reduced not only by improving the dust systems but also by having workers keep their respirators on all the time that they were working in high-dust areas (thus implying that this may not always have been the practice). An AEC inspector noted in 1947 that although respirators were supposed to be worn in high-dust areas such as the ore grinding and

orange production area, they were seen to be worn around the neck or even not at all in areas immediately adjacent to the cited areas; these adjacent areas were visibly covered with finely divided particles that could clearly be made airborne when swept off the floors and walls by drafts (AEC 1947a). Mason (1958a) stated that MED and Mallinckrodt agreed in the early years of the work that production would proceed on a priority basis, with the understanding that in high dust areas extensive use of respirators would need to be made. Thus during 1946–1948, respirators were used for "practically all" plant operations. Mason (1958a) commented that the exposures received depended partly on the effectiveness of the respirator program (at that time).

Mallinckrodt's policy in the later years was that routine respirator use was not acceptable practice and that they were a temporary expedient for unusual conditions only (MCW 1955d). The requirements for them were spelled out in standard operating procedures (MCW 1955d). Even so, AEC inspectors noted instances where visible dust clouds were present or they measured clearly significant dust levels, yet the operators were not wearing respirators ((AEC 1954b; AEC 1954c; AEC 1954e; AEC 1954f; AEC 1954g; AEC 1955e).

A Mallinckrodt official observed in 1958 that in the plants they tried to keep below the MAC, but that if the concentration were greater than 1 MAC for a specific operation, they would not necessarily require the operator to wear a respirator (Utnage 1958c). He explained that this would depend on the worker's integrated exposure, taking all operations into consideration, and that if some short-term high alpha concentrations in the air were found, they made it a practice to have personnel wear respirators temporarily until the situation was corrected. He concluded that Mallinckrodt did not subscribe to the use of respirators as standard control equipment. Breslin (1958) stated that the time-weighted average exposures measured by AEC-NYOO did not include corrections for respirator use and so should be viewed as potential exposure; however, he also asserted that in very few cases would these be substantial overestimates "as the use of respirators was inadequate and spotty." This is borne out by the various AEC dust studies that, as noted above, pointed out cases of significantly elevated dust levels where respirators were not being worn.

MED (1946b) gave acceptable types of respirators for use in uranium processing work, as follows. For use in U_3O_8 dust, the MSA "Comfo" 2101 with the All Dust 2133 filter was acceptable; for use in UO_2 dust, the MSA "Comfo" 2101 with the Dust & Mist 2130 filter, the MSA Dustfoe 2147 with the Dustfoe 2138 filter, or the Willson 770 2119 with the Fume 2123 filter; and for use in UF_4 dust, the Duper 46 2111 with the 2124 filter or the MSA "Comfo" metal frame 2101 with the Dust & Mist 2139 filter. A 1955 list of Plant 6 process cells, dust collectors, and tanks, together with the then-current uses of the tanks, appears in MCW 1955g; maximum emergency nonsurvey stay times (i.e., for urgent access and not inspections) and the general respiratory protection (mask) types are also given in this reference. It appears that the stay times are based on external dose rate, not on inhalation considerations.

In the absence of any firm figures on respirator use and efficacy at Mallinckrodt, it will be assumed that respirators were not reliably used.

5.3.4 Radon

As noted earlier, radon levels could be significantly elevated in enclosed areas where material containing uranium daughter products was stored. ORAU (1989a) stated that a short burst exposure was more typical than a sustained exposure and this appears to be borne out by contemporary descriptions of the various operations in which radon might be released.

Radon measurements by Mallinckrodt and AEC were reported in units of 10^{-10} Ci/L. It is clear from MCW 1955k (which, despite its lack of company heading and date, is assumed to be a Mallinckrodt procedure circa 1955) that for both the "environmental" radon measurements and the breath radon

measurements, it was just the radon and not the radon daughters in the air that was reported. That is, the procedure specifies that the air sample be alpha-counted for 14 hours, i.e., allowing the radon to come to equilibrium with its daughters Po-218 and Po-214, and that the first two hours of counting results are to be discarded, i.e., discarding the contribution of the radon daughters already in the air at the time of sampling. The data from 2 to 14 hours is then extrapolated back to zero. As also stated by MCW (1955k), the chamber standardization value is given as a theoretical 266 counts per hour per pCi of "radon in equilibrium with its daughters," with half the counts due to the radon and the other half due to the two daughters. The radon decays are assigned a counting efficiency of 100% in the ionization chamber, but the daughters are assigned an efficiency of only 50% because they deposit on the walls of the chamber. Thus in that laboratory and with that type of chamber, the count rate was actually 220 counts per hour per pCi of radon in equilibrium with its daughters, for an effective total efficiency of 83%. However, because the net counts per hour are divided by the chamber standardization value, the result is in pCi of radon alone, not radon and its daughters.

Operations involving radon exposure potential were examined by the Mallinckrodt health physicist and supervision to determine if there was any step in which transient exposure to flood (sudden high) radon concentrations were a possibility (MCW 1950e). From perhaps the mid-1940's on, radon samples were taken once a week in high-radon areas (MCW 1950e). This included the outdoor yard areas, from which measurements Mallinckrodt concluded that some outdoor area was always downwind and that the Plant 6 outdoor background (based on "ordinary" emissions to the outdoor plant atmosphere) was on the order of 1×10^{-11} Ci/L (MCW 1949n). AEC (1949g) stated that Mallinckrodt had constructed several radon measuring devices for its own use and were in fact in the process of constructing one for NYOO. The standard used by Mallinckrodt was made up by the National Bureau of Standards (AEC 1949l). AEC (1949g) also reported that the author of the reference, an AEC inspector, had visited the airport (SLAPS) with Mallinckrodt health personnel and had assisted them in taking radon samples by using an extension pole device designed by Mallinckrodt; samples could thus be taken at levels as high as 20 feet above the ground. It seems clear that based on (1) the long history of radon sample taking at Mallinckrodt, with the start preceding by some years the processing of high-radium and thus high-radon pitchblende ores, and (2) the apparent competence of the Mallinckrodt health and safety, and instrument people at developing and using radon-measuring instruments, the radon measurements can be regarded as reasonably representative of the conditions.

Some early radon measurements from 1945 are shown in Table A-23. The principal locations where difficulty was found in 1946 in keeping radon concentrations below tolerance levels were the railcars during unloading of ore drums and in the ore and residue storage area (MED 1946c).

MED (1946c) noted that a railcar could be unloaded fast enough that the then-current ventilation methods and restrictions spent on time in the railcars were usually sufficient to keep below tolerance levels. Still, the radon problem became more acute with the heavy use of pitchblende ore and in 1948 AEC provided or arranged for new railcars to be used that could accommodate installation and de-installation of fans at the ends of the cars at the delivery points (MCW 1948h). Presumably the openings were covered with panels while the railcar was in transit. In October 1948, Mallinckrodt tested the efficiency of the ventilation in one of these new railcars (MCW 1948h). The door was left open two feet overnight, and then closed for three hours until the start of the test. The fans were started and at subsequent intervals the radon level was measured at two points at the center of the car halfway between the door and either end. The result was that the radon level fell from an average of 7.03×10^{-10} Ci/L at time zero to about 0.5×10^{-10} Ci/L after about 3.5 hours, reaching the 1.0×10^{-10} Ci/L point some time around 20 minutes, although the levels fluctuated at and between points. While the ventilation was seen to be effective, two drawbacks were noted. First, the gamma dose rate at the top and side of the car was 20–32 mR/ hr and it took two or three workers about 1.5 hours to install the fans, so that the workers who installed the fans received 30–50 mR, according to pocket chamber readings. Second, because the total time to unload a car increased to more than two hours with the

addition of the fan installation step, the car could be on the siding for an extra day before being unloaded and thus people passing by and working near the car received extra exposure. Hence Mallinckrodt recommended that the fans be left permanently installed in the railcars (MCW 1948h). It is not known if AEC allowed this.

The problem was more complicated in the storage area because worker occupancy times were of necessity longer. There was no forced-draft ventilation in the ore storage area at that time, only a natural exchange of air provided mostly by a four-foot opening on either end of the building. The result was that radon samples likely averaged on the order of the maximum permissible concentration (1×10^{-10} Ci/L) or higher. These openings appear to have been permanent, since AEC (1947e) states that the (each) whole end of the building could be removed, but if not, a large opening still remained.

In the Scalehouse Sampling Room, samples of K-65 residue were taken from open K-65 drums sitting in the sampling bays on the level below the Sampling Room (MCW 1948j). This was done with a thief sampler through holes in the Sampling Room floor. Although there were several small exhaust fans that were supposed to draw the radon away from the sampling workers, the turbulence caused by a unit heater resulted in the radon being distributed throughout the room. Also, although most of the time the exhaust fans maintained adequate control over the open pans into which the drawn samples were deposited, at times the turbulence also drew radon from the thief and the pans as the sample was being dumped out. The concentrations found in the Scalehouse itself were very erratic, showing that here too the radon was being carried in momentary eddy currents about the room. High concentrations usually coincided with the pulling out of the drums on pallets from the storage bins and the removal of the drum lids. It was noted that a worker could be present in the Scalehouse and the Sampling Room for up to 4 hours on some days.

Besides the ore and residue handling and storage areas, some processing equipment was also associated with elevated radon levels. In August 1948, a ventilating fan was installed in the wall of the K-65 centrifuge room to exhaust thermally hot air (MCW 1948l). However, this created a suction from the neighboring Wash Oliver (filter press) room into the centrifuge room, drawing appreciable quantities of radon off the Wash Oliver filters and into the centrifuge area. To solve this problem, a door was installed between the two rooms. Prior to the installation of the fan, the overall average radon concentration in the centrifuge room was 0.83×10^{-10} Ci/L; after the installation of the fan, it was 1.25×10^{-10} Ci/L; and after the installation of the door it was 0.62×10^{-10} Ci/L. Further ventilation improvements were apparently made in the centrifuge area.

A significant short-term exposure to radon would occur when the Feinc Niagara filter press, which was used to produce the high-radium K-65 residue, was opened for the washing of the plates (MCW 1950b). This occurred about 12 times a day when the processing was “operating on digest” because the plates could not effectively be washed down by remote control in this regime. It was necessary for a worker to open the press and hose down the cake. Approximately once a week, the plates became “blinded” (clogged) and had to be manually removed for cleaning with caustic (MCW 1950b). When the Niagara was opened, the radon concentration in the near area would suddenly go as high as 34 times tolerance, then went back to tolerance level over about 5 minutes. As the last of the cake was washed into Tank M-289, the radon concentration would double again because of the venting of M-289 as the pipe cleared and air from the tank was displaced back to the open Niagara and thus to the room. The concentration fell back quickly to nondetectable levels when the line to M-289 was closed. Radon levels at the small tank where the plates were cleaned, however, were low or nondetectable.

Radon concentration in enclosed spaces in MED/AEC refineries produced levels of up to 10^{-8} to 10^{-7} Ci/L, which were eventually significantly lowered by ventilation improvements (Eisenbud 1975). After these improvements were made at Mallinckrodt in about early 1949, all Mallinckrodt operating areas in Plant 6 were found by AEC to be below the preferred level of 10^{-10} Ci/L, with the exception of the K-65 return (drying) oven, the ore thaw house, and the Wash Oliver cell, as shown by some of the

results in Tables A-24 and A-25 which cover the years 1947–1949 and 1950–1957 respectively. However, Mallinckrodt (MCW 1949m) reported the results of measurements taken in the Ore Room and its addition soon after ventilation and remote handling equipment was installed; some of these results are shown in Table A-24. The improvements significantly reduced radon levels in most areas, but there were still some operational problems (see Section 5.2.1). Because as MCW (1949m) states the radon hazard was greatest near newly opened drums and because the ventilation system apparently was not very effective at taking care of this hazard for close approaches to the drums (i.e., the radon die-off to less than 1×10^{-10} Ci/L after a drum was opened took 25 minutes), radon was a continuing concern in the ore drum storage and handling areas. The operational problems that forced operators to approach open drums appear to have been corrected thereafter.

Most of the information regarding radon levels from 1947 on comes from the weekly "MZ" radon reports (Mz was a code for radon) (MCW 1955d; MCW 1947–1957). Additional data are shown in Table 5-3 (from AEC 1949b, Table 1), which gives typical radon exposures for different areas at the Middlesex facility over the years 1944–1949 (covering the early years of pitchblende use). These would be comparable to the railcar unloading and Ore Room operations at Mallinckrodt.

Table 5-3. Middlesex ore storage worker radon exposures, January 1944–January 1949.

Area	Level		
	Min	**Avg**	**Max**
Railcar unloading	200		250
Drying room	1	6.7	21.7
Storage area	0.1	0.8	2.9
Sampler rooms	0.1	0.2	0.5
Crushing area	0.1	0.2	0.9
Crusher pit	0.3	0.8	1.3
Sampling lab	<0.1	<0.1	<0.1
Weigher's booth	<0.1	<0.1	<0.1

Radon levels are given in multiples of the radon MPC or preferred level of 10^{-10} Ci/L. Use of blower-equipped railcars starting in about early 1949 reduced levels to below the MPC.

Tables A-24 and A-25 also give information that has been found about the radon levels in the plants other than Plant 6. However, because in the plant with the greatest exposure potential (Plant 6) and in SLAPS the levels were lower than tolerance (1×10^{-10} Ci/L) in all but very enclosed areas and because the thorium and radium were removed in the production of UO_3, it is likely that the radon levels were well below the tolerance level in areas where ore and pre-UO_3 residues were not present.

A further item regarding radon content of the residues was noted by AEC (1947e). A certain percentage of the radon produced during decay would be adsorbed on the surface of the ore particles (the percentage depending on the particle size of the ore, the temperature, the moisture level in the ore, etc.). When the ore was digested in acid, the adsorbed radon was released and the gamma activity of the ore would drop. But when the radium was precipitated as a sludge, as was done at Mallinckrodt, the precipitate would adsorb some of the radon and there would thus be an increase in gamma activity as the precipitate "aged." This meant that the radon content of the digest vent exhaust, the residue, etc., could be variable depending on process conditions.

ORAU (1989a) estimated the radon exposures of approximately 184 Mallinckrodt Plant 6 workers as part of a larger study. They calculated the working level (WL) for each job title using the mean radon concentration value from all available surveys in 1946–1957 for each job title's assigned work area; exposure estimates were then calculated in units of working level months (WLMs) for each job title. ORAU (1989a) assumed that an equilibrium factor of 0.25 applied for radium and its daughters, based

on plant and memoranda, other documents, and findings from uranium mine and residential radon studies. Their approach of assigning a WLM value for each job title for a single grouped period of years (rather than breaking it down by years) was due to the lack of survey data for many of the years. The "roving operator" and the production/processing/manufacturing operators were assigned the average area radon levels for the entire Plant 6 area and the highest daily work time breakdowns of all the production processes. Weekly rotation as practiced at Mallinckrodt was handled by assigning an average radon level of all available survey data from those work areas in the rotation plan for that job title. Pertinent results are shown in Table 5-4 for information. These results are for the years of pitchblende processing and so would presumably be conservative for the pre-pitchblende years.

Note that for use in dose reconstruction, radon concentrations reported in units of Ci/L must be converted to units of working level months (WLM) before they can be used in calculations. One working level (WL) is the total amount of energy given off over a long period of time by the short-lived radon-222 daughters in equilibrium with 100 pCi (10^{-10} Ci) of radon, taken to be in one liter of air. Since the daughters will typically not be in equilibrium with the radon if the ventilation is good, this

Table 5-4. Exposure rates of 184 Mallinckrodt workers, based on surveys done in 1946–1957 (ORAU 1989a).

Job title	No. of workers	WLM per month worked
Manufacturing operator	3	0.138
Operator, process develop	1	0.138
Production operator	2	0.138
Roving operator	3	0.138
Cleanup operator	8	0.127
Maintenance (general)	1	0.111
K-65/GLC sampler	1	0.102
Pot Room operator	14	0.097
K-65/AJ-4 sampler	4	0.096
Raffinate operator	9	0.092
Barium operator	6	0.091
C-3 (Centrifuge) operator	18	0.084
Feinc operator	12	0.084
Director, technical	1	0.077
Mail boy (office)	2	0.057
Porter, Production	6	0.056
Ore Room operator	16	0.055

Job title	No. of workers	WLM per month worked
Recovery operator	13	0.052
Guard	3	0.047
Porter, Lab	1	0.044
Digest operator	2	0.042
Pilot Plant operator	4	0.041
Clerk, Manufacturing Office	1	0.040
Clerk, Production Office	8	0.040
Feed operator	2	0.038
Filter press operator	3	0.038
Plant monitor	1	0.030
Health office	2	0.020
Engineer, senior mechanical	1	0.018
Furnace operator	12	0.010
Industrial relations (office)	1	0.010
Ether House operator	17	0.008
Machinist (instrument)	2	0.008
Chemist	4	0.003

conversion is not simple, but depends on the ventilation conditions. Some reported results are given in Tables A-23 through A-25 of this technical basis document in the original units.

5.3.5 Surface Contamination

Although surface contamination levels per se are not indicative of airborne contamination levels or external dose rate, they can suggest whether or not a potential for exposure exists. Little surface contamination measurement data appears to have survived, presumably because it could vary so much and because excessive levels, when found, were cleaned up but not necessarily documented.

Mallinckrodt (MCW 1958; MCW 1959) gave the results of a plant-wide surface contamination and external dose rate study that Mallinckrodt did after some preliminary post-operation decontamination of the site. These reports indicate that ground areas adjacent to the production plants were heavily contaminated, with average surface alpha activity of 2,500 dpm/100 cm^2 and average beta activity of

2 mrep/hr; high spots of 35,000 dpm/ 100 cm^2 alpha and 15 mrep/hr beta were not unusual. High spots of up to 20 mR/hr gamma were found west of the UF_4 loading dock where ore cars where cleaned prior to 1950. In Plants 6 and 7, the administration building (Building 112) (except for the storeroom and maintenance shop), the Boiler House (115), the Service Building (117) (except for the laundry and the regulated locker room), and the Magnesium Building (708) were not considered significantly contaminated. The average alpha activity on floors in the excepted areas was 3,000 dpm/100 cm^2 and the beta-gamma activity was generally at background levels. In Plant 4, beta activity measured at contact with surfaces in production areas averaged between 10 and 50 mrep/hr with the overall average activity measured at contact with surfaces estimated at a level of 25 mrep/hr; occasional high spots were found up to 80 mrep/hr; activity measured at the three-foot level in the center of production areas ranged from 1 to 5 mrep/hr. Gamma activity measured at contact with surfaces was 0.02–0.9 mrep/hr, with the highest readings being in some yard areas and the slag processing area. The overall plant average measured at the three-foot level in the center of production areas was 0.07–0.1 mR/hr.

Data from this Mallinckrodt study (i.e., the study partly documented in MCW 1958 and MCW 1959, quoted by Utnage (1958a)), also showed fixed floor surface contamination levels of greater than 10,000 alpha dpm/100 cm^2 at various floor locations in the ore sampling area after vacuuming; it was highest at the hopper loading and weighing stations. In the metal reduction area (Plant 6E), the floors of the crucible disassembly areas and the saw areas measured 2,200–3,300 dpm/100 cm^2 and the center of the maintenance cage (where there was no uranium processing) measured 1,200 dpm/100 cm^2. Other stations in the "pitchblende (ore) area" (Plant 6) showed levels of 1,000–60,000 dpm/100 cm^2; in the uranium products warehouse, 4,500–21,500 dpm/100 cm^2; and in the metal plant (6E), 1,000–9,000 dpm/100 cm^2. The UF_4 production plant (Plant 7) had no reading higher than 1,200 dpm/100 cm^2. Since these figures represent fixed contamination, loose contamination removed by the vacuuming could have been present at far higher levels (Brobst 1958). Thus these figures, while suggestive of where the worst areas were, cannot be considered to be representative of operational total surface contamination levels.

Although as noted above resuspension is assumed to be included in the measured airborne concentrations, some available information about the relationship between loose surface uranium-bearing contamination and airborne concentrations will be summarized here in case it becomes relevant in individual cases. A study was done at the Oak Ridge Gaseous Diffusion Plant to ascertain the relationship between alpha airborne activity and alpha surface contamination (Becher 1958). The air samples were measured with Whatman #41 filter discs and fixed counting equipment, with an overall counting and collection efficiency of 30%. The surface transferable activity was measured with a Samson alpha survey meter, with an overall counting and efficiency factor of 20%. The data shown in Table 5-5 indicate that the airborne concentrations ranged from 0.36 to 5.05 dpm/m^3 for every dpm/cm^2 of surface contamination, or an air concentration of 3.6 to 50.5 dpm/m^3 for every 1,000 dpm/100 cm^2 of surface contamination.

Table 5-5. Ratio of alpha airborne activity to surface contamination (Becher 1958, Table 2).

Source of data	Ratio[a]
Two operating areas having the highest contamination levels (1953)	
Shift-length air samples	0.64
Spot air samples	1.9
Plant-wide operations (415 surveys over 9 months in 1958)	
Shift-length air samples	0.36
Spot air samples	5.05
Special test conditions (1953)	
Simulated conditions	13
Worst possible conditions (short periods)	20

a. Units of the ratio are dpm/m^3 of air per dpm/cm^2 of surface.

Other fixed surface contamination data are given in Table 5-6 for various surfaces and pieces of equipment in the laundry (from Table 1 of Utnage 1958b).

With surface contamination there is the potential for two modes of exposure other than inhalation. These are ingestion and skin doses from contamination on skin and clothing. Ingestion would most likely take place during eating or smoking breaks. No information is available as to the likelihood of ingestion during eating or the quantities that might have been taken in. However, some information is available on recommended AEC limits on hand contamination and on ingestion as a result of smoking.

A 1947 AEC letter to Mallinckrodt (AEC 1947b) stated that surfaces in the lunchroom should show less than 100 dpm alpha on a smear test and less than 500 dpm alpha per 100 sq cm (fixed plus removable); the maximum hand count should be equivalent to no more than 0.35 mg of uranium on either side of the hand. In 1949, dust samples taken in the lunchroom at various times over one lunch period, showed that the level ranged from 6 dpm per cubic meter with only 7 workers present to 57 dpm per cubic meter when the room was full; the level was 12 dpm per cubic meter at the start of the

Table 5-6. Contamination levels on various surfaces and pieces of equipment in the laundry.

Unit	Beta + gamma, cpm
Presser pad surface	2,000
Cloth hamper surface	5,000
Wooden hamper surface	1,000
Work tables and surfaces	200–1,000
Lint ball/dryer lint trap/roof lint trap	4,000/2,000/3,000
Inside washer	300
Inside dryer	1,000–4,000
Under washer	20,000–60,000
Under dryer	100–40,000
Floors, average	300–500
Walls	100–300
Overhead pipes, etc.	300–1,000

post-lunch cleaning and then went up to as high as 65 dpm per cubic meter following the cleaning due to dust suspended in the air (MCW 1949d). The same sampling study showed that levels in a conference room in association with a service group (operators') meeting were 4, 22, and 30 dpm per cubic meter respectively before, during, and just after the meeting. In both the lunchroom and conference room, the workers wore cover clothing over their work clothing. In 1951 it was reported that the average dust level in the Plant 6 lunchroom (MCW 1951b) was 1.3 dpm/m^3. Thus although it was stated in MCW (1949d) that the sub-tolerance levels reported were acceptable, clearly the lunchroom levels were reduced over time by better clothing change and contamination control practices.

Smoking areas were typically adjacent to the working areas. In 1951, in response to AEC's pointing out that Plant 6 workers entering the smoking room habitually slapped their dusty gloves and brushed material from their clothing after they entered the smoking room, Mallinckrodt agreed to provide improved ventilation in the smoking room and to put a small vacuum cleaner inside the smoking room for workers to use to vacuum their gloves and clothing after they entered but before they smoked (MCW 1951d). Mallinckrodt also agreed to have greater enforcement by supervisors of the requirement that gloves be removed before smoking (MCW 1951d).

These findings may explain the observation by AEC (1951a) that in a majority of the jobs evaluated at Mallinckrodt, the contribution to radioactive dust levels from time spent in the smoking (cigarette break) areas was greater than the contribution from the time spent in the operations area. In 1951 it was reported by Mallinckrodt that air samples taken in the smoking room in Plant 6 were always above tolerance, even after UO_2 production had moved to Plant 7 (MCW 1951b); the average dust level was 116 dpm/m^3, versus 1.3, 4.2, and 66 for the lunchroom, locker room, and change room respectively, and the typical daily individual occupancy of the smoking room was 60 minutes. This all suggests that the contribution to the ingestion of radioactivity by a smoker might be significant, although AEC apparently did not do any studies of this at the time.

Tests done in about 1958 at the Oak Ridge Gaseous Diffusion Plant with UNO_4, UF_2, and UF_4 (Bailey 1958) indicated that when loose uranium-bearing material was placed on the palmar surfaces of the hands, the palmar transfer of uranium from the hands to the cigarette amounted to about 1% of the material on the hands and that inhalation of the material during smoking amounted to less than 1%. They also tested absorption by placing material on the backs of the hands. They concluded that a maximum of 2.5×10^5 dpm on the palm of each hand, for a 20-cigarette-a-day smoker, would be allowable for him not to exceed the maximum permissible inhalation of uranium by cigarettes alone; that a maximum of 2.5×10^5 dpm on each hand would correspond to the maximum permissible ingestion; and that a maximum of 2.5×10^5 dpm on the back of each hand would correspond to the maximum permissible absorption dose. Taking the reciprocal of the sum of the reciprocals, they obtained a maximum of 8.6×10^4 dpm per hand for the total considering all three routes of exposure. They assumed a 15% geometry factor for the hands (based on their instruments) and concluded that the total limiting level was 13,000 cpm per hand.

The allowable amounts given in Bailey (1958) corresponded presumably to National Bureau of Standards Handbook 52 allowable intakes, since they cited Handbook 52 although they did not quote the figures. The allowable amount was assumed to be on the hands continuously for 5 days per week, 8 hours per day. This level or greater is likely to have been on workers' hands at times but not to have been on the hands constantly. Thus while a potentially significant contribution to the dose from hand contamination cannot be ruled out, it seems unlikely that most smokers would have had a sustained level of contamination of this magnitude on the hand during breaks, especially since they were likely to have worn gloves during most of the processes (due to heat, acidic content, etc.). This suggests that ingestion is a negligible source of internal dose during operations, compared to inhalation.

Regarding clothing, Table A-27 shows contamination levels and some associated dose rates from clothing (Utnage 1958b). The contamination measurements in cpm were taken with a Thyac beta-gamma meter with thin-wall tube, while the measurements in mrep/hr were taken with an unspecified air ionization chamber. At the time the measurements were taken in 1957, the laundry had been in operation for almost ten years and had never been decontaminated; there were nine laundry workers; and the laundry processed 25,000 coveralls and 25,000 "soft" items (handkerchiefs, socks, and underwear) each month. Clothing used in contaminated or potentially contaminated areas ("regulated areas") was kept separate from clothing used in non-regulated areas. However, regulated-area clothing was worn interchangeably by anybody, so that "a uniform contamination level [was] eventually obtained" (Utnage 1958b). Gloves were discarded when soiled and were treated as contaminated clothing (MCW 1950e).

At the Oak Ridge Gaseous Diffusion Plant (ORGDP), test measurements in 1957 on clothing showed that the highest spot reading was typically about 3.5 times the average reading (Becher 1958); this is probably roughly applicable to Mallinckrodt as well, although the uranium compounds at ORGDP were mostly soluble whereas the Mallinckrodt compounds were mostly insoluble. The ORGDP tests also showed 1,620 alpha dpm/cm^2 to be equivalent to 9,700 cpm/100 cm^2 as measured on a Samson alpha meter, giving an "efficiency-geometry" factor of 6%. (Note that for the "surface transferable

activity" on filter paper used for air sampling also reported in Becher 1958, an efficiency-geometry factor of 20% was assumed for the Samson alpha meter.) Finally, the ORGDP measurements showed that about half the uranium applied to the clothing at the beginning of the test had dropped off within the first two hours of wearing. This suggests that uranium that gets on clothing can come back off it readily and that surface contamination on clothing can contribute to airborne levels via resuspension.

Railcar interiors were invariably found to be contaminated above 2,500 dpm/100 cm^2 after unloading uranium oxide, UF_4, or uranium metal at uranium processing plants, even though the sites made an effort to decontaminate them (AEC 1949b). AEC advised that strippable coatings would eventually need to be used (AEC 1949b), but there was no evidence that this was ever done. This suggests that even where closed containers of uranium-bearing materials were being unloaded, it must be assumed that surface contamination was typically present.

Monitoring for surface contamination was done using portable alpha and gamma-beta survey meters and smear tests (MCW 1950e). Tools to be moved from contaminated areas were to be cleaned to a stated level (MCW 1950e), given in 1947 as 100 cpm, presumably beta-gamma (AEC 1947b). If the article could not be decontaminated, it was to be securely wrapped in paper or placed in a clean container and marked with handling instructions. However, these checking and control requirements did not apply to tools belonging to outside contractors, who presumably could take away tools contaminated to any level (MCW 1950e). Alpha hand counting devices were not used after some time prior to 1950, supposedly because AEC-NYOO requested that their use be discontinued (MCW 1950e). As of at least 1950, hands and feet were not checked when workers exited a process area to go to the lunchroom to eat or smoke (MCW 1950e; AEC 1947a), but they had to go through the personnel decontamination cleanup in the change room area, with a strict "clean side, dirty side" regime maintained (MCW 1950e) (see Section 5.5.3). Visitors were not checked for contamination before leaving the plant, at least through about 1950 (MCW 1950e).

5.3.6 Information and Available Data Regarding Urinalyses

Mallinckrodt uranium processing workers were given a pre-employment physical that included an initial urinalysis and a blood count (MED 1942) and they were given an annual physical that included a routine urinalysis and a blood count (MED 1942 (which says it was a "followup" examination); MCW 1955d; Mason 1958a). From about the summer of 1948 on (MCW 1950c), this included a measurement of uranium in the urine. In addition, up to March 1954 some worker classifications had more frequent urinalyses, either every 4 months or every 6 months depending on the worker classification (MCW 1955d; Mason 1958a); after this time, the frequency was no more than semiannual (MCW 1955d). As urinalysis records indicate, some office workers appear to have been given urinalyses, but it is not clear whether this was done on a regular basis.

The Mallinckrodt radioactivity urinalyses were first performed by the University of Rochester under contract to AEC-NYOO up to about 1948. At one point, according to ORAU (1983b), there were some problems with the running of standards because there had been uranium plateout on a table. This was corrected. In 1948, Barnes Hospital began to do the urinalyses for Mallinckrodt. However, an AEC health official stated (AEC 1948) that while it had been his understanding that the analyses were being done at Barnes Hospital (at Washington University), it turned out that they were being done in laboratories at the Mallinckrodt St. Louis site. This came to light when it was discovered, apparently in late 1947, that some urinalysis samples were contaminated due to contamination in the laboratory. An undated, untitled urinalysis listing found in dose reconstruction project files indicates that closed, blank samples were found to have significant levels of uranium in them, indicating contamination in the laboratory; it was suggested that this might explain the high levels of some of the non-blank (worker) samples. Thus at least the early urinalysis samples must be considered to have been

potentially contaminated (i.e., some of the uranium content may have come from the laboratory analyzing them).

Apparently Barnes Hospital resumed doing the urinalyses (AEC 1949g, MCW 1950e). However, in 1949, AEC compared the Mallinckrodt analyses against those for other sites handling similar material and concluded that the results were consistently inexplicably high (MCW 1950e), although Mallinckrodt thought the agreement was acceptable (MCW 1949j). AEC then sent Mallinckrodt some spiked samples and also had an independent Mallinckrodt chemist prepare a stock solution of known concentration. The spiked samples and samples of the stock solution were sent to Barnes as regular samples, while Barnes standards and samples of the stock solution were sent to NYOO for analysis. AEC also compared Barnes' methods and equipment to standard ones. The conclusion was that the samples were indeed reading too high at Barnes. (It is not clear if the spiked sample comparison referred to in MCW 1949j is this same set of samples, but if so, the data can be found in MCW 1949j, along with a statement that the reliability of the Mallinckrodt sample testing is +/- 15%). Subsequent data analysis showed a gradual precipitation of uranium in the Barnes standards, which meant that the daily standard curves showed a gradual loss of slope over time, up to 30%. Also, Mallinckrodt had been called three times over the previous year to service the Barnes instrument because of sensitivity loss, when the problem was actually the standard. The maximum error in the urinalyses over the preceding 14 months was estimated to be +89%.

AEC technical personnel thought that the affected data were of doubtful value (AEC 1950l). Still, AEC (1950i) asked Mallinckrodt if the urinalysis data could be salvaged, i.e., if there was a consistent factor that could be applied to all of the subject urinalyses; MCW (1950q) thought that there was not. AEC also recommended that a note regarding the problem should be inserted into the medical files of the affected individuals (AEC 1950b), presumably to aid in the interpretation of the results. It is not clear whether this was done. AEC-NYOO stated that it was not possible for them to take over the urinalyses again since the number of samples to be analyzed was too high for their capacity (AEC 1950l).

It is not clear who did the urinalyses from 1950 to 1954; although MCW (1950m) suggests this was no longer being done at Barnes Hospital but at AEC-NYOO, presumably at HASL. Also, in September 1951 AEC-NYOO was clearly performing them, but directed the AEC St. Louis area representative not to have any more routine samples sent during the last quarter of 1951 because of an "unusual work load" that its chemical laboratory had (AEC 1951c); emergency samples could still be sent, however. In 1954 AEC gave Mallinckrodt permission to perform their own urinalyses (MCW 1954e, ORAU 1983b), presumably in the laboratories at the Mallinckrodt St. Louis site. From the Mallinckrodt Health Office monthly reports, they were analyzing for "X in urine" (i.e., uranium) and it appears that at times there was a significant backlog of overdue analyses, at least in the early 1950's. Eventually AEC-NYOO (HASL) must have resumed performing the analyses, because a 1955 Mallinckrodt report describing its health program stated that NYOO was doing so (MCW 1955d). This report stated NYOO was analyzing about 2,500 Mallinckrodt urine samples a year and urine samples that were taken were split, with half going to AEC-NYOO for the radiological analysis and half to Barnes Hospital for the medical analysis.

Referring to urine samples sent to the University of Rochester from any AEC site, ORAU (1983b) stated that samples were collected from workers in four-ounce glass bottles with Bakelite caps and shipped to HASL. After 1949, only samples taken within one hour of the start of the weekly shift were accepted (ORAU 1983b).

The radiological analysis was apparently only for uranium content (referred to as "X in urine" or "uranium-in-urine"). However, one set of urinalysis records shows for a single individual and for periods from March to May 1956 the notation "Shoot for radium." Thus it appears that radium in urine could be analyzed as a special case. It is not clear whether the thorium (ionium) processing workers

in Plant 7E had special urinalyses for thorium or not. However, this is a possibility, as suggested by Mallinckrodt's health and safety director's obtaining a copy of a Los Alamos Scientific Laboratory procedure on urinalysis for plutonium (LASL 1955) and the director's noting on his copy that he was told that urinalysis for thorium could be done by the same method.

ORAU (1983b) stated that all urinalyses done at the University of Rochester used the fluorometric method; the urine was dried in a platinum dish, then fluxed with either sodium fluoride or a lithium-calcium fluoride mix and counted. Ross et al. (1975) states that for all AEC contractors before 1961, estimates of lung dose were made on the basis of urinalysis and that this was usually done on the basis of electrodeposition and subsequent counting. AEC (1949l) states that Barnes Hospital (at Washington University in St. Louis) used "fluorometric (photoelectric ultraviolet)" methods in performing urinalyses for Mallinckrodt.

ORAU (1983b) states the following about samples analyzed at the University of Rochester. These samples were run in triplicate, with the results usually being within ± 2 µg/L of one another; if this turned out not to be the case, it indicated that there had been poor fusion of the flux and the samples were re-fused and re-run, which usually corrected the discrepancy. The value recorded was the median value of the three. For insoluble uranium, it was considered that 30 µg/L in the urine corresponded to an air concentration of 50 ug/m^3. The analysts felt confident of readings greater than or equal to 5 µg/L. However, if more confidence was desired for lower-level samples (e.g., for special projects), the urine was concentrated either by ion exchange or by extraction, or more aliquots were run.

The uranium fusion photofluorimetry urinalyses performed by the University of Rochester and the AEC NYOO were similar to those performed at other AEC facilities. Based on the lack of clear information regarding a detection threshold for Mallinckrodt urinalyses, the default detection threshold for uranium urinalysis may be 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, as was reported for other AEC facilities (Wilson 1958).

Because of the questions regarding the validity of the samples, the apparent variations in sample analysis methods, and even who was doing the analyses, the Mallinckrodt urinalysis data should be used with caution, at least when the data were taken by Barnes prior to about 1951. However, it appears that the errors, if any, are in the conservative (high) direction and thus are favorable to claimants.

Urinalysis records appear to be available, but many appear to be handwritten notes on cards. These are found scattered in various dose reconstruction project files. Fortunately, in about the 1970's, the records were entered into the Center for Epidemiological Research's (CER) computer database for research purposes and have been used in that form since then by Oak Ridge Associated Universities and other research groups. The resulting file has more than 40,000 records (i.e., lines, with each line representing one urinalysis) [ORAU 2005]. Some bioassay records are also available in the Project site research database (SRDB).

5.3.7 Information and Available Data Regarding Other Types of Bioassay

Breath radon measurements began to be made in June 1945 (as shown by, e.g., MED 1945e and MCW 1946g), but only for workers who worked in areas where there was a potential for radium intake. MCW (1950l) gives a list of worker types or occupational areas, along with a rating of the need for workers of each type or in each area to have their breath sampled; most of the Manufacturing (process), Stores (warehouse), and Maintenance workers were in the "Definite" category, while most of the Power Plant, Occupancy, Plant Protection (guard), Research, Laboratory, and Laundry workers

were in the “Possible” category and most of the Health & Safety, Office & Administration, and Plant 4 workers had most of their people in the “Improbable” category.

The Massachusetts Institute of Technology (MIT) or the National Bureau of Standards (NBS) did the breath radon analyses for MED/AEC until 1951, when HASL obtained an ion chamber of the type needed to perform the analyses (ORAU (1983b). Initially, samples were taken in the infirmary of the MED/AEC site because it was thought that this area was removed from the production areas; later a respirator with bottled air was used to collect samples in order to control for radon in the ambient air (ORAU 1983b). However, the first breath radon measurements were thought to be worthless by MED because the MED expert concluded that the samples were contaminated at the time they were taken (MED 1945e). As a result, MED directed Mallinckrodt to have breath radon samples taken only in a room away from the plant and only when the employee had not worked for at least 48 hours and while he was still wearing his street clothes (MED 1945e).

Breath radon samples were collected by obtaining one-liter samples of exhaled breath after two days of non-exposure, usually on a Monday morning (AEC 1949g; AEC 1950a; MCW 1950g). The samples were measured at the NBS (AEC 1949g) or at HASL (AEC 1950a, MCW 1955d) by an “automatically recording pulse-counting device” (AEC 1950a). If a sample was over the tolerance level of 1×10^{-12} Ci/L, then a recheck (repeat sample) was made immediately (AEC 1949g). The lower limit (of detection) at HASL was 0.1 pCi/L and there was confidence in readings of greater than or equal to 0.5 pCi/L (ORAU 1983b). In 1946, it was reported that of 40 workers tested, the maximum level was right at the tolerance level of 1×10^{-12} Ci/L (MCW 1946g).

In early 1950 AEC apparently became concerned about the high background that seemed to be present where the samples were being taken (MCW 1950g). Mallinckrodt agreed to take test samples elsewhere than in their usual testing area and also to take a room air sample in their normal testing room; these samples were then sent to AEC-NYOO. The normal testing room sample showed a radon content of 0.8×10^{-12} Ci/L, which AEC judged was a high background for a breath radon sampling area (AEC 1950k). It is known that in 1950 the Mallinckrodt medical department was located adjacent to the change rooms, which enabled workers to take their physicals after a shower without getting dressed (AEC 1950m); if the breath radon samples were also taken there, that could explain the relatively high background radon. In early 1951, Mallinckrodt (MCW 1951g) reported the results of a further test done at the behest of AEC in which they took breath radon samples from the same four workers in the usual location (background of 0.8 pCi/L) and in a lower-background area (background of 0.2 pCi/L). Mallinckrodt admitted that although they had been told earlier by the (National) Bureau of Standards that the test area background did not matter as long as it was on the same order as the sample, AEC had turned out to be correct in its concerns about the background: the differences between samples taken in the lower-background area and the samples taken in the higher-background area differed by almost exactly the difference between the two backgrounds (MCW 1951g). Mallinckrodt apparently corrected this problem by then using the special respirator-testers provided by AEC ((MCW 1951e); they may also have moved the breath radon sampling location to a lower-background area. Note that Srivastava et al., in their study of uranium miners (Srivastava 1986), found that post-shift measurements (i.e., after breathing ambient radon in the workplace) were 2 to 4 times higher than pre-shift measurements, which confirms the confounding influence of background radon.

A baseline (start of employment) breath radon test was not administered; the routine test during operations was thought to be sufficient (MCW 1950w). In 1949, the nominal breath radon sampling frequency was quarterly (AEC 1949g), which seems to have been the typical frequency for eligible workers (ORAU 1983b). In 1955, AEC-NYOO was analyzing about 500 Mallinckrodt samples a year, taken semiannually at a minimum but about quarterly when permitted by AEC-NYOO sample capacity (MCW 1955d). It was not always possible to obtain a termination breath radon sample because some workers left without notice or because the sample had to be taken after 48 hours of non-exposure,

i.e., usually on a Monday (MCW 1950w). Mallinckrodt thought that about 80% of terminating employees had termination medical examinations (MCW 1950w), but it is not clear if this was also true of the breath radon analyses for the relevant workers. Breath radon records are available in scattered form in reconstruction project files; possibly all of it is found in the large urinalysis research file mentioned in Section 5.3.6 above.

AEC considered that many of the early breath radon samples likely represented transient as well as fixed burden and that the background level at the point of sampling (which was generally ignored) was likely to have been relatively high; thus the resulting estimates they made of alpha radiation to the bone based on breath radon measurements would typically be higher than was actually the case (AEC 1950a). ORAU (1989b) quoted a report by the MIT Radioactivity Center that stated that their lower limit of detection for breath radon was 0.006 pCi/L and that this corresponded to a minimum detectable body burden of radium-226 of 0.00059 µCi. ORAU (1989b) also quotes the MIT report as stating that assuming that 65% of the radon generated by the body burden of radium was exhaled, 1 pCi/L of radon in the breath corresponded to approximately 0.1 uCi of Ra-226 in the skeleton, which ORAU (1989b) verified in its own calculation. This can be compared to the assumptions made by Srivastava et al. (Srivastava 1986), who took breath samples of uranium miners using a controlled radon intake respirator apparatus: the equilibrium percentages of the radium-226 body burden were taken to be 33% in the lungs, 39% in cortical bone, 14% in trabecular bone, and 14% in other soft tissues and the corresponding radon escape fractions were taken to be 1.0 for lungs and other soft tissues and 0.7 for bone. Srivastava et al. thus concluded that 84% of the radon produced by decay of the Ra-226 was exhaled, a figure applicable to those working in the mines for several years (i.e., to workers chronically exposed for an extended period).

ORAU (1989a) reported the results of a study of ambient radon exposures to some 184 Mallinckrodt workers. In addition to the lung doses from the ambient radon exposures, they attempted to estimate the contribution from breathing radium dust and used breath radon data and the associated skeletal radium burden as an indicator (as per ORAU (1989b). These estimates are given in ORAU 1989a, and as with the ambient radon exposures, the subjects are listed only by their ORAU study identification numbers.

Whole body and lung counts appear to have been performed rarely if at all, since workers had to be sent to sites outside Missouri for this to be done or a mobile counter would have had to be brought to St. Louis and individual whole body and lung count data (if any) appear to be unavailable.

5.4 EXTERNAL DOSE CONSIDERATIONS

External doses for Mallinckrodt workers varied widely depending upon the activity they performed. Operations at the refinery (Plant 6) involved primarily gamma radiation, while operations at the metal plants (i.e., Plant 4 and later 6E) entailed primarily beta radiation (AEC 1949b; AEC 1951b)). ORAU (1980b) stated there did not appear to be any circumstance that would produce an exposure of 3 rem or greater in less than several hours and they found no incident in which an acute exposure rate of greater than or equal to 3 rem/hour was produced. Tables 5-7 and 5-8 are an adaptation of Table I and a summary of information given in Tables II of ORAU 1980b; the first shows the total annual gamma dose by dose-level and the second shows the 10 highest gamma doses to workers, both from 1947 through June 1957.

Table 5-7. Annual gamma exposures, 1947–June 1957 (ORAU 1980b).

Year	Workers monitored	Annual gamma exposure, R				
		0–1	1–5	5–10	10–15	>/= 15
1947	253	70	131	27	18	7[a]
1948	366	120	171	47	19	9[b]
1949	554	370	141	41	2	0

1950	615	475	133	7	0	0
1951	694	512	171	11	0	0
1952	757	659	88	10	0	0
1953	763	619	142	2	0	0
1954	756	566	188	2	0	0
1955	871	766	105	0	0	0
1956	958	944	14	0	0	0

[a] Maximum value for 1947, as reported in Table 5-8, below, is 23.5 R.
[b] Maximum value for 1948, as reported in Table 5-8, below, is 20.3 R.

Information regarding dose rates for ore and residue drums is given in Table A-32 and regarding dose rates for various forms and areas in Table A-33. There is little information about conditions in Plants 1 and 2 during the wartime startup; however, some dose rate measurements from 1943 and 1944 appear to have been taken, as shown in Table A-33. As noted previously, film badging did not start until late 1945, when Plants 1 and 2 were in the process of largely shutting down. Doses might have been somewhat higher than in Plants 4 and 6 due to possible greater manual involvement and probably somewhat greater bodily proximity to sources, but on the other hand the quantities involved were much lower. The dose rates given in Table A-33 suggest doses were likely to have been higher in later years due probably to the greater volume of uranium processed and to the use of pitchblende ores.

It should be noted that the era of pitchblende use (early 1945 on) was mostly covered by film badge monitoring, so the doses characteristic of this work are known. Thus it is considered to be favorable

Table 5-8. Ten highest gamma doses to workers, 1947–June 1957 (ORAU 1980B).

	Annual dose, R			Weekly dose, R/week		
Year	Min	Avg	Max	Min	Avg	Max
1947	14.4	16.1	23.5	0.28	0.31	0.45
1948	14.9	17.0	20.3	0.25	0.33	0.39
1949	7.7	9.0	13.3	0.15	0.17	0.26
1950	4.5	5.4	7.1	0.09	0.11	0.14
1951	5.0	5.9	7.1	0.10	0.11	0.14
1952	5.1	5.9	6.6	0.10	0.12	0.13
1953	4.0	4.6	5.7	0.08	0.09	0.11
1954	3.9	4.4	5.1	0.08	0.09	0.10
1955	3.9	4.4	5.1	0.08	0.09	0.10
1956	1.1	1.4	1.9	0.04	0.06	0.07

to claimants to assume the doses at Plants 1 and 2, for the same type of work, were similar to those at Plant 4 and Plant 6 around 1948.

According to MCW (1955f), at least late in the life of the site, gamma surveys were done bimonthly in most Plant 6 processing areas and monthly at the vent ducts in the digest area. Although these reports do not appear to be available, Table A-33 shows some area film badge monitoring results that show what conditions were and of course film badges were consistently worn in the later years. A 1955 list of Plant 6 process cells, dust collectors, and tanks, together with the then-current uses of the tanks, appears in MCW 1955g; maximum emergency non-survey stay-times (i.e., for urgent access and not inspections) are also given. It appears that the stay-times were based on external dose rates. In general, the operator stay-times were half the maintenance stay-times, presumably because of the need for more frequent access by the operators.

See also Sections 5.1–5.2 above for some addition external dose information associated with particular handling activities or operations.

5.4.1 Gamma, Beta (Electron), and Nonspecific Beta-Gamma Exposures

After high-grade pitchblende ores began to be used, refinery workers were exposed to photons from radionuclides in equilibrium with U-238 and U-235. Ra-226, through its Pb-214 and Bi-214 daughters, contributed gammas to workplaces where ore was stored or processed. Upon removal of the uranium daughters, processed material became radiologically innocuous until the passage of time resulted in the ingrowth of Th-234 and Pa-234m and the consequent domination of the dose profile by electrons. Mallinckrodt worker dose records demonstrate this difference, with significant doses for mixed photons and electrons in the refinery operations and high electron doses with little photon dose in the metal plants. Dose reduction measures in plants and equipment resulted in low doses in Plants 6E and 7 compared with the mixed beta-gamma doses in the refinery operations.

In 1946 the principal large-scale source of gamma radiation was said to be the drums of ore as they were stacked in the receiving warehouse (MED 1946c). The gamma dose rate could be as high as 50 mR/hr near stacks of drums of Belgian Congo ore at 25% concentration and with a radium content of about 100 mg/ton (Eisenbud 1975). A 1958 AEC report on uranium mills gave dose rates of 0.8 to 8.0 mR/hr, with an average of 3.0 mR/hr, as the gamma dose rate at three feet from bulk ore concentrates (AEC 1958, Table XI); these dose rates are assumed to be for domestic ores. Dose rates from wastes could run even higher than those for the ore. Dose rates at points adjacent to stacks of drums of radium-bearing residues (precipitates) could run as high as 100 mR/hr adjacent to stack of drums (~ 300 mg Ra/ton) (Eisenbud 1975, Table 2) or up to 275 mR/hr at contact (MCW 1949g). AEC (1948d) gave the gamma contact dose rate with the (Ra-containing) Feinc filtrate residue under equilibrium conditions as over 300 mR/hr; however, they stated, they had no way of knowing how close to equilibrium it was. The dose rate depended strongly on how "aged" the material was: sample pans filled with fresh K-65 read 9 mR/hr, while pans held over a day read 20 mR/hr (MCW 1948j).

A study done by AEC of the dose rates from four drums of "aged" K-65 residue grouped on a pallet showed the dose rate at 6 feet from the grouping was 28 mR/hr, of which the back two contributed 16% and the front two 84% (AEC 1947c). Furthermore, it was found that the dose rate varied approximately as the square of the distance over the range of three to twelve feet from the center of the grouping. With lead shielding interposed, it was found that the first half-value layer (HVL) was 1/4" and the second was 3/8."

As noted in Sections 4.7 and 5.2.3, K-65 was brought back in drums from SLAPS and reprocessed starting in early 1948. In January 1949, the gamma dose to the hands of operators opening these drums was studied by placing film badges on their wrists (MCW 1949E). It was found that the gamma dose varied from 3.3 to 5.0 mR per drum opened, with an average of 4.0 mR; for the typical situation of 44 drums opened per 24-hour day, six days per week, by three operators, the total weekly exposure per operator was 352 mR. It was estimated that this could increase by up to a factor of 2 due to drums that might require more time than average to open, variations among operators in opening the drums, and in the number of drums opened per shift. Hence the maximum wrist dose was estimated to be 700 mR per week per operator. At the time, the individual whole-body gamma dose to the operators was 300–500 mR per week; it was thought that 33–67% of this dose was due to the drum opening (MCW 1949e).

Additional specific information regarding gamma doses and dose rates in the ore, refinery, and metal processing areas are shown in Tables A-32 and A-33: dose rates from drums and railcars are shown in Table A-32 and for various plant locations and tasks in Table A-33. Additional gamma-beta dose data for ore storage at the Middlesex plant during 1944–1949 is shown in Table 5-9 (AEC 1949b, Figure 3); this should be comparable to Mallinckrodt experience because presumably the ore was being routed through Middlesex to be distributed to the processing sites. AEC (1949b) states that the Middlesex doses were about 65% gamma.

Table 5-9. Middlesex ore storage worker dose, 1944–1949 (AEC 1949b, Figure 3).

Worker type	Number of workers	Weekly gamma-beta dose, mrep
Guard	11	150
Laborer	20	500–600
[redacted]	1	250
[redacted]	2	300
Maintenance	10	150–500, avg 300
Office	---	100
[redacted]	1	250

It should be noted that operations that were particularly manual were (1) the various dumping, scooping, and scraping operations in which feed, UO_2, UO_3, UF_4, and dust were handled or crucibles and furnaces were cleaned; (2) the "plowing" (scraping) of the centrifuges; and (3) the scraping of cake off the Feinc filter cloths (this was the pitchblende cake during the pitchblende years) and the changing of these cloths. Thus significant external dose reduction usually followed any mechanization or improvement of these processes.

Because the gamma dose arose mainly from the radium and its daughters, the gamma dose was usually significant only in those areas where the source material had not yet had the radium separated or where radium-bearing residues were present. This meant that the gamma doses tended to be highest in Plant 2 and later in Plant 6 (AEC 1949b), especially around ore drums and storage areas for the radium-bearing residue, K-65. Thus some shielding had been designed into Plant 6 and more was added in 1948 in some areas (AEC 1949b, MCW 1950e). Still, due to the high doses Mallinckrodt found it necessary in mid-1949 to establish additional restrictions and rotation requirements on warehouse workers, who moved stored pitchblende ore drums from the airport waste storage site (apparently also an overflow ore storage site); brought "sand" (residue) drums back from the airport; unloaded the incoming ore drums from railcars; weighed the ore drums coming in from the railcars and airport site; and loaded K-65 residue drums into the railcars (MCW 1949p). It was estimated, e.g., that the following were typical weekly activities: three trips for retrieving ore drums from the airport pad, three or four drum weighing sessions, one trip for retrieving residue drums, two K-65 railcar loadings, and two ore railcar unloadings (MCW 1949p). It was required that pocket chambers be used when retrieving K-65 drums from the airport pad (MCW 1949p).

The highest principal Feinc cloth operators' dose had been found to be an average of about 465 mrep/week (total beta and gamma) in 1949 and 1950 and the second-highest dose was similar (MCW 1951g). In January 1951, a study of beta and gamma exposures associated with preparing, repairing, cleaning, and changing cloths for the Feinc, C-3, and Recovery filters (MCW 1951a) found that operators received an average of 294 mrep per day and 1,470 mrep per week gamma and an average of 82 mrep per day and 408 mrep per week beta. (See Table A-33 for some of the measured dose rates.) The "per day" figures were an effective daily dose since the operation was not actually performed daily. These figures were comparable to those found in a previous 1949 study; although some of the tasks the cloth operators were doing in 1949 had been given to the area operators to do (MCW 1951a).

Mallinckrodt (MCW 1950t) summarized the gamma dose data for all high-dose workers as in Table 5-10. Although it would appear from the disparity between the two averages below that a few individuals were getting significantly higher doses than the rest, Mallinckrodt contended that the doses were fairly evenly distributed among workers in the five rotation groups and thus that all dose reduction that could be accomplished using rotation had been accomplished. For comparison, group data reported by AEC (AEC 1951b) for two periods in 1948–1949 and 1950 are shown.

Table 5-10. Comparison of gamma and beta doses, 1946–1950.

MCW 1950t				
	Date	**Avg of high badges, mR or mrep**	**Avg of 90th percentile badges, mR or mrep**	
Gamma only	1946	780	250	
	1947	860	290	
	1948	590	250	
	1949	410	170	
	1950 (1st quarter)	320	---	
Gamma plus beta	1950 (1st quarter)	700	235	
AEC 1951b				
	Period	**Number over 30 mrep/week**	**Number over 150 mrep/week**	**Number over 300 mrep/week**
Gamma only, Plant 6	11/1/48–1/24/49 (267)	103	47	17
	1/2/50–6/19/50 (314)	124	47	11
Beta only, Plant 4	11/1/48–1/24/49 (91)	83	35	32
	1/2/50–6/19/50 (89)	65	29	12

The AEC 1951b figures are weekly averages. The number in parentheses after the period is the total number of badges worn per week, on average. The beta figure for "over 300 mrep/week" for 11/1/48–1/24/49 included 8 over 700 mrep/week, 5 over 1,000 mrep/week, and 2 over 1,500 mrep/week; the corresponding inclusions for 1/2/50–6/19/50 were 2, 1, and zero mrep/week.

As noted in Section 5.2 above, there was also up to 2.6 mCi of radium built up in the residue that was processed in 1955–1957 to concentrate thorium, although this was distributed in the 350 tons that was processed into the 3,600 gallons of solution sent to Mound (Tables A-4 and A-6).

Doses registered on film badges worn by people not working directly with the uranium and equipment, such as guards and office workers, were more likely from gamma exposure than from beta exposure. This is because they were usually at some distance away from the source (the uranium and its daughters). It is true that the dust was found throughout the plant to varying extents, but that would likely not contribute to the external dose rate much in or near buildings where there was a substantial radium content in any uranium product or residue.

A 1958 AEC report on uranium mills gave 1.5 to 25 mrep/hr, with an average of 15.5, as the beta dose rate at three feet from bulk ore concentrates (AEC 1958, Table XI). AEC estimated the dose to an operator's hands from removing lids from ore drums at 200–300 mR/day, even after a proposed body shielding window was erected (AEC 1948e). AEC (1948d) gave the beta contact dose rate with the (radium-containing) Feinc filtrate sludge (K-65) under equilibrium conditions as over 500 mrem/hr; however, they stated, they had no way of knowing how close to equilibrium it was.

Regarding experience at the Paducah site, Baker (1958) reported that the Th-234/Pa-234 combination (from U-238 and U-234) produced about 1,500 alpha dpm/mg U and 1,500 beta dpm/mg U at equilibrium, producing 240 mrad/hr at the surface of U metal, 208 mrad/hr at the surface of UO_3, and 183 mrem/hr at the surface of UF_4. Further, during UO_3 prep by "our suppliers" (e.g., Mallinckrodt), much of the beta-active material was removed, but built back up to 50–100% by the time it got to the UF_6 production facilities (Baker 1958). This suggests that significant buildup could occur before the UO_3 left the Mallinckrodt facilities since the storage time might be weeks and the transport time was likely less than a few days. Eisenbud (1975) pointed out that 90% of equilibrium beta activity was restored by 90 days after vacuum casting. Eisenbud (1975) reported high dose rates, up to 1 rad/week to the body and even more to the hands, from loading of UF_4 into UF_6 reaction vessels. This too implies that if enough time had elapsed, UF_4 loaded at Mallinckrodt into the bombs could also produce relatively high beta dose rates. Metallic uranium in equilibrium with Th-234/Pa-

234 could produce up to 235 mrad/hr to the basal epithelium when the metal was in contact with bare skin; heavy gloves would significantly reduce this (Eisenbud 1975).

In addition to the beta dose rate from the uranium as natural uranium, uranium oxide, etc., there were two waste concentrates that produced high beta dose rates. First, when ether was used to extract the uranium from uranyl nitrate, Th-234 and Pa-234m (also called UX1 and UX2 respectively) were left in the aqueous phase (also called the aqueous uranium tails) (Eisenbud 1975). This aqueous solution was filtered, resulting in a residue (cake) containing the beta emitters. MED (1942) stated that 1942 measurements indicated that the intensity was low and that no precautions needed to be taken for disposal; however, MED/AEC appears to have been more concerned about this later on. Another source of the tails was the UO_2-derived shotgun sample, which could have the Th-234 and Pa-234 concentrated to 30–300 times their activity in normal uranium metal in equilibrium, depending on how long the UO_2 had stood between production and sampling (MED 1944m). The fourth and final ether extraction performed in processing a shotgun sample produced a liquor so concentrated with these beta emitters that it was said the tolerance dose of beta radiation could be reached by keeping the hands above the liquor for 10 minutes per day. Besides that, the chemist handled the sample for 5–10 minutes from removal from the furnace to bottling, wearing no gloves and directly touching the containers. MED (1944m) advised changing from rubber gloves to leather gloves (to increase the dose rate reduction from a factor of 2 to a factor of 3) and using crucible tongs (to increase the distance to about 10") for conveying the evaporation dish to the heating areas.

Second, in the vacuum recasting of the uranium metal, impurities in the metal volatilized and condensed on the cooler portions of the furnace, creating spot deposits (AEC 1949b; Eisenbud 1975). The impurities contained Th-234 and Pa-234, which were concentrated to a significant degree in the deposits (AEC 1949b; Eisenbud 1975); this deposit residue could have "up to 1,000 times the beta activity of natural uranium" (AEC 1949b). Manual contact with these deposits during charging, discharging, cleaning, and repair of the furnaces provided "opportunity for hand irradiation of a greater magnitude than whole body" (AEC 1949b), possibly as much as 2–3 rads/week to exposed skin and perhaps to the eyes when the original ore was pitchblende at 25% average enrichment (Eisenbud 1975). Mallinckrodt (MCW 1949a) observed that 25% of Plant 4 workers received over 500 mrep/week beta and 3–6 workers per week received 2,000 mrep or more; AEC (1949g) also observed that the beta values (on film badges) from Plant 4 consistently ranged up to 2.7 rep/week.

Because of the high hand doses, the processing of the derbies and billets was studied in 1948 by Mallinckrodt (MCW 1948b). They gave the results to the designer of the new Plant 6E for use in redesigning the process to reduce the doses, first by eliminating exposure to large open surfaces on uranium forms and second by preventing exposure to and accumulation of scale and powdered residues (in which the UX1 and UX2 were concentrated), especially in the recasting or remelting step.

Regarding the processing of residues to concentrate thorium, Table A-6 shows that with the interruption in the chain occasioned by the removal of the original radon (by venting) and the radium early in the process, the daughters had to build up again to equilibrium from the time the cake was stored through the maximum 15 years of storage. Consequently the strong beta emitters down the chain, such as Pb-214 and Ac-228, are present only in very small quantities.

Some dose rate information for exposure rates from laundry equipment and clothing appears in Section 5.3.5 and in Table A-27 (from the text and Table 1 of Utnage 1958b). This is mainly beta radiation.

MED did some studies to determine the shielding afforded by gloves and clothing. MED (1943c) reported that leather gloves of 1 mm thickness cut the beta dose rate by a factor of 2, while 2-mm gloves cut the beta dose rate by over a factor of 4. MED (1944i) gave the reduction factor as 2 in a 1944 study of rubber gloves, with the source being uranium metal in equilibrium. MED (1944a)

reported the results of July–September 1944 measurements of the activity inside 16 pairs of gloves; the results showed that contamination did appear to get into gloves used at the recast furnaces but not in those used for billet sawing. This implied that some of the recast dose to the hand came from contamination inside the gloves. Based on all these results, MED (1944i) gave the time limit for handling uranium metal as 4 hours per day with rubber gloves and recommended that the time be limited to 2 hours per day with other gloves.

AEC did some further glove and clothing shielding and contamination studies using an 18" x 24" sheet of uranium metal in equilibrium with Th-234 and Pa-234 (AEC 1950i), with the following results. Denim coveralls (9-oz weight) "absorbed" an average of 22% of the beta from the source, with a standard deviation of 7.5%, for distances varying from 5 inches to 3 feet. Neoprene-covered cotton gloves shielded an average of 50%. Measurements on the inside surfaces of three cotton gloves used to handle uranium showed contact beta dose rates of 23–47 mrep/hr from contamination; these gloves had been taken at random from workers. (These figures are included in Table A-27.) The Mallinckrodt glove program for contact with radioactive material was said to be sketchy and inadequate (MCW 1955d), implying that the use of gloves was not consistent.

AEC (1949l) stated the following regarding pocket meters (pocket chambers). These were typically worn two at a time by a worker for an entire work day before recharging. The readings of the two were averaged and the averaged reading was tabulated with the film badge results. The pocket meters were vibration- and leakage-tested before first use, then calibrated for 100 mR +/- 5 mR full-scale and 50 mR +/- 10 mR half-scale. Mallinckrodt suggested discontinuing the use of the pocket meters in 1949 (AEC 1949g, MCW 1949f). In MCW (1949i), they argued that the highest possible (gamma) dose rate in their plants was 300 mR/hr, that exposures of greater than 1,000 mR per week were almost unknown anymore, and that operations were such that extended occupancy of high-dose-rate areas was not necessary. They stated they had not found any dose-heavy sources or operations that could not have been found by the use of film badges or surveys; also, their latest statistical calculations showed a greater than 99.9% probability of a true correlation between film badge results and pocket meter readings, but the error at the 90% limits around the regression line gave an error of +/- 38% for a dose of 300 mR per week. Thus, they concluded, using both film badges and pocket meters constituted an unnecessary double check of dose. AEC at first refused to allow them to discontinue using the pocket meters (AEC 1949g), presumably because it was the only real-time check and the only immediate post-work check of accumulated dose available, but then relented and allowed such use to be discontinued (AEC 1949h; MCW 1950e).

Detector types and measurement methods were not specified in most reports and papers. However, it is known that there were numbered, set survey points ("observation stations") at which detector measurements were always made (AEC 1949g). MCW (1946g) stated that external dose rates were measured with an "Ion-meter." AEC (1949g) stated that one Mallinckrodt health physicist preferred the Victoreen 247 gamma survey meter and the Landsverk electrometer, while the other preferred the Zeus meter (detector) for general use. Utnage (1958b) stated that for surface contamination measurements in the laundry (of clothing, equipment, and floor surfaces), a Victoreen 356 alpha survey meter and a Thyac beta-gamma meter with a thin-wall tube were used.

AEC (1949a) gave information regarding the Rauland Zeus detector used by Mallinckrodt, e.g., the window area and the accompanying table of data. However, the conclusion was that the free area of the window was only slightly greater than 50%. This information was supplied to Mallinckrodt in the context of comparing film measurements and detector measurements, with the conclusion that the assumed effective size of a Mallinckrodt source (such as a tank or contaminated area) might be greater than had been assumed.

Counters and meters were maintained and calibrated weekly or monthly on a set schedule by Mallinckrodt technicians (MCW 1955d). Because of the lack of space and the corrosive atmosphere

in the plant, there were no instrument monitors (i.e., instantaneous, continuous, or integrating monitors) in any area except for one provided by AEC on an experimental basis (MCW 1950e). Hence film badges were placed at selected locations in the process areas to serve as integrating area monitors (see Section 5.4.3.6 below).

5.4.2 Neutrons

No neutron exposure measurements are available. However, Dupree-Ellis et al. (2000) deemed neutron exposures at Mallinckrodt to be minimal. This conclusion appears to be correct based on what is known about the source material and its handling. Nevertheless, neutron production by the alpha-neutron reaction and by the early RaBe source used in the Shotgun Laboratory (see Section 5.2.4) was analyzed in the preparation of this technical basis document. Note that this document does not currently consider spontaneous fission neutron dose, which might add to dose in areas where large quantities of uranium are present.

In the analysis of neutron production by the alpha-neutron reaction, the forms of uranium and thorium that would produce neutrons at the highest rates were identified as UF_4 and ThF_4, the latter being an intermediate product in the processing of the thorium-containing waste cake to a thorium nitrate solution (see Sections 4.5 and 5.2.3). The uranium oxide forms, soda salt ($Na_2U_2O_7$), and thorium nitrate were also considered, as indicated in Table A-34. Note that as long as there is a reasonable amount of target material (fluorine, oxygen, or sodium) available and it is intimately mixed with the source material (uranium or thorium or their alpha-emitting daughters), neutron production essentially depends on the amount of the source material.

Regarding the thorium, the total amount of cake processed to obtain the thorium nitrate solution was 350 tons, or 700,000 lbs (Table A-4). It is not known how much was processed at a time. However, it is conservative to assume that the processing was done in the same type of large batch-processing tank system used for processing ore (this maximizes the quantity at one time). This is also appropriate because the cake was digested and subject to extraction in the same manner as the ore and soda salt feed. From Table A-4, at one time a typical monthly processing would include about 80,000 lbs of Eldorado black oxide, 120,000 lbs of Vitro black oxide, and 60,000 lbs of Vitro soda salt, for a total of 260,000 lbs per month or about 8,700 lbs/day. Also from Table A-4, K-65 ore was processed at another period at the rate of 8000–12,000 lbs/day. Thus it is appropriate to assume that a reasonable high average processing volume of feed per day was 10,000 lbs. At this rate, it would take 70 workdays to process the cake.

It can be assumed, from the way the ore and other feeds were processed, that one batch was moved from the digest tank through etherization, etc., without being mixed with another batch, at least until after the ether extraction. Thus it can be concluded that no more than 1/70th of the total Th amount was present as ThF_4 at any time. This is conservative because it assumes that the amount processed in one day was together in one tank or container at a time. It is also conservative because the processing is known to have taken up to 18 months, not just 70 workdays, so the batches are likely to have been much smaller and the amount of ThF_4 present at any time in a container would also have been much smaller. This is particularly likely since the ThF_4 was said to have been moved to the Hot Lab (in Plant 6) in liquid form for final processing to thorium nitrate (AEC 1955c) and thus the individual transport container quantity was limited by the amount that could be transported as a liquid. Finally, it is conservative because any self-shielding or container shielding has been ignored. The spontaneous fission half-times for Th-232 and Th-230 are greater than 1E+10 times greater than their physical half-lives (BRH 1970), and so neutron doses from thorium spontaneous fissioning are not significant compared to those calculated from the alpha-neutron reaction in materials with low atomic numbers.

Regarding uranium forms, as shown in Table A-4, a fiber or steel drum container of UO_3, UO_2, or soda salt would weigh 75 lbs and a steel drum container of UO_2O_8 (ore feed) would weigh 100 lb; most of this weight would be uranium, so it may be reasonably and conservatively assumed that the entire weight is uranium. While a larger volume could be found in, e.g., a digest tank, the liquid and the thick tank wall would provide a great deal of shielding. A larger volume could be found in an array of containers, but a great deal of self-shielding would be involved and a person would likely not spend a great deal of time near an array. Thus it is likely that that dose rate from a single container (being temporarily stored, loaded, or transported) will be the typical dose source.

The following conservative assumptions were made regarding the conversion from alpha-neutron production rate in the container to an annual dose at the receptor point.

Point source geometry used to produce a nominal ambient dose rate, with the distance to the receptor point being taken from the center

Irradiation geometry of 75% AP and 25% ROT (from Table A-18 of this technical basis document for "ionium plant operator")

A U-238/U-235 breakdown of 99.3% to 0.72% by weight (for the natural uranium forms); a Th-230/Th-232 breakdown of 11.6% to 88.4% (for the thorium forms)

Neutron energy of 1.5 MeV (1.4–1.6 MeV is the energy range of the neutrons produced by the thorium isotopes and 1.0–2.0 MeV is the energy range of neutrons produced by the other isotopes; also, the neutron flux-to-dose conversion factor varies slowly in this range)

Neutron flux-to-dose conversion factor for 1.5 MeV of 1.3×10^{-4} rem/hour per neutron/cm^2-sec

1 hour per day spent by the receptor at 1 foot from the container and 3 hours per day were spent at 3 feet, every working day for a year

For the purposes of considering the effect of including daughter contributions, for full equilibrium of the daughters of natural uranium or the thorium cake mix down to radon (which would not be in chemical union with the target and would likely be largely vented), the neutron emission rate due to the parent isotope would be multiplied by the following factor: 8.1 for U-238, 13.5 for U-235, 2.2 for Th-230, and 20.9 for Th-232. However, this was applied only to demonstrate the maxima, since the daughters were not likely to have built up significantly from the parent for the uranium forms and were separated before the production of the ThF_4 in the thorium case

The results are shown in Table A-34. Conversion was made from ambient dose equivalent (H*(10)) to organ dose equivalent using the factors given in Appendix B of NIOSH (2000a). Neutron dose estimates for facilities that had similar source terms and processes, Fernald (ORAUT 2004) and Weldon Spring (ORAUT 2005b) assign uranium-produced neutron doses using a neutron to photon ratio method and the method based on actual measurements of dose rates at Fernald and so would account for both the alpha-neutron dose and the spontaneous fission neutrons, and so the method in these documents is presented in Section 7.5 to account for neutron doses from uranium.

In the analysis of the RaBe neutron production, the source was taken to contain 100 mg of Ra-226 (Mason 1977). There is no indication as to how long the source was used, so the period of use may be taken to have started in about April 1942 and, as indicated in Section 5.2.4, to have ended in September 1944. According to Shleien (1992), Tables 7.5 and 8.4.1, a RaBe source emits neutrons of average energy 4.0 MeV at a rate of up to 1.3×10^7 neutrons per sec per curie and the specific activity of Ra-226 is 0.0366 TBq per gram, or 0.989 curies per gram. This gives a source strength of

1.29 x 10^6 neutrons per sec for the 100-mg source, resulting in whole-body dose rates of 16 mrem/hr at one foot and 1.77 mrem/hr at three feet.

Assuming that a laboratory worker spent one hour per day at one foot from the source and one hour per day at three feet from the unshielded source, the worker would receive a dose of 10.7 rem over the 29 months, or 4.44 rem per year. Note that these estimates are on the high side since by the various descriptions of laboratory work, most of the time in the laboratory would have been spent in preparing the samples (e.g., by grinding or chemical additions) and the source would have been completely shielded when not in use and likely partially or completely shielded when in use. These results are shown in Table A-34, along with the organ doses. Conversion was made from ambient dose equivalent (H*(10)) to organ dose equivalent using the factors given in Appendix B of NIOSH (2000a).

5.4.3 Information and Available Data Regarding Film Badges and Extremity Dosimeters

5.4.3.1 Information Regarding the Type and Composition of Film Badges Used at Mallinckrodt

The same film badge was in use throughout Mallinckrodt uranium operations for AEC (MCW 1961a), i.e., from some time in 1945 through the end of operations in 1958. This was a two-element type of dosimeter. It is not clear whether the same type of film badge was used during the decontamination period (see Section 8.0), but it would appear so.

Mallinckrodt (MCW 1956i) described the badge as follows. The badge frame was made by the A. M. Samples Machine Company of Knoxville. The front was shaped so that a 1-mm thick cadmium shield could be inserted to cover the upper two-thirds of the film, with a similar 1-mm cadmium shield covering the back of the film. A large rectangular window covered the badge front to allow the identification number (the “health number”) perforation in the cadmium shield to be unblocked. A small rectangular window in the lower part of the badge front below the cadmium shield was covered only by the identification picture sandwiched between plastic sheets; a similar window in the badge back, below the cadmium shield, was covered only by a sheet of clear celluloid. The film was a DuPont Type 552 film packet containing two dental-size films wrapped together. The more sensitive of the two films was Type 502 and the less sensitive was Type 510. Mallinckrodt (MCW 1956i) remarked that the beta and gamma radiation generally encountered at the Mallinckrodt plants had less effect on photographic film than the same dose of X-rays that were often monitored with such film badges.

Mallinckrodt (1955i) also described the badge as having a metal frame made by the A. M. Samples Company and as using DuPont Type 550 x-ray film provided by the Dick X-Ray Company. The identification picture was said to be laminated between two pieces of thermo-coated acetate, each 0.005 inches thick, with the total thickness not exceeding 0.02 inch. MCW (1950m) stated that the Mallinckrodt badge had 3.3 mm between the face of the badge and the first surface of the film; the average absorber density between the badge face and the film was given as 81 mg/cm^2.

In an unpublished report the badge was described as follows:

> The A.M. Samples stainless steel badge holder with open-window and cadmium filters permitting beta and gamma differentiation and measurement. DuPont Type 552 dosimeter film was used in the badge. The film was processed by techniques calibrated and standardized with film exposed to standard gamma and beta radiation sources. Gamma standards were obtained by exposing film to a platinum encapsulated radium needle. Beta standards were obtained using an aged, natural uranium block as a source.

According to MCW (1956f), before the badge was issued, the week number was exposed on the edges of the film with 70 kV, 10 ma X-rays for 0.33 second. Control badges were exposed to a 10-mg radium source in a platinum needle, which was the primary gamma standard and whose intensity was taken to be 8.4 mR/hr at one meter. An earlier standard, No. R-515, sent to Mallinckrodt in 1948 by an AEC consultant on behalf of AEC, had 9.98 mg of radium, with a platinum-iridium wall thickness of 0.5 mm, producing 5.4 mR/hr at one meter from the center of the capsule (AEC 1948l).

The primary beta standards were aged metallic uranium slabs about 1/16" thick. Eight-month-old uranium was regarded as "aged" enough to have the Th-234 and the Pa-234 in secular equilibrium with the U-238; the beta contribution of the Th-230 and its daughters was considered to be negligible. The beta intensity at the surface was taken to be 239 mrep/hr (see also Section 5.4.3.2 below). Other details of the calibration, such as exposure times and distances, do not appear to be available.

5.4.3.2 Film Badge Technical and Processing Information

The University of Rochester processed the Mallinckrodt film badges from at least 1 July 1947 to 1 June 1948 (Rochester 1950, MCW 1950k); Rochester presumably also processed the badges before that under contract to AEC, as suggested by MCW (1950k). Mallinckrodt processed its own film badges from 1 June 1948 to 1 January 1950 (Rochester 1950, MCW 1948g, MCW 1950k). As is indicated by the Mallinckrodt health group monthly reports (e.g., MCW 1951b) and the 1955 Mallinckrodt health program description (MCW 1955d), Mallinckrodt appears to have continued to process their own badges even after this period. As the health group monthly reports (AEC 1950m; MCW 1951f) indicate, however, Mallinckrodt often had a significant backlog in reading the film badges; Mallinckrodt (MCW 1951e) observed that doses were frequently reported a week or more after the dose was incurred and thus expedited processing was requested for badges from such workers as the burnout and Feinc operators. But it was not unknown for this problem to occur when Rochester was processing the badges: results typically took two weeks to be sent back to Mallinckrodt and on about 19 August 1946 results were almost two months later in coming back to St. Louis from Rochester because of Rochester personnel's being on duty at the Pacific Crossroads tests (MED 1946c). This was one of the reasons that Mallinckrodt took over the processing of its own film badges.

No procedures and little other film badge specification data have been found to date. See Section 5.4.3.1 for information about the film badges themselves. There is also not much information about how the film badges were processed by either Rochester or Mallinckrodt. However, MCW (1950r) stated that an AEC report (NYOO-57) was an attempt to measure the surface dose rate from uranium (presumably metal) received through the stratum corneum of the fingers, at 7 mg/cm^2. According to MCW (1950r), this report gave a dose rate of 239 mrep/hr through a depth of 7 mg/cm^2 and 178 mrep/hr through 44 mg/cm^2. Mallinckrodt had been using a value of 265 mrep/hr in their film badge measurements, but now agreed to use the NYOO report value of 239 mrep /hr. Mallinckrodt did so because the report results were based on a filter closely approximating the dead skin layer; thus this basis was more similar to Mallinckrodt's operating conditions than their old value's basis. However, as MCW (1950r) pointed out, AEC's tolerance level was based on the "field strength" of the radiation, not on the amount of radiation at any particular depth of any particular material; it was thought that any other reference level would be impossible because of the energy distribution of the betas.

There are some documents indicating problems or variations from the norm in badge readings. MED (1945l) stated that recently read films worn from 26 November through 4 December 1945 showed abnormal density combinations and that it was inconceivable that all of the density was due to radiation exposure. It was noted that a Mallinckrodt manager had admitted that the films might have been subjected to high temperatures. It was also noted that the problem could not have occurred in Rochester (where the films were being read at the time): the Mallinckrodt films of two weeks earlier

had also shown high exposures and since that time, Rochester had been very careful in handling films from Mallinckrodt.

Mallinckrodt (MCW 1948d) reported that there was considerable fluctuation in readings on badges worn in the digest and Feinc filter areas; the explanation was given that any interruption in the process that caused a holdup of material allowed the material to "age" (i.e., daughter products to build up) and thus to exhibit more gamma activity. Breakdowns of equipment, which tended to result in higher exposures to operators doing the repairs, were another reason given for the variations.

There was a series of meetings and correspondence between Mallinckrodt and AEC regarding whether certain readings were due to beta or soft gammas and whether the AEC and Mallinckrodt methods of correction for shield absorption (in the badge) were consistent (AEC 1950b; AEC 1950f; MCW 1950k; AEC 1950g; AEC 1950i; MCW 1950x). This issue involved the subtraction of the film density value under the beta "shield" from the value under the window. Section 7.1 of this document states the assumption to be made about this subtraction; however, the references cited may be consulted in case of any suspect beta readings corresponding to the 1949–1950 period. In connection with this issue, Mallinckrodt (MCW 1950x) undertook an experiment to determine whether the beta reading from the open window of the film badge was due to primary (directly emitted) beta radiation from surface contamination in an area or to secondary beta (i.e., produced by scatter of the hard gammas). A radium source was used to expose four sets of film: one pair was exposed with a 4,800-gauss magnet in place and the other pair with a set of phantom magnet yokes in place. Additionally, one of each pair had a 7/16" Lucite shield in place to eliminate direct betas from the radium source. In this way, the betas were drawn off by the magnet (including any secondary betas) or were taken out by the shield, allowing for a 98% reduction by the magnet in beta radiation arriving at the appropriate films and thus the assumption of a nearly pure gamma component being measured by those films. Mallinckrodt determined that at most a reduction of 19% in the open window could be attained by aggressive cleaning of surface contamination in an area, i.e., that most beta measured by an area film badge was not direct beta. MCW (1950x) observed, however, that film badges actually worn by workers showed greater window densities for equivalent shield densities than area film badges. This was attributed to workers' badges' more frequently actually "seeing" a primary beta source, e.g., during manhole access. Thus during some types of work, workers actually received beta radiation that they would not receive merely by standing in the area.

Mallinckrodt (MCW 1948k) stated that while badge readings were supposed to be accurate within 10% (apparently an AEC requirement), Mallinckrodt's standards were within 5% as checked by "New York" (presumably Rochester or NYOO). Mallinckrodt regarded the method of reporting by Rochester prior to 1 July 1947 as "inconclusive" (MCW 1950k), presumably because of the rounding off to the nearest percent of the tolerance level and possibly also because of uncertainty in the interpretation of what the tolerance was and of what zero dose might actually translate to.

Prior to readout at Mallinckrodt, badges were disassembled in a laboratory hood (MCW 1956f). A Weston photographic analyzer, Model 877, with two stabilizers, was used in reading the films in 1949; in 1956, a Welch Densichron densitometer was being used (MCW 1956f). Due to the assumed near proportionality of film density and radiation exposure of any given type, Mallinckrodt assumed that the following relationship was valid: Net window density from beta exposure alone = Actual net window density - Net window density from gamma exposure alone (MCW 1956f).

5.4.3.3 Film Badge Monitoring Periods and Wearing Practices

Workers were not individually monitored for external dose prior to June 1945. Film badge records are available for the weeks ending 10 June, 24 June, and 1 July 1945 (by memorandum report, MED 1945o) and for 29 July, 5 August, 12 August, and 26 August 1945; then there is a gap until the week ending 9 December 1945. Total (accumulated) doses for the period from 9 December 1945 to 25

March 1946 were reported by individual in a memorandum from the University of Rochester School of Medicine and Dentistry (Rochester 1950). Besides the 1945 records, records appear to be available, with some gaps, for most weeks from 1946 through 1948; 1950 through 1951; 1952; and 1954 into 1958. Furthermore, film badge records for the postoperations decontamination period (see Section 8.0) may not be available either. It is not clear why records are missing after 1945, since clearly film badges were used continuously from 1945 on. Hence it is possible that these records may be found at some later time.

ORAU (1980b) stated that all Mallinckrodt employees who were cleared to have access to production areas wore film badges at all times, with the purpose being to provide maximum assurance that all exposures were registered. Contemporary references indicate that film badges were issued as a combination security-exposure badge to all employees, except for "office females" who presumably never entered process areas (MCW 1955d, MCW 1955c, MCW 1956i). MED (1944p) describes the film badge as being numbered and being combined with a photo ID. AEC (AEC 1948c) states that for Plant 6, the badge was a "photo [ID] film badge" for cleared employees; a film badge with a red insert and the employee clock number for employees awaiting Q clearance; plastic film badges for technicians, engineers, and management, with photo film badges in a separate rack at guard shack or changehouse for when they entered the plant from the clean buildings; plastic photo badges for office employees who did not go into plant areas; film badges with a red insert bearing a large letter V and a number, for subcontractors going into Limited and/or Contaminated areas (such badges to be issued by the guards); and a plastic badge (with no film) with bearing a large letter V and a number, for subcontractors going into Controlled and/or uncontaminated areas and for business visitors to the offices (also to be issued by the guards). MCW (MCW 1955c) also states that all visitors and outside contractors entering process areas were issued badges. It is not clear how early the practice of issuing film badges to visitors and subcontractors entering process areas began.

AEC (AEC 1948c) states that film badges were to be used at Plant 4 for a trial period, suggesting that that Plant 4 employees were not badged prior to early 1948; it was recommended that employees be issued film badges but that subcontractors and business visitors be issued a plastic badge (no film) with a green insert and number.

In 1955, toward the end of operations, it was realized that since an "expansion" group had moved to new quarters in the "Rock Island Building" (presumably in St. Louis), film badges had not been worn by this group during normal activities, thus leaving a gap in exposure data for these individuals (MCW 1955a). A directive was therefore issued for badges to be worn by this group, but of course the missed period was not covered in the records. Similarly, the Mallinckrodt Uranium Division employees who transferred to the Weldon Spring site startup group in 1956 were not being monitored any longer for radiation exposure with film badges; those who might still have business at the Mallinckrodt St. Louis site were to have their badges kept for them in St. Louis (MCW 1956b). Thus these individuals were likely to have intermittent badge readings associated with the St. Louis site.

Since there were no potential sources of acute external exposure, the aim was to keep chronic exposures below tolerance levels (MCW 1950e; MCW 1955d). All exposures over 50% tolerance were reported to supervisors (MCW 1955d).

From 22 April 1946 through the end of MED/AEC work in 1957 or 1958, film badges were processed on a weekly basis as part of a routine dose monitoring program. Badges for Plant 4 began to be changed only every two weeks in early September 1954 (MCW 1954d); all badges began to be changed every two weeks as of 30 January 1955, because of a shortage of health personnel to read the badges and the comparatively low doses then being recorded on the badges (MCW 1955b, MCW 1956i). Mallinckrodt (MCW 1955d; MCW 1956e) stated that (all) badges were changed every two weeks or more often when desired for information or because of expected higher dose. Film badge results were summarized quarterly and annually (MCW 1955d).

The guards were directed that if there was no replacement film badge available for a given used badge when the badges were exchanged by the guards at midnight on Sunday, they were to remove the used one anyway (MCW 1948d). The guards were to notify the safety department of the situation on Monday morning and the individual was to wear his "current" badge for the first half of the shift, until a replacement badge was provided by the safety department. It is not clear from the reference if the used badge was for the week that ended on Sunday or for the week before that, although if it was the latter, that would explain why the individual still had a current badge that he could wear.

Workers were directed to wear their badges when they went to the Airport (SLAPS) or "the Range" (MCW 1949q); the Range appeared to be a firing range (near or at the storage area) where the guards would practice shooting and where some materials were stored (e.g., AEC 1949e reports that some UO_2 was drawn from this storage area for use in production). Plant 6 workers were also told to wear their Plant 6 badges when they visited Plant 4, and vice versa for Plant 4 workers, and not to wear a visitors' badge (MCW 1948k).

As shown in the comparison table in Section 5.4.1, data from AEC 1951b show that a weekly average of 358 badges were issued to Plants 4 and 6 workers in November 1948 through January 1949 and a weekly average of 403 badges were issued in January to June 1950. From the series of Mallinckrodt health group reports (an example of one is MCW 1951c), some 2,000–3,600 badges were read per month in the early 1950s, corresponding to about 460–830 badges issued weekly; these included visitors' badges and probably also some area monitoring badges and some experimental, duplicate, and supplementary (double-badging) badges.

5.4.3.4 Film Badge Record Types, Arrangement, and Availability

Mallinckrodt dose records were of three types: complete records of weekly film badge results, listings of total doses by employee over a specified time period such as the "Mallinckrodt_1946" file (MCW undated), and plant dose summaries. Records found to date show weekly badge processing cycles, with the following exceptions: records that show total dose by specified time period, records from the very later period of operations, and records from the decontamination and decommissioning period. Assignment of individual annual doses was based on deep-dose exposure (Dupree-Ellis et al. 2000).

For most of the period of operations, the complete records are weekly lists of employee names with beta and gamma doses. For the gamma doses some results are shown as "50*" and the asterisk refers to a footnote that reads "indicates less than" (MCW Undated). Values of 60 and 80 are sometimes asterisked in the beta column. Occasional values of "0" are found in the gamma column as well. Some records list employee names with total doses over specified time periods, with a start date and end date.

Listings of total doses by employees over a specified time period other than a week are found in the dose reconstruction project file "Mallinckrodt_1946" (MCW undated). The earliest results are of this form and are recorded by total dose and number of weeks worked in the dose reconstruction project file "Mallinckrodt Radiation Summary APR 46 to MAR 48." This document also supplies other important information for external dose reconstruction. Many of the 1948–1958 records have annual totals written on them; ORAU (1980a) stated that a sampling of records showed that the summing for the 1950–1958 records was sufficiently accurate that the totals could be accepted (i.e., for epidemiological study purposes), but not the summing for 1948–1949.

Dose summaries (in memorandum form) generally listed doses by plant, number and percentages of badges in dose ranges from 0–50 mrep/week, 51–100 mrep/week, 101–150 mrep/week, etc. based on the total beta and gamma for an employee. Doses are not listed for employees having less than 150 mrep in a week; for the dose categories above 150 mrep/week, individual names are listed with

gamma and beta dose results. All employees not working at Plants 4, 6E, or 7 were included in the Plant 6 report (MCW 1956a).

Up to 1950, Mallinckrodt recycled clock numbers, i.e., reused them as employees left and new employees were hired (MCW 1950a). However, this created difficulties with keeping dose records because as Mallinckrodt recognized, dose records needed to have identification numbers that would "remain unique in perpetuity" for tracking purposes. The film badge numbering system was therefore changed as of January 1950 and clock numbers were no longer used on the badges. However, in tabulating the doses (e.g., in memorandum form), the clock numbers were used. The potential for badge confusion due to non-unique numbers prior to 1950 must be recognized.

Some codes used in the records to identify the type of job or work area (e.g., M for maintenance) are found in MCW 1956g and similar memorandum reports or in Table A-5 of this technical basis document. Some codes used in the records to denote readout problems or other items of interest (e.g., GL for Gone Through the Laundry) are found in ORAU (1980a). These are also been shown in Table A-5.

Complete records and/or dose summaries may not have been located for all periods of MED/AEC operation as of this writing. This results in gaps for dose monitoring data when no information is available for workers in a given plant, or in some cases, for any Mallinckrodt worker. Dose summaries, when no complete records of weekly film badge results are also available, give no individual data for personnel receiving less than 150 mrep in a week. Many gaps in data are the result of accidents or damage in the workplace or during badge processing. These incidents are usually documented in the record.

5.4.3.5 Extremity Dosimeters

One record of extremity dosimeter results (as ring badge readings) has been found. Because of the high extremity doses in cleaning the high-beta deposits out of the recasting furnaces, in 1949, film rings began to be used "by selected groups" in the metal plant (AEC 1949b). The results were reported for 25 April through 30 May 1949 in AEC 1949d. Figures were said to be "the Oak Ridge results" based on a radium gamma calibration, so presumably these films were read at one of AEC's Oak Ridge sites. The beta exposure was taken to be a factor of 1.2 times the difference between the open window and the shielded reading. Such data from other sites had been found to be variable and inconclusive, probably, AEC thought, because of improper wearing of the rings and the regular badges worn at the same time; AEC had determined that the ring response depended very much on the direction and angle of the beta sources in the process areas. Individual records of the film ring readings do not appear to be available among the regular film badge records, but AEC (1949d) has a long table giving the results by worker name and identification number.

5.4.3.6 Film Badges Used as Area Dosimeters

Film badges were placed in selected locations in the process areas to serve as integrating area monitors, i.e., to register integrated dose in an area regardless of actual occupancy (MCW 1955d; MCW 1955h). Mallinckrodt (MCW 1955h) opined that such film badges were sometimes hung in out-of-the-way places and not in the area of highest dose rate during occupancy; however, this did not appear to be demonstrated by the comparison between the dose rates measured by the film badges and those measured by a gamma survey meter (MCW 1955h). There is no information as to how often these area film badges were collected and read.

5.4.4 Information and Available Data Regarding Occupational X-Ray Examinations

MED (1944d) stated that the medical program recommended by MED was being followed by Mallinckrodt. This included a routine chest x-ray prior to employment and annually thereafter and a pelvis x-ray for those employees handling fluorides (MED 1944j). MED (1944d) thought that the pelvis x-ray could be dispensed with and apparently this was subsequently done. Later documents also indicate that Mallinckrodt uranium processing workers were given a pre-employment physical that included a chest x-ray (MCW 1955d); Mason 1958a); they were also given an annual physical that included a chest x-ray (MCW 1955d; Mason 1958a). That these x-rays were actually given is indicated in the series of Mallinckrodt Health Office and other reports (e.g., MCW 1951b; MCW 1954e; MCW 1955d). No information is available as to how much dose was received during these examinations or if all workers received annual x-rays. Therefore if no other information is available for a claim, it is assumed that all personnel who worked in the plants covered by this technical basis received an annual occupationally required medical chest x-ray. Personnel working with hydrogen fluoride or in the UO_2-to-UF_4 conversion process in 1942–1944 probably received an annual pelvis x-ray.

5.4.5 Skin Contaminations and Other Radiological Incidents

No records appear to be available regarding skin contaminations. It seems likely that due to the relatively low radioactivity level of most of the uranium forms and the pervasiveness of the uranium-bearing dust, skin contaminations would have been regarded by safety officials at the time as not significant and thus would not have been recorded. See Section 5.3.5 regarding surface contamination, including clothing and smoker hand data.

The following incidents were documented: a 1942 or 1943 explosion in the denitration process area in which agitators began to bind until the motors driving them finally tore loose from the concrete floor (Fleishman-Hilliard 1967); a 1943 ether fire in Buildings 51 and 52 involving a dryer blown apart by an explosion of ether vapors due to burning ether (MED 1943a); a 3 July 1943 fire in a rubbish truck containing “lime” sweepings and other floor sweepings, possibly including metal slag (MED undated b); a 4 May 1946 explosion at Plant 6 involving an explosion due to seepage of ether into the nitric acid tanks due to a malfunction of a check valve; a 19 August 1946 potential significant exposure to workers, probably in the removal of K-65 in the storage area, following which working space was rearranged and the pileup of residue material at the location was reduced (MED 1946c); and a 1947 or 1948 explosion causing the rupture of a nitric acid holding tank due to mechanical failure of a check valve (MED 1948; Fleishman-Hilliard 1967).

Also, there were indications of frequently occurring incidents, such as the occasional spontaneous catching on fire of uranium metal derbies at the derby cleaning station in Plant 6E, which would have put particulates into the air; this problem was spoken of as being brought under control (AEC 1952b). This may have been a longstanding problem, however, since the reference in early 1944 to the loss of material in “burnout” in the reduction step apparently was to this spontaneous ignition of derbies (MED 1944o). Another such recurring incident was the plugging of floor drains, with the consequent formation of puddles of contaminated liquids on the floor at Plant 6 (AEC 1950m).

One incident of concern to the health department was the hand loading of raw pitchblende ore on 21 February 1950, without the knowledge of the health department (MCW 1950d). Apparently there was a malfunction of part of the ore drum conveyor. Operational pressures motivated the production supervisor to have the star valve at the bottom of the ground ore hopper feeding into the secondary elevator disconnected. A three-man crew then picked up open drums off the conveyor using a chain hoist and tipped their contents onto the floor. One worker then shoveled the ore across the floor to another worker and he to the third worker, who shoveled it into the chute to the secondary elevator. One crew worked one half-hour session and a second crew worked another half-hour session,

together handling 12 drums of ore. The crews wore respirators and the downdraft ventilation into the chute was working, but the workers were not otherwise protected from direct radiation or radon, and a crew of maintenance people working around the rod mill nearby were not wearing respirators. It was noted that the gamma exposure at the surface of such an ore drum was 80–100 mR/hr (MCW 1950d); in addition, Table A-24 shows some radon levels for open pitchblende ore drums. However, it was also noted by MCW (1950d) that health department clearance would have been granted for such an operation if the workers had worn oxygen or air line masks, if stay-times were limited to 1 hour per week per worker, and if workers were taken from low-dose areas such as the Ether House or the furnace room.

5.5 OTHER DATA OF DOSIMETRIC INTEREST

5.5.1 Number of Workers

The initial April–July 1942 uranium pilot plant effort included 24 people working as a single project group under a project manager (Fleishman-Hilliard 1967). In 1944, there were 55 guards; 330 workers (including guards) with a clearance for MED work, and 1,500 workers on the entire site (presumably including non-MED workers) (MED 1944p). Regarding the total number of workers with potential for exposure, Fleishman-Hilliard (1967) and Mallinckrodt (1994) listed the total number of workers as 250, the former stating that this was in 1948; AEC (AEC 1948e) listed the total number as 250 at Plant 6, but 400 if Plant 4 was included; AEC (1949b) listed the number of workers at Plant 6 as 272 and the number at Plant 4 as 94; Mallinckrodt (MCW 1950w) gave the total number as 487 and added that 275–300 individuals who worked on the project for more than three months had terminated as of 1 October 1949. Mason (1958a) stated that as of the beginning of 1948, more than 100 of the original employees working during the period 1943–1946 were still on the payroll. AEC (1951b) stated that in early 1951, Plant 4 employed 100 people.

AEC dust study reports in the 1950's gave the number of each classification of workers and the number on each shift (e.g., AEC 1954b); some of these AEC reports even listed the names of process and supervisory workers and their job classifications in an appendix. For Plant 6 alone, Mallinckrodt (MCW 1956a) gave the number of manufacturing personnel as 100 and the number of non-manufacturing personnel as 550. As noted above in Section 5.4.3.3, over 2,000 film badges a month were processed in the 1950's.

5.5.2 Number of Hours Worked per Week

From AEC dust study reports (e.g., AEC 1954b), information regarding time usage is provided in Table 5-11.

Table 5-11. Information on time usage from AEC dust study reports.

Length of work day, including breaks and locker room time	480–520 minutes (8–8.6 hours)
Lunch break	30 minutes
Smoking breaks	30–40 minutes
Clean locker room	20 minutes
Regulated locker room	15 minutes

The longer workday applied to operators and craftsmen, who presumably had to leave their work areas to smoke. There was a 10–15 minute variation in the work day among plants as well. The total smoking break time was 30 minutes for Plants 6E and 7, but 40 minutes for Plants 4 and 6 through about 1955; after that it was 30 minutes for all plants.

AEC-NYOO took the number of work-hours per week to be 48 (or six 8-hour days) in calculating some of their early time-weighted average airborne concentrations (AEC 1949b). Also, AEC (1951b) stated

Plants 6E and 7 operated on a six-day, three-shift schedule. However, this does not imply individual Mallinckrodt workers worked six days a week. MCW (1949g) states that the workweek is 8 hours per day, 5 days per week. Lippmann (1958) used 40 hours in reporting data regarding Harshaw workers and Harshaw (1946) described its rotation schedule used for round-the-clock operation, which involved a 40-hour week for most individual workers and a 42-hour week for some workers. Besides these references, AEC, in its dust study reports, used the actual time worked, as given above, implying a five-day week. It can thus be assumed that Mallinckrodt workers typically worked for a full 8 hours a day, 5 days a week, or 40 hours per week. When using daily weighted average dust sampling data (e.g., in Tables A-12 through A-16 and A-19 through A-22), it is important to understand that break, lunch, and locker time was factored into the weighted averages reported by AEC and Mallinckrodt in their air dust studies.

Fleishman-Hilliard (1967) states that once the Plant 2 operations started (ether extraction), they were carried out 24 hours per day. It is not clear what other early processes ran 24 hours per day, but AEC (1951b) implies that Plants 4 and 6 did not. However, individual dust studies cite three shifts for many process workers' positions, indicating that operations were in fact carried out 24 hours per day, although perhaps not on the weekends. Guardhouses were manned around the clock, with three shifts per day (MED 1944p).

5.5.3 Job Types, Job Histories, Work Areas, and Work, Access, and Clothing Practices

After about 1950, film badge reports included a short note or keyword about the job or work done or the work area occupied by the individual during the week. After about 1948, many urinalysis sheets also listed such notes or keywords. Various AEC dust reports also list job titles and functional work types. Job titles and types discovered to date are given in Table A-18. Note that in the absence of further information, it is not possible at present to distinguish in these records and documents between ordinary or process decontamination and the decontamination that may have been part of preliminary decontamination prior to the decontamination and decommissioning of buildings and plants; however, it is known that there was a decontamination group that did ordinary or process decontamination and special decontaminations as necessary (e.g., of a lab area), so when "decontamination" appears in a record it is this type of work that should be assumed.

As previously stated, to aid in classifying workers whose job titles do not appear in Table A-18 and whose work descriptions do not make it clear which job title is appropriate for use, Table A-5, the keyword table, which includes information from these notes and from operational information in other references (particularly MED 1946a; AEC 1949b; and AEC 1967) is provided. Tables A-5 and A-18 should be used to help determine the principal occupational activity for an individual with missing or conflicting monitoring data.

According to ORAU (1983b), prior to 1 October 1949, there was no "concise" or in-one-place employment history for Mallinckrodt workers in the Uranium Division (i.e., doing MED/AEC work). Then because of the high doses, it was apparently thought that workers who had received more than 90% of their (unspecified) "lifetime" exposure to dust should be removed from uranium work. Consequently, a work history was reconstructed by Mallinckrodt for the period of 1942 to 1 October 1949. Mallinckrodt tried to be as accurate as possible because of the possibility of having to remove workers and apparently the workers examined the reconstructed records, because "the work history had to withstand the scrutiny of each worker" (ORAU 1983b). Four volumes of records were produced: one master list of workers, one volume with histories of those terminating prior to 1 October 1949, one for current Plant 4 workers, and one for current Plant 6 workers.

In the Mallinckrodt Uranium Division, workers in maintenance (shop personnel, skilled craftsmen, and maintenance mechanics) and in plant services (guards, porters, nurses, laundry workers, power plant personnel, hygiene and safety personnel, etc.) were not usually assigned to a particular process, but

served the entire division (Hickey and Dupree 1984). An exception may be the "area mechanic" mentioned in some AEC dust sampling reports, but even then it may be that the mechanic was assigned to cover multiple areas and his exposure may not have been characteristic of only one area. However, Hickey and Dupree (1984) note that the uranium monitoring records they examined showed a reasonably uniform exposure for both the field and the shop maintenance personnel and skilled craftsmen.

ORAU (1977) stated that the highly exposed workers were transferred out of uranium operations in 1950; these were presumably some or all of the 52 workers found to have 100% or more of the lifetime tolerance dose as of October 1949 (AEC 1950a). Mallinckrodt (MCW 1951b) and AEC (1950e) also stated that some 34 workers were transferred in the summer of 1950: the former states that this was from Plant 6 to Plant 1 "for health reasons" and the latter states that this was from Plants 4 and 6 on the basis of their estimated accumulated exposure to uranium dust. While Building 51 (Plant 2) was said by ORAU to have been closed about 1 January 1947 and by Mason (1977) to have been "sealed" in about 1947, when Plant 6 started up, and information in ORNL (1981) suggests that Plants 1 and 2 might have been in use for some support work until decontamination began in 1948; also, MCW (1949e) indicated that special badges would be issued to workers at Plant 1, although this may have been for intermittent work in Plants 4 and 6. Thus the Plant 1 work, if any, would presumably have been non-uranium work. Whatever the case, Mallinckrodt stated that the transfer had been considered for over a year before it occurred and that it would send a report to AEC (1950d); this report does not appear to be available. Possibly partly as a result of the study reported by AEC (1950a), Mallinckrodt used an employee rotation program from about 1950 on (Fleishman-Hilliard 1967; AEC 1950b; MCW 1955d), the point of which was to keep the weekly dose below the weekly tolerance level or, after about mid-1950, to keep the average weekly dose over a three-month period below the weekly tolerance level.

A MED (1944p) security survey report gave the following information. In 1944 and presumably all other years as well, access into the MED areas was only through guarded entrances. Hourly rounds of the entire site were made during evening and early morning hours and all day Sundays and holidays; it took a guard 40 minutes to make a complete round of Plant 2. Non-Mallinckrodt truck drivers were allowed to come in, but not truck drivers' helpers unless needed to unload; all trucks were escorted while within the site. MED (1944l) stated that personnel in the "MED plant" were segregated as much as possible from the general (non-MED work) personnel, with the main point of contact being during the lunch hour.

From April 1949 on, the film/ID badges were color-coded to control access (MCW 1949h); for example, Plant 6 was divided into seven zones, each with its own color. "Controlled" areas were areas not expected to become contaminated, such as the offices, the power plant, the pumphouse, and the yard areas. "Limited" areas included the main processing building, the warehouse, the Scale House, the laboratories, and so forth. Mallinckrodt's 1955 formal description of its health program (MCW 1955d) gave the following information, indicating that the area control system was continued throughout the processing years although the definitions might have changed somewhat. Mallinckrodt maintained three levels of controlled areas. These were the regulated areas, which were described as the areas where radioactive materials were processed and handled; the grey areas, which were areas where any radioactive material and contamination was incidental to the function of the area, e.g., labs and production instruments departments; and the clear areas, where radioactive materials were not required and not permitted, e.g., offices and the cafeteria. Although zero contamination was not possible in the latter areas due to their proximity to the other areas, that was the stated goal of control efforts.

An internal Mallinckrodt memorandum circa April 1948 (AEC 1948c) stated that the Building 101 facilities had been "revised" (implicitly for better control of contamination) and access status in the building and yard areas was to be broken into two classifications. The first was the "clear area,"

consisting of all areas in which the presence of "plant products" could be completely eliminated or reduced to negligible amounts. The designated clear areas were the guard office, the locker room, the lunchroom, the Health Unit offices and laboratory, the AEC offices, the MCW offices, and the MCW laboratory offices. The second area was the "regulated area," consisting of all areas that could not be kept clear of plant products.

MED (1942) stated that employees were required to change work clothes daily, with the "uniforms" being provided by Mallinckrodt. AEC (1948c) states that in the clear areas, either street clothing or plant clothing with cover clothing was allowed, except in the lunchroom, where only street clothing was allowed; in the regulated areas, either plant clothing or street clothing with cover clothing was allowed. In 1955, the Mallinckrodt health program was said to include the following requirements regarding clothing (MCW 1955d). Work clothing "from the skin out" was provided for all persons assigned to regulated areas; regulated clothing could not be worn outside regulated areas except under cover clothing; and cover clothing was also provided for brief visits to regulated areas. Because wearing contaminated regulated clothing on public land was undesirable, vehicular transportation was required for workers traveling between regulated areas (even with the cover clothing) (MCW 1955d). Regulated area workers were issued two changes of clothing per day as of 1955 (MCW 1955d) and probably much earlier due to contamination control requirements involving showering (see below).

Visitors were provided with cover clothing (smock, rubbers, etc.) (MCW 1950e). However, as of at least 1950, outside contractor personnel wore their own personal work clothing, on the grounds that visitors' garb would be "too restrictive" and thus unsafe (MCW 1950e). Besides that, suitable change room facilities were not provided for outside contract personnel (MCW 1950e).

Process (manufacturing) workers were required to shower before changing into "clear" (clean) clothing; they typically took two showers a day in 1955 (MCW 1955d), but only one in the 1942–1944 time frame (MED 1942, MED undated a) and apparently only one in April 1950 (MCW 1950e). The procedure was as follows (MCW 1948c). After punching in, workers who would be changing into plant clothing would remove their street clothing in the locker room, don plant clothing in the change room (apparently the same clothing from the second half of the previous day's shift), and enter the work area. At lunchtime, workers would remove the plant clothing in the change room, shower, don street clothing, and go to the lunchroom. After lunch, they would put on a clean set of plant clothing in the changes room and go back to work. At the end of the shift, workers would remove the plant clothing in the change room, shower, and don their street clothing in the locker room. An extra 15 minutes was allowed for the midday showering and changing and clogs were provided for traffic between the locker room, change area, and showers (MCW 1948c). The one-way door allowing traffic to pass only from the locker room to the change area was to be supervised at shift change and lunch hours (MCW 1948c). No one was allowed to leave the plant in plant clothing (without cover clothing, presumably) (MCW 1948c). By February 1949, an AEC consultant, inspecting the change room for Plant 6 process workers, termed the operation of the change room "creditable," i.e., in line with AEC directions (AEC 1949k).

Plant 6 warehouse personnel were to follow the same general procedure in their change room, as were maintenance workers who used the process area locker room. The warehouse personnel leaving Plant 6 on trips to other regulated areas (such as Plant 4, SLAPS, or "the Range"), were allowed to make the trip in plant clothing, but in a "regulated" vehicle only; these vehicles could be jeeps, dumpsters, or large trucks) (MCW 1948c). Also, warehouse personnel leaving on trips to clear areas outside Plant 6 had to shower and change as if they were leaving work and they had to use a "clear" vehicle only (MCW 1948c).

Laboratory personnel who normally wore plant clothing were to follow the general procedure for process workers, except they used their own locker room and change room; personnel going to the

laboratory offices (a clear area) from another clear area could go directly in street clothing but had to use cover clothing to go to the laboratory; and personnel going from working in a laboratory to the lab offices had to put on cover clothing over their plant clothing (MCW 1948c).

The change requirements given above for process workers also applied to maintenance personnel who used the maintenance shop locker room: they were to use the same procedure but in their own locker room (MCW 1948c). Since the maintenance men in the shop might also work in the now non-AEC Plant 1 and presumably other clean areas at the general Mallinckrodt facilities, they had to change into special blue coveralls and either street shoes or clean safety shoes when visiting those areas; similarly, any Plant 1 maintenance men going to the AEC areas to work were to follow the change procedure as for the process workers (MCW 1948c). Instrument Shop personnel going to Plant 4; however, could go in plant clothing but in a regulated vehicle only (MCW 1948c).

Mallinckrodt (MCW 1948c) stated that no one was permitted to eat in plant clothing; that no one who had been working in plant clothing was allowed to eat without previously showering; and that there was to be no eating in regulated areas. Soft drink dispensers and washing facilities were provided in the change room, but hands were supposed to be washed before drinking (MCW 1948c). According to MED (1944p), smoking was not permitted in operational areas except in designated smoking areas or smoking rooms. Smoking was permitted in offices and labs, except where ether or other flammable substances were handled. In 1944, the penalty for smoking in other than permitted areas was loss of employment. Thus it is likely that nearly all smoking was done in designated spaces.

5.5.4 Miscellaneous Product Information

Table 5-12 lists quantities and dimensions of potential radiological interest (e.g., for special external dose calculations). See also Table A-4 and Section 4 for other amounts.

Table 5-12. Quantities and dimensions of potential radiological interest.

Bomb	10” OD × 40” long	MED 1946a
Bomb liner (lime, etc.)	Depth: 1”	MED 1946a
Uranium billet	4.75” OD × 18” long	MED 1949b
Uranium billet	~ 6” OD	Mason 1977
Ore barrel	3’ high × 18” across	MED 1945a
U metal samples		
Glass tube	2” OD × ¾” long	MED 1945a
Cardboard packing box	5” sq, 1–2 lbs filled	MED 1945a
U eggs (samples from billets)	Packed eight to a box	MED 1945a
Billet packing box, wood	5” × 5” × 13”	MED 1945a

5.5.5 Missouri and St. Louis Area Background Levels

Table 5-13 gives some Missouri and St. Louis area background measurements, except that the Applied Nuclear Safety measurements were taken at Building Z of the Mallinckrodt site, used as a control. Note that these measurements were all taken many years after the end of operations and were made for the purpose of characterization for possible future remedial action.

Table 5-13. Missouri and St. Louis area background measurements.

		ORNL 1979		ORNL 1981		Applied Nuclear Safety 1986	Bechtel 1987
Measurement	**Unit**	**Range**	**Average**	**Range**	**Average**	**Average**	**Average**
Ac-227	pCi/g	Below detectable					
Ra-226	pCi/g	0.3–1.3	1.05 ± 0.3		1.18		

Th-232	pCi/g	0.3–1.3			1.15		
U-238	pCi/g	0.3–1.7			1.25		
Gamma background at points distant from site	uR/hr		6.0 ± 1.7	7–9	8		11
Beta-gamma (GM)	mrad/hr		0.02	0.01–0.04	0.02		
Radon concentration	pCi/L				1.0	0.33	0.3
Radon daughter concentration	WL				0.01	0.002	

6.0 RECONSTRUCTING INTERNAL DOSE AT THE ST. LOUIS MAIN SITE DURING THE OPERATING YEARS (1949–1958)

Internal doses related to Mallinckrodt operations (and initial decontamination) at the main plant site are only to be assigned for the period January 1, 1949, through December 31, 1958. Table 6-1 summarizes work categories for the purpose of assigning internal doses to individuals not in the special exposure cohort and who might have had no bioassay. This section does not apply to SLAPS employees *because NIOSH has determined, and the Secretary of Health and Human Services has concurred, that reconstruction of internal dose is not feasible for the period January 3, 1947 through November 2, 1971 (HHS 2010*). Information on reconstruction of internal dose at SLAPS is in Section 9 of this document. In Section 6.4, information for assigning radon exposure is provided.

Table 6-1. Summary of internal dose reconstruction assignments by work category.

Category	Description	Period of applicability	Dose reconstruction (if individual bioassay are not available)
General	Probably had no contact with process area.	1/1/1949–12/31/1958	**Coworker data**: assume lognormally distributed uranium intakes with a minimum GSD of 3, if uranium bioassay data for an individual are not available.
General	Had contact with process area.	1/1/1949–12/31/1958	**Coworker data**: assume constant distribution and use 95th percentile uranium intakes, if uranium bioassay data for an individual are not available.

6.1 URANIUM INTAKES

The uranium photofluorometry urinalysis detection threshold is assumed to be 0.01 mg/L, which is consistent with the value used for other sites during this period. Uranium is assumed to be either absorption type M or S.

6.1.1 Assignment of Uranium Intakes for Unmonitored Workers or Unmonitored Periods

For workers with no associated bioassay, the coworker uranium intakes based on the CER data provide a basis for uranium dose determination. The CER data is a set of worker and workplace monitoring data compiled by Oak Ridge Associated Universities for epidemiological studies (ORAU 2005). The compiled worker information only includes data for white males. Reviews of the accuracy of the compiled urinalysis results performed by individuals from Sanford Cohen & Associates, Inc. and NIOSH revealed small differences between the original data and the CER data. A small number of differences in dates, results and type of data entered were found by the contributors to this document, but it is unlikely these few differences will grossly change summary analysis results of the CER uranium urinalysis data. (These differences were readily apparent in the claim file data, and so the appropriate data are readily available for use in individual dose reconstruction.) The geometric mean and 84th percentiles were determined by year from the CER uranium urinalysis results in mg/L for each of the years 1949 through 1957 using methods in ORAUT-OTIB-0019, were adjusted to units of pCi/d by multiply by 682.96 pCi/mg and by 1.4 liters of urine per day, and are shown in Table 6-2.

Table 6-2. Uranium bioassay results (in pCi/d).

Year	Number of results	Geometric mean	84th percentile
1949	638	0.016	0.065
1950	1,091	0.009	0.030
1951	1,279	0.009	0.023
1952	1,910	0.009	0.024
1953	2,421	0.008	0.022
1954	1,943	0.006	0.018
1955	1,897	0.006	0.017
1956	,802	0.005	0.013
1957	1,038	0.004	0.014

The intakes shown below were calculated with IMBA Expert™ ORAU-Edition, Version 4.0.9, assuming an absolute uniform error of 1 and normal error distributions for each annual bioassay result, which was assigned a date of July 1 for its year. The geometric standard deviations (GSDs) for the intakes were calculated by dividing the intake from the 84th percentile regime by the intake from geometric mean intake regime.

If uranium urinalysis results are not available for a worker or for an extended period of employment, uranium intake rates estimated for coworkers based on compiled bioassay results may be used. The lognormal intake distribution information derived from the coworker data is used to estimate organ dose distributions for workers, who were unlikely to have had assignments associated with uranium and associated radioactive material processing operations, as determined from claim specific information. For workers, who were likely to be associated with process work or process work areas, the 95th percentile of the CER derived intake distribution using a minimum GSD of 3 is used to determine organ doses and is assumed to be a constant distribution. These uranium intakes are shown in Table 6-3.

Table 6-3. Uranium lognormal distribution and 95th percentile intakes based on CER urinalysis data.

Type	Start	End	50th percentile intake rate (pCi/d)	GSD	95th percentile[a] intake rate (pCi/d)
			Workers outside process, storage and waste areas		Process and waste workers and workers in process and radioactive material storage buildings
M	1/1/1949	1/1/1950	270	4.15	2,810
	1/1/1950	12/31/1958	95.8	2.79[b]	517
S	1/1/1949	1/1/1950	8,440	3.87	78,000
	1/1/1950	1/31/1958	762	1.87[b]	2,130

a. To calculate the 95th percentile intake, the 50th percentile intake was multiplied by the GSD (using a minimum of 3) raised to the 1.645 power

b. A minimum GSD of 3 should be used for estimating dose.

The source term is natural uranium, but U-234 can be used for intake and dose calculations once results are converted to activity. Either type M or type S uranium is chosen, but not both. The dose distribution type is either lognormal for the 50th percentile intakes or constant for 95th percentile intakes.

6.2 RADIUM INTAKES

The **radon breath analyses**, when available for an individual, should be used to estimate Ra-226 body activity using the method in ORAUT-OTIB-0025, i.e., by multiplying the radon breath result in pCi/L by 2.52E5 to get the activity in the body at the time of the bioassay. The lower limit (of detection) at HASL was 0.1 pCi/L (ORAU 1983b). The radon breath analysis recording level (the level

at or above which a finite result was recorded) was 0.1 pCi/L for the vast majority of Mallinckrodt radon breath analyses (AEC 1949–1956), and this is to be employed as the detection threshold.

Although there are some factors that could cause radon breath results to be underestimated, the available information indicates that the collection of these samples would likely result in reasonable estimates of radon in breath for the purpose of this program, in other words, no information has been found to indicate that these results would have been underestimated. The records indicate that a number of Mallinckrodt samples were collected in areas of elevated radon (MED 1945e), which resulted in the breath radon emanations from radium within the body to being overestimated. In addition, breath radon samples should not have been collected within one to two hours after a meal. (Eating appears to increase the radon breath concentration and waiting would reduce the body emanation concentration by up to a factor of 2 and thus allow for appropriate application of the factor to convert from radon breath concentration to radium activity concentration within the body.)

6.3 THORIUM INTAKES

About 70 thorium urinalysis results for the period March 4 through April 19, 1955 have been located for some workers, and should be used for individual dose reconstructions. Most results are reported as a value followed by a +/- and another value. The results are reported in dpm/L and the average of the +/- value is 1.1 dpm/L (AEC 1954–1955), and twice this value is assumed to be the detection threshold, because the result are near background and the lower limit of detection is about 2 times the one-sigma background counting error. It is suspected that most workers who had thorium bioassay results were ionium (Th-230) workers, engaged in recovery of thorium from AM-7, which occurred during the period January 1, 1955 through January 1, 1958, but this bioassay (chemical separation of thorium and gross counting for quantification) would also have detected intakes from earlier process work. Later some workers were involved in the dismantling and decommissioning of this area.

6.4 RADON EXPOSURE

Area radon data are used to assign radon exposure. CER radon data for Plant 6 and subsets of the Plant 6 data by areas were considered. A set of lower exposure data for areas including Dispensary, Electric Shop, Furnace Room, Health Office, Instrument Shop, Laboratory, Locker Room, Machine Shop, Maintenance Shop, Manufacturing Area, Metal Dissolver Building, Millwrights Shop, Nitric Acid House, North Laboratory, Open Area, Open Storage Area, Orange Packing Area, Outside Area, Recast Area, Receiving, Refrigeration Room, Research Laboratory, Rest Room, Shipping & Receiving, Shotgun Laboratory, Slag Building, Slag Pilot Plant, Smoking Room, South Laboratory, Welding Shop, and X-Ray Laboratory, where the radium source term was not predominant, are also considered to assign radon exposure to workers who did not enter areas associated with radium and associated processing or storage areas. Data for the Ore Storage and Scalehouse were also analyzed.

The CER data were analyzed by assuming the data are lognormally distributed. Data were ranked from low to high. The z-scores of the ranks and the transformed data were fit to a line for determination of the 50th percentile and geometric standard deviation of each distribution in accordance with ORAUT-OTIB-0019 methods. Results that were “less than” results were ranked, but not fit. No attempt was made to sort data prior to analysis to remove those data that were not representative of occupied areas; for instance, measurements taken in a drum head space or in the thawing furnace would likely have been included. For some areas, the large geometric standard deviations provide some indication that two different concentration distributions are being measured. A summary of the results is shown in Table 6-4.

Table 6-4. 1949–1957 range of radon exposure distribution parameters for different percentile categories based on data in CER.

Location	50th (pCi/L)	GSD	84th (pCi/L)	95th (pCi/L)	95th occupancy 0.5	95th occupancy 0.05
Low radon areas	1.6	4.7	7.36	20.04	–	–
Plant 6	3.4–19	3.3–6.6	20.4–72.2	58.9–244	–	–
C-3	4.9–35	2.7–9.9	32.7–231.6	78.9–1,012	–	–
FEinc	3.6–28	2.2–5.3	13.9–66.5	33.3–181	–	–
K-65 centrifuge	3.1–13.3	2.2–8.3	14.6–59.5	23.9–192	–	–
Ore storage	1.2–26	3.7–22	13–150	41–590	22–300	2.2–30
Scalehouse	1.1–59	3.2–8.3	4.2–260	9.6–680	5–340	0.5–34
Summary	**All < 59**	**–**	**Most less than 100**	**Most less than 200**	**–**	**–**

To determine exposure due to a specified radon concentration (assumed to be Rn-222), the concentration C in pCi/L was converted to potential alpha energy exposure (PAEE) per year units of working level months (WLM)/y using:

$$PAEE = C * F* M / (100 \text{ pCi/L per WL})$$

where the equilibrium factor F was taken as 0.4, a value recommended by the ICRP (1981) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1993) and M is the number of months of exposure, 12, in a year, where a month is assumed to be 170 work-hours.

To assign radon exposures, workers are categorized into three exposure categories as shown in Table 6-5. By 1949, workers were being restricted in the number of hours they could work at the Scalehouse. Workers were rotated through some of the higher radon exposure jobs. Therefore it would be reasonable to apply an occupancy factor for the Ore Storage and Scalehouse. A bounding value would be 0.5, but it is more likely on the order of 0.05. The selection of the radon exposure values for Table 6-5 included consideration of the occupancy associated with the Ore Storage and Scalehouse.

Table 6-5. Radon exposure assignments.

Category	Description	Period and exposure			Basis
General plant	Did not work in or routinely enter process or associated radioactive material storage/waste areas.	1949–1958 0.962 WLM/y			Constant distribution. 95th percentile of the low radon areas plus outdoor storage area
Process areas	Worked in on near process areas, but did not encounter ore products, residues or associated storage areas directly.	**Year**	**WLM**	**GSD**	Lognormal distribution of the Plant 6 radon concentrations includes the possibility of lower and higher exposures
		1949	0.52	6.62	
		1950	0.91	3.57	
		1951	0.82	3.39	
		1952	0.54	4.30	
		1953	0.45	4.11	
		1954	0.40	5.65	
		1955	0.47	4.68	
		1956	0.24	4.48	
		1957–1958	0.16	6.04	
Process workers	Includes operators, ore samplers, residue samplers, laborers, maintenance workers, etc.	1949–1958 14.4 WLM/y			Constant distribution. Based on radon concentration of 300 pCi/l, but records indicate these levels trended downward over time.

6.5 UNMONITORED RAFFINATE EXPOSURES (1949–1958)

NIOSH has determined, and the Secretary, Health and Human Services has concurred, that it is not feasible to reconstruct internal radiation dose for individuals who worked at Mallinckrodt prior to 1949 (HHS 2005a). For the period 1949 through 1958 NIOSH has determined, and the Secretary, Health and Human Services has concurred, that it is not feasible to reconstruct internal radiation doses from internal exposures to non-uranium radionuclides for Mallinckrodt raffinate workers, nor is it possible to identify which workers were raffinate workers (HHS 2005b, HHS 2009). Consequently, only internal radiation doses associated with specific bioassay types (uranium, radon in breath, and thorium) and radon area measurements will be estimated for individuals who worked for Mallinckrodt during the period 1949 through 1958.

7.0 RECONSTRUCTING EXTERNAL DOSES AT THE ST. LOUIS MAIN SITE DURING THE OPERATING YEARS (1949–1958)

This section applies to determination of external gamma, beta, and neutron doses at the Mallinckrodt Main Plant Site prior to 1958. Prior to 1949, external dose for individuals for whom monitoring data is available should be assigned based on the available monitoring data only without consideration of exposure during periods during which monitoring data is not available.

This section does not directly apply to St. Louis Airport Site workers; however, information in this section can be used to interpret individual claimant data as necessary to complete dose reconstructions for former SLAPS workers. Information on reconstruction of external dose at SLAPS is in Section 9 of this document. For external doses during the remediation period see Section 8.0. Film badge coworker data have not been completely analyzed, but if needed for more accurate compensability determinations, they could be more rigorously evaluated.

7.1 ASSUMPTIONS AND GENERAL INSTRUCTIONS

The following assumptions should be made in the determination of external dose:

1. Most external dosimetry monitoring records appear to be available, but where such records are missing doses must be estimated. As alternatives for dose estimation information, area monitoring data for external radiation is sparse and although much is known about the characteristics of the process material (source term), the lack of knowledge of such relevant factors as geometry make dose estimation using this data subject to a great deal of uncertainty. Thus the approach incorporating the least uncertainty is likely to be using existing dose monitoring records to create an applicable surrogate(s) set of data.

2. Mallinckrodt dose records demonstrate that a substantial proportion of employees had film results recorded as 0–50 mrep or mr. From this it can be assumed that the dose-monitoring program was sufficiently conservative that even many individuals who did not receive significant occupational exposure were also monitored. It can be further assumed that the converse is true, that individuals who were not monitored were unlikely to receive significant occupational exposure. This assumption is supported by the observation of Hickey and Dupree (1984) that Mallinckrodt health physicists and industrial hygienists presumably monitored those jobs and workers where they thought the problems were and that it can thus be inferred that infrequently monitored workers such as the general administrative staff were not considered to be at risk of significant exposures.

3. Photon doses for all workers should be assumed to be in the 30–250 keV energy range. This is consistent with NIOSH (2007). It is also consistent with the fact that all but a fraction of the gammas emitted by U-235, U-238, and their daughters down to radon are in this range, including the principal gamma of Ra-226 (0.186 MeV) and the principal gammas of Th-230 and Th-232.

4. For the purposes of dose reconstruction, the “beta” readings in the Mallinckrodt dose records are assumed to be equal to the shallow dose, Hp(0.07). Beta dose should thus be assigned as shallow dose from electrons of energy greater than 15 keV.

5. The descriptions of the film badge in Section 5.4.3.2 above do not suggest calibration using a phantom, so it is likely that open-air calibrations were performed. Thus the recommendation is that Mallinckrodt recorded doses be converted using dose conversion factors for Roentgen-to-HT dose for photons from Appendix B of NIOSH (2007). While film badges are known to overestimate doses from low-energy photons, the low-energy component does not seem to be a significant characteristic of the Mallinckrodt spectrum. Thus no modification is proposed to recorded deep doses, once converted to organ doses using the Roentgen-to-HT dose conversion factor.

6. Examination of entries for “gamma” and “beta” in the Mallinckrodt dose records shows that the beta doses were obtained by subtracting the optical density for the shielded portion of the film from that of the unshielded part. This is also shown by a series of memoranda between the AEC and Mallinckrodt (AEC 1950f, AEC 1950h, MCW 1950o) in which the method of subtracting the two quantities was discussed. For Mallinckrodt, it is assumed that the beta readings were obtained by subtracting the density under the shield from the density under the window and assuming the difference in density was due to beta radiation (MCW 1950o).

For the purposes of dose reconstruction, the minimum level of photon detection should be assumed to be 50 mrem, based on the fact that Mallinckrodt individual dose monitoring records list many entries in the gamma column as “50*” and the asterisk refers to a footnote that reads “indicates less than.” The minimum level of electron detection should be assumed to be 80 mrem. Note, ‘missed dose’ is only assigned after 1949.

OCAS-TIB-0013 (NIOSH 2006) geometry factors should be used to adjust external doses in individual records and in this document for operators and material handlers and for trades and crafts personnel.

7.2 INFORMATION REGARDING THE 1950 AEC CUMULATIVE DOSE RECONSTRUCTION STUDY

The lack of early external monitoring data for Mallinckrodt reflects the novelty of the uranium processing industry, the provisional nature of early uranium activities at Mallinckrodt, and the assumption that airborne exposure was the primary hazard. The implementation of a more comprehensive health and safety program at the end of the war and in the early post-war period led to questions about external doses that previously had gone unmeasured. This resulted in the publication of the AEC report "An Estimate of Cumulative Multiple Exposures to Radioactive Materials, Mallinckrodt Chemical Works Plants 4 and 6, July 1942 to October 1949" (AEC 1950a). AEC's results are not quoted here for two reasons. First, in dose reconstruction different assumptions are made than AEC made. Second, the study develops cumulative dose data, but unfortunately does not apply it to individual workers or distinct work groups, while doses applied to individual workers for dose reconstruction should rely on recorded doses for actual worker or worker groups. However, dose reconstructors should be aware of this report.

The cumulative exposure estimates covered workers then employed at Plants 4 and 6 who had been employed in MED/AEC work at Mallinckrodt between July 1942 and October 1949 and who had more than six months of exposure to radioactive materials. AEC's estimates for the dose to the skin were based on film badge data.

7.3 GAMMA AND BETA DOSE

NIOSH (2007), the external dose reconstruction guide, states that the hierarchy of dose determination sources is personal dosimeter (the film badge worn by the individual); pocket ionization chamber; and group or co-worker dosimeter. Pocket chamber data does not appear to be available for Mallinckrodt and in fact, use of the pocket chamber (pocket meter) was discontinued in 1949, as explained in Section 5.4.1. However, such data may come to light at a later date and in that case, some calibration and other information can be found in Section 5.4.1 and the references it cites. NIOSH (2007) does not list the area monitoring dosimeter, such as Mallinckrodt used in many areas as a secondary means of monitoring. However, such data, if available, could be used in a comparative way if none of the other data sources can be found.

Generally, for a given claim, dates of employment should be compared to the available dose monitoring information. If dose monitoring records are likely to be available, the dose reconstructor should request project personnel to search the available records.

7.3.1 Selecting a Surrogate Cohort and Formulating a Surrogate External Data Set

Surrogate (analogous co-worker) data, in Mallinckrodt cases, is a matter of identifying an appropriate set of workers with a similar work history. That is, in general, to form a surrogate set the dose reconstructor should identify at least several other workers with appropriate monitoring data who did the same work at the same time as the subject worker; the monitoring results for these surrogate workers should then be pooled to arrive at a statistical representation of the likely dose to the worker.

For the monitored years, many, perhaps most Mallinckrodt film badge records and urinalysis records had some indication of job title, task, or work area. Thus the formation of a surrogate set of data should be possible for all monitored years by inspection of the weekly dose reports, supplemented as necessary by inspection of the quarterly urinalysis reports. (Note that the urinalysis reports are a useful and available additional source of co-worker and job assignment information for external dose

reconstruction, even though the urinalysis results themselves are not relevant to external dosimetry.) Dose reconstructors must compare information available from the DOE record and the computer-aided telephone interview (CATI) to the records in order to identify workers with a similar work history.

One complication of selecting a surrogate set for the monitored years is that from some point on in the postwar years (maybe beginning in 1949), a rotation system was used in work assignments in order to reduce individual process worker external exposure (MCW 1950t; AEC 1951b). The work done by an individual would therefore vary over the course of a year as he was rotated in and out of high-exposure areas. Thus for best results, where data for an individual known to be working at Mallinckrodt in AEC operations are lacking or are unclear, some care must be taken to identify co-workers whose assignments are most analogous to the unmonitored workers. The rotation system was done principally on a crew basis, i.e., the same small subgroup of individuals were assigned to the same work at any given time, so the most appropriate individuals are those whose names appear on the known records for the individual as doing the same work at the same time and not, say, individuals doing the same work in a later period. However, if the number of same-time co-workers is deemed by the dose reconstructor to be too small to provide adequate statistics in view of the variation in the doses, the similarly assigned co-workers doing the same work in the period immediately before or after the period of interest should be included. The rotation system apparently ended when the doses went down sufficiently, probably some time in the early 1950's. Hence from about 1952 on, the records will likely show more sustained assignment of the same work to an individual and identification of same-time coworkers would be less important.

7.3.1.1 Notes Regarding Dose Summaries

Monitored workers may have received up to 150 mrep in a week without the dose being recorded in a dose summary. There is some probability that the dose received was actually zero: dose summaries consistently show a significant number of badges in the 0–50 mrep dose range. For the purpose of dose reconstruction, the most favorable to claimant assumption is that any monitored worker assigned to a given plant, but not specifically listed in the dose records for the plant for that week, received a dose of 150 mrep that week. Division of the total between gamma and beta components should be based on an average ratio derived from the weeks with specific dose monitoring entries for that individual.

7.3.2 Determining Dose–Monitored Period 1949–1958

This section applies to workers for whom doses must be estimated for the operating years, i.e., 1949–1958. Plants 1 and 2 were not used for AEC work after about 1946 and underwent decontamination and decommissioning (D&D) in 1948–1950, after which they were released to Mallinckrodt in 1951 for non-AEC work. Similarly, the other plants stopped being used at varying points in 1957–1958 and underwent D&D thereafter. This section does not apply to any worker or work area after the end of operations; see Section 8.0 for dose estimation for the D&D years and the later post-operations years.

After the operations and D&D years, Mallinckrodt received a license from the AEC for the use of certain radioactive materials and so some workers may have been continued to be badged. Also, there may be continuing badge records for some individuals for years after operations ended at the St. Louis (Destrehan) site because these individuals transferred to or made visits to the Weldon Spring site, also run by Mallinckrodt, and had badges issued for work there.

7.3.2.1 Monitored Workers

When there are missing data in the monitoring records, they should be filled in by bridging small gaps by interpolation and bridging larger gaps using statistical surrogate data and/or standard missed dose estimates.

7.3.2.2 Unmonitored Workers–Plants Still Operating under MED/AEC Contracts

As stated above, most workers who received significant occupational exposure were likely to have been monitored and thus if a worker was not monitored, especially for a lengthy period of employment, this indicates that he was deemed to have little or no exposure potential. To account for the possibility of an unmonitored individual receiving incidental exposure to photons, dose should be assigned to unmonitored Mallinckrodt employees as follows.

1. An attempt should be made to find a surrogate category.

2. If no surrogate category can be identified – i.e., if there are no monitored workers with the same job title or the job title listed in the worker's records cannot be associated with any surrogate job title—then either the Mallinckrodt subject matter expert for the dose reconstruction project should be consulted for guidance (and possibly further research) or the worker should be assigned a nominal category. Normally, the appropriate nominal category will be a low-exposure job title such as office worker.

7.3.3 Unmonitored Workers–Plants No Longer Operating under MED/AEC Contracts

Unbadged non-decontamination and decontamination workers, if any, should have their 1949–1950 exposures determined on the basis of decontamination worker surrogate data (see Section 8.0).

For the period after decontamination and decommissioning, i.e., from 1951 on, the exposures should be determined as described in Section 8.0.

7.4 X-RAY DOSE

7.4.1 Mallinckrodt-Specific Information

Employees of Mallinckrodt (cf. Section 5.4.4) received an annual occupationally required medical x-ray (MCW 1955d; Mason 1958a). Up to some time in 1944, a pelvis x-ray was also performed for employees working with fluorides (see Section 5.4.4). The annual chest x-rays and presumably the pelvis x-rays were taken at the Barnes Hospital (the Washington University School of Medicine) (AEC 1950m; MCW 1955d) and the x-ray records remained the property of the hospital (AEC 1950m). There is no evidence so far in the Mallinckrodt documents to indicate when the annual chest x-rays began, although Fleishman-Hilliard suggests that this was done from the start since Mallinckrodt insisted at the outset that the Washington University School of Medicine be engaged to do the physical examinations. Since the radiographs were made at a hospital, and hospital procedures routinely used both PA and lateral chest projections much more commonly than non-hospital facilities, the annual dose from chest x-rays for Mallinckrodt workers should consist of the dose from both projections. No evidence so far indicates that photofluorographic chest films were performed. A physical checkup of all prospective decontamination and decommissioning workers was provided. This included chest x-rays (PA and lateral, using full-size 14 x 17 films). Based on the fact that the medical X-rays were conducted offsite and at an uncovered facility, dose from such examinations should not be included in dose reconstructions.

7.5 NEUTRON DOSE

As indicated in Section 5.4.2, there was no neutron monitoring done at Mallinckrodt. Therefore it is not expected that there will be any neutron monitoring data or neutron dose rate measurement data found for Mallinckrodt. Section 5.4.2 describes the Mallinckrodt sources of neutron exposure. Table A-34 shows the results of the alpha-neutron dose rate calculations based on mixing of uranium and thorium with low atomic number materials such as fluorine and oxygen and also some calculated

doses, together with the occupancy assumptions on which they were based. Assumptions not given in the table may be found in Section 5.4.2.

The annual neutron dose from the uranium is accounted for with a neutron:photon dose equivalent ratio of 0.2 [0.1 x 2 based respectively on ORAUT 2004, Table 6-10 and ORAUT 2004, Section 6.6.2], which is assigned as the geometric mean of a lognormal distribution with a geometric standard deviation of 1.71, for a neutron energy range of 0.1 to 2.0 MeV as mentioned in Section 5.4.2 and as derived for Fernald (ORAUT 2004). These doses are assigned to workers who spent time in the process areas and to residue workers (see table in Section 6.0).

The thorium neutron doses in Table A-34 should be considered as appropriate for thorium worker dose reconstructions. This dose (constant distribution) is applicable only for those years or parts of years in which the thorium was processed, i.e., from after July 1955 through approximately March 1957.

7.6 OTHER DOSE CONTRIBUTIONS

7.6.1 Extremity Dose

Given the relatively small number of claims and the unknown proportion requiring calculation of extremity dose, this subject is not treated in this document. Extremity dose estimates, when necessary, will need to be formulated on a case-by-case basis. See Section 5.4.3.5 for information about individual ring dose data and interpretation.

7.6.2 Submersion Dose

Submersion dose is likely to be significant only for the skin, testes, and breast, and is not used when testes dose is used to estimate dose to the prostate. As dose reconstructions are based upon the partial film badge dose monitoring records, submersion doses are not separately calculated.

7.6.3 Shallow Dose

As stated in Section 7.1, Item 6, Mallinckrodt dose records contain “beta” values obtained by subtracting the optical density of the film behind the cadmium shield from that behind the open window. These recorded values are assumed to be equivalent to $H_p(0.07)$.

8.0 Determination of Exposures at the Mallinckrodt Downtown Site for the Post-Operational Period

As part of the process of dose reconstruction, the doses from postoperational decontamination and decommissioning activities and from postoperational work activities must be determined, insofar as they are due to residual contamination remaining after MED-AEC operations ceased. For this purpose, operations at the Mallinckrodt St. Louis main site are considered to have ended in 1957–1958 and decontamination and decommissioning (D&D) of the various buildings used for MED/AEC work to have begun in 1959 and continued through 1961; and the postoperational period to have extended through 1962. Doses from remediation activities in 1995 are to be included for workers who were exposed to radiation/radioactivity from this activity. The dates of applicability for the tables in section 6.0 overlap the periods described in this section. For most workers, individual dosimetry and work descriptions will be available to make the determination of which intake values should be used. If such information is not available, the dose reconstructor should default to the exposure that is most favorable to the claimant.

8.1 Description of the Decontamination and Demolition Work at the St. Louis Main Site, Including Health and Safety Precautions

As noted in Section 3.0, for buildings in Plants 1 and 2, decontamination had been done some years earlier. Mason 1977 states that this started in 1949; Mallinckrodt (1994) states that there were programs to do so in 1950 and 1954 and even in 1970; and ORNL (1981) mentions only the decontamination of 1948–1950. Little is known of the Plants 1 and 2 decontamination campaign because although Mason (1977) states that detailed reports of the work, including the final surveys, were prepared, these records are not available.

What is presently known is as follows. In 1946, Mallinckrodt took core samples of the subsoil under Buildings 51 and 52 in Plant 2 (MED 1946f), boring through the concrete floor, presumably at AEC's behest. This indicates that even the earliest characterization effort likely took place after the start of film badging and urinalysis; decontamination workers may have been given badges and urinalysis due to the dust and dose rate potential of the work. The decontamination that began in 1949 was performed by "Main Plant" (Plants 1 and 2) crews under directions from Mallinckrodt Uranium Division "monitors," as the health and safety specialists were called (Mason 1977). The contaminated waste material was collected and delivered to AEC, presumably in drums or boxes, while contaminated equipment was either recycled to Plant 6 or was transferred to AEC for disposal (Mason 1977). Some of the material apparently ended up buried at SLAPS. When the work was done to the satisfaction of the AEC St. Louis Area office, monitoring personnel from AEC-NYOO did a final survey of Plants 1 and 2 (Mason 1977). When AEC-NYOO was satisfied, AEC released the plants to Mallinckrodt for unrestricted use in 1951 (FUSRAP 2002; DOE 1981).

With regard to Plants 4 and 6, some preliminary work, such as some initial cleanup, was done in 1955 and in 1958–1959 (AEC 1955b; MCW 1958; MCW 1959; MCW 1961b). For example, the process equipment was thoroughly cleaned by Mallinckrodt at the time the plants went into standby, before the formal decontamination and decommissioning work began (MCW 1961b). Some initial surveys to evaluate Plants 4, 6, 6E, and 7 were then performed (AEC 1955b; MCW 1958; MCW 1959; MCW 1961b). It was determined that many buildings at the site were so contaminated that it would have been too expensive to clean them to usable levels, and they were torn down. All of the Plant 4 buildings and most of the Plant 6 buildings were torn down, but much of Plant 6E and 7 survived (Mallinckrodt 1994), amounting to about 20% of the MED/AEC plants at the site (MCW 1961b).

MCW (1961b) describes the health and safety (H&S) aspects of the decontamination and demolition (D&D) work at Plants 4, 6, 6E, and 7; this is the source of the information that follows in the rest of this section (8.1), except where another source is explicitly indicated. This work was performed by several construction and demolition companies apparently contracting directly with AEC. Mason (1977) states that one of them, or the principal one, was Arch Wrecking Company. H&S coverage was provided by Mallinckrodt, again under contract with AEC, because AEC considered that while the D&D companies were qualified to deal with normal hazards of the work, they were not experienced in the sort of chemical and radiological hazards they would encounter at the Mallinckrodt site (MCW 1961b; Mason 1977). The Mallinckrodt H&S coverage was provided by experienced full-time personnel from the Destrehan (St. Louis) site and part-time personnel from the Weldon Spring site, which was also run by Mallinckrodt (MCW 1961b; Mason 1977). Oversight was provided by AEC (MCW 1961b; Mason 1977); Mason (1977) states that only AEC made the decisions regarding items that could be released for restricted or unrestricted use. The Mallinckrodt Uranium Division performed a final decontamination survey of the four remaining plants for AEC in 1960–1961 and gave a report to AEC (Mason 1997). Only part of the report of this closeout survey is available.

A physical checkup of all prospective workers on the project was provided. This included chest x-rays (PA and lateral, using full-size 14" x 17" films) and blood tests. Approximately 125 contract workers were examined. Work clothing was provided and post-work showers were required.

Film badges were issued to all persons working in or visiting the Destrehan site during all phases of equipment removal, decontamination, and demolition. These were of the standard badge type always used at Mallinckrodt: an A. M. Samples stainless steel film badge holder with open-window and cadmium filters, using DuPont Type 552 dosimeter film; the gamma standard was a platinum-encapsulated radium needle and the beta standard was an aged natural uranium block. Film badges were processed monthly, with 80 to 124 contractor badges processed each month. Film badges worn by Mallinckrodt and AEC personnel were those provided them through the Weldon Spring facility for their work at the Destrehan site in St. Louis.

Workers were also required to submit urine samples before the start of the project, at approximately six-week intervals during the project, and at the end of the project. The regular samples were taken on Friday after work and on Monday before work. Special samples were taken from those working in high dust exposure areas or in special operations such as sandblasting contaminated tanks. Urinalysis was done at Weldon Spring as a uranium-in-urine fluorometric analysis using a Jarrell-Ash fluorimeter, sodium fluoride as the fluxing agent, and a platinum dish as the sample holder. Each urine sample was analyzed in triplicate, with a 0.1 ml aliquot used each time.

AEC, the Mallinckrodt H&S people, and the D&D companies held pre-work planning discussions to determine how to do the work on the basis of the surveys. As work began in each area, additional meetings and work area inspections were held to re-evaluate the approach for cleaning the particular area, based on how much contamination was revealed by equipment removal, how tenacious the contamination was, etc. Thus any of various decontamination and survey methods were used, depending on the characteristics of the area. Methods used for decontamination included mechanical "scratching" (to remove embedded particles on tar and gravel roofs); dry sandblasting; water blasting; shotblasting; steam cleaning with caustic-detergent additives; paint stripping; acid-detergent wash; immersion in solvents; burning; and sweeping, shoveling, and vacuum-cleaning.

Some particular operations performed and precautions taken were as follows.

1. In scrap removal and decontamination, areas were first inspected to verify that there was no gross radioactive material content and to plan the means of containment, such as removal to containers or sealing. Approximately 80% of the equipment was handled during the D&D work.

   To steam-clean scrap, surfaces were wetted using high-pressure fog or spray, to which a caustic-detergent agent had usually been added; the scrap was removed with hoists; and washing with water hoses was done, with runoff retained in the localized area. Grossly contaminated items were steam-cleaned on a grating placed over a vat, with the overflow going into the sewer through a weir. Half-face respirators were used for steam cleaning.

   Paint stripping was also done where necessary prior to steam cleaning, with the stripper being applied by brushing or dipping, often on the grating over the vat. Nickel-bearing steel pieces were cleaned in the open air by lowering the pieces into a vat containing acid-detergents and allowing them to soak for several hours; then a wire brush was used to loosen the scale and steam-cleaning was used to wash it away. Solvents (chlorinate hydrocarbons) were used on some items of low contamination level; this cleaning was done in the open air using one vat for cleaning and one for rinsing, with the solvent recirculating through a 5-micron Cuno filter and with the workers wearing face shields and gloves. After draining, the items were dried with forced air.

   For sandblasting of relatively portable items, a large walk-in hood in Building 116 of Plant 6E was reactivated. Tarpaulins were used to extend the hood area and to enclose the hood face partially. The hood exhaust was through a high-efficiency bag filter. For any item that

could not be taken to this hood, a portable canvas hood was set around the item, with ventilation provided. About 60 vessels were cleaned by dry sandblasting; the remaining several vessels (5%) that could not be cleaned to required levels had been used in the pitchblende digestion and radium extraction operations.

Insulation was burned off cable with added fuel, followed by a water rinse.

2. In building and structure decontamination, the most effective and intensive surface cleaning was done by dry or wet sandblasting. Dry sandblasting was the preferred method for removal in depth of masonry materials, paint, and encrusted surface contamination. A method called Vacu-blast, using steel shot, was also used; it provided vacuum pickup of the resulting particulates, but recovery of the shot was time consuming. Full-face air-line supply masks and hoods were required, so care was taken to locate the air pump intakes upwind of the sandblasting operation or in a dust-free area. Generated dust was recovered or washed to sumps. Air changes were minimized by controlling outside openings; it was recognized that this increased interior concentrations in the short term, but it decreased exterior concentrations and, by decreasing air velocities in the area, accelerated the settling of the dust.

   Water blasting was used on many roof structural parts and beams and was also used on other parts to remove loose particles before sandblasting. Scrubbing with a detergent and brush was also used. Sweeping, shoveling, and vacuum cleaning were generally done with respiratory protection, due to the dust.

3. In decontamination of concrete pads in the yard, dry sandblasting was done in a canvas-covered booth on wheels, which was moved by two workers to sit over the spot to be blasted. Ventilation in the booth was provided by a fan discharging through a large furnace cleaning bag; the materials collected in the bag were removed every time the bag was moved. The operator in the booth wore supplied-air respiratory protection and his helper outside wore a half-face mask. It was noted that the radiation levels of the particles collected by the fan and caught in the filter bag were higher than the levels of the coarser particles that remained on the surface being cleaned, so that capture of radioactivity appeared to be efficient.

Dust from process areas was considered to be contaminated even before sampling and thus masks at a minimum were required for all dust-producing and fume-producing operations, including torch cutting. Respirators used for radiological hazards included high-efficiency mechanical dust respirators; bottled-air-supplied masks (for short-duration entries into high-concentration atmospheres and emergency use); and airline-supplied masks and hoods. Airline-supplied masks and hoods were required for sandblasting operations. The half-face dust masks were typically the MSA Dustfoe 66.

Regarding interior air sampling, samples were taken on a routine basis during the work shift, with filters being changed at the end of each daily sampling period; also, additional samples were drawn, either in the general work area or downwind, during the particular operations listed above and during other scrap cleaning. Air sampling was done with high-volume air samplers by Gelman Hurricane, Staplex Type TF1A, or the equivalent. The collection medium was Whatman #41 or HV-70 filter paper or Gelman AM-4 membrane filters. Sampling rates averaged 5 liters of air per square centimeter of filter media. Analysis for uranium was done by acid-leaching the filter, then counting an aliquot by photofluorometric analysis.

It was estimated that about 1% of the work during equipment removal, decontamination, and demolition was in areas where the airborne uranium concentration was on the order of 10–100 MPCa; for this category, full-flow air-supply masks were used. 10% of the effort was estimated to have been

spent in areas where the concentration was 1 to 10 MPCa; for this category, personal half-face, dust-type masks were used. The rest of the work was done in areas of less than 1 MPCa. General area ("zone") concentrations during sandblasting were found to be higher around the local tarpaulin enclosures than around the fixed hood, but still below the (unspecified) AEC guide levels.

Regarding exterior air sampling, the generation of dust during demolition was at or near ground level; there were no discharge points to the upper atmosphere since the stacks were not being used. Dust sampling stations were established around the property line so as to have at least one always downwind of the work. The average of the uranium-in-air concentrations measured outside the buildings during demolition was 4×10^{-13} uCi/cc, said to be about one-tenth of the MPCa. It was observed that the gross alpha concentrations in the outside air were not much different from the uranium measurements, leading to the conclusion that radionuclides other than uranium were not present in significant quantities. The gross beta activities measured were judged to reflect the background seen at the time due to nuclear weapons testing.

The cleanup goals were surface alpha activity, 1,000 dpm/100 cm^2 average and 5,000 dpm per 100 cm^2 maximum spot; beta-gamma activity, 0.1 mrep/hr average and 1.0 mrep/hr maximum spot. This was achieved for the site and buildings, although the average beta-gamma level in some areas was somewhat above 0.1 mrep/hr. For alpha radiation surveys, the survey meters were calibrated in dpm per 100 cm^2 against normal uranium; they could be of the air ionization, proportional, or scintillation type and could detect 500–50,000 dpm per 100 cm^2, depending on type. For beta-gamma activity surveys, the survey meters were calibrated in mrad/hr or mrep/hr against normal uranium; they could be of the Geiger tube, air ionization, or scintillation type, could measure 0.3 to >1.0 mrad/hr, depending on type, and had to have a minimum unshielded probe face area of 2 square inches.

For surveys of removable contamination, for both alpha and beta-gamma, two wipe passes with half of a 4" disk of Whatman paper over 100 cm^2 were performed. All material items exceeding 50 lbs were monitored separately. Material items weighing less than 50 lbs, except for pipes, were monitored as a lot using a 20% random sample, providing the lot was from the same plant sources; if destined for uses other than smelting, they were monitored individually. Items were monitored both inside and out, for both fixed and removable contamination. If an item could not be monitored internally, it was considered contaminated. If it could be, then for beta-gamma, an item was considered to be contaminated if any surface scan reading was greater than 1.0 mrep/hr or if any smear exceeded 0.3 mrep/hr; no wipe test was done if all scan readings were less than 0.3 mrep/hr. For alpha, an item was considered to be contaminated if any surface scan reading was greater than 25,000 dpm per 100 cm^2, if the average of the surface scan readings was greater than 5,000 dpm per 100 cm^2 or if any smear exceeded 2,000 dpm per 100 cm^2; no wipe test was done if no scan reading exceeded 2,000 dpm per 100 cm^2.

Because alpha probes were too large to be put inside pipes but Geiger tubes were not, the beta-gamma measurement was used as a surrogate for the alpha measurement; this was said to be because Th-234 and Pa-234, both beta emitters, reached equilibrium with uranium in approximately 250 days. However, it was recognized that nonequilibrium conditions or the presence of other beta and gamma-emitting isotopes could significantly affect the accuracy of the estimate of inferred uranium content. Pipes were not sampled as a lot. They were cleaned and unbent or unkinked, when possible, before monitoring. The presence of visible uranium deposits automatically caused a pipe to be classified as contaminated, as did the presence of bends, elbows, valves, fittings, or crushed sections. A Thyac meter on a ten-foot pole ("ten-foot probe") was used for long sections.

Final contamination measurements are given in detail in MCW (1961a) and in summary in MCW (1961b). During the final survey, the following instruments were used: for alpha, the Eberline PAC-3G gas proportional counter and the Victoreen Model 356 ionization chamber survey meter; for beta-gamma, the Victoreen Model 389C Thyac (G-M) survey meter, background about 0.1 mrep/hr.

Calibrations were as given above. A spot sampling method was used for wall, ceilings, and beams, while a path scanning method was used for floors, yards, pads, and roofs. The alpha measurements for the roofs, however, were spot readings. During demolition and the final survey, it could be seen that some amount of residual contamination was buried at the site. This contamination was generally located adjacent to foundations, between joints and concrete floors, under storage pads, and between joints and structural steel members. This was judged to be fixed and not to present a problem.

Table A-37 shows the experience reported on a group-wise basis in MCW (1961b), including film badge, urinalysis, and air sampling results.

8.2 POST-DECONTAMINATION CONDITIONS AT THE ST. LOUIS MAIN SITE

After the decontamination of Plants 1 and 2, the plants were released to Mallinckrodt in 1951 (FUSRAP 2002; DOE 1981). No information about post-decontamination conditions for Plants 1 and 2 appears to have been produced until the ORNL survey of 1977 (ORNL 1981).

Following the decontamination or demolition of the buildings composing Plants 4, 6, 6E, and 7; post-decontamination use of the site with residual MED/AEC contamination began. This is considered to have started in 1962 and continued through 1995, the year when the Formerly Utilized Sites Remedial Action Project (FUSRAP) took over the site for final decontamination to modern standards. But in fact, release of the site to Mallinckrodt may have occurred plant by plant over 1961–1962, as suggested by Mallinckrodt (1994). A survey was done at the end of the decontamination period to demonstrate that the site was ready for release by AEC. This survey is documented in MCW (1961a).

No further survey of any of the plants to gauge the residual contamination appears to have been done in the post-D&D period until 1977, when a survey team from Oak Ridge National Laboratory did a detailed contamination, radiation, and radon survey of the site (ORNL 1981). A summary of the ORNL contamination findings is shown in Table A-38. Also shown in Table A-38 are radon concentrations reported in 1981 by ORNL (1981) and in 1986 and 1990 by Applied Nuclear Safety (1986; 1991). These show that the post-decontamination radon levels were low compared to the levels of the operational years (Table A-25).

8.3 GENERAL CONSIDERATIONS AND APPROACH FOR ST. LOUIS MAIN SITE DECONTAMINATION AND POST-DECONTAMINATION DOSE RECONSTRUCTION

As noted in Section 8.0, exposures during the D&D work appear to have been completely monitored, with film badge, urinalysis, and supplementary air sampling data being available. For individual D&D workers for which personal monitoring data are unavailable, surrogate exposure data could possibly be assembled.

An applicable note in MCW 1961b should be mentioned here with respect to surrogate data for the D&D period. MCW (1961b) stated that Mallinckrodt experience at the Destrehan plant during the operating years was that for individuals whose daily integrated particulate air exposure was 50 µg of uranium per cubic meter of air, the after-work urine samples collected on Friday typically were in the range of 0.050–0.060 mg per liter and the before-work samples collected on Monday were in the range of 0.025–0.030 mg per liter. The D&D urine samples typically were found to be about half this level. (Note that the reference gave 50 “mg” per cubic meter of air as the daily integrated exposure, but it is likely that 50 micrograms per cubic meter was meant, since that was the standard tolerance level and would have been the logical quantity to cite.)

It should be noted regarding the post-D&D years that although some employees (remaining) at the St. Louis main site may be found to have urinalysis records extending into the late 1960’s, this monitoring was apparently done for Mallinckrodt’s post-AEC work with radioactive materials (e.g., its columbium-

tantalum processing operations). These urinalysis records may be helpful in establishing the elimination curve of radioactivity from the body for anyone who (1) worked in the uranium processing operations up to 1958 and then worked in Mallinckrodt's non-AEC operations or (2) was involved in the D&D work and then continued to work at the site in Mallinckrodt's non-AEC work. Although these records may be misleading because they may indicate new intakes from non-AEC sources, they can be used to bound dose. Also, people who worked in the decontaminated and released buildings from the release date on would likely not have been covered by film badge and urinalysis programs; in any case, persons monitored after 1961 or 1962 were not monitored under the aegis of AEC. Thus bioassay or external dose information for them, if any, may not be available in dose reconstruction project files.

8.4 CALCULATION OF DECONTAMINATION AND POST-DECONTAMINATION INTERNAL AND EXTERNAL EXPOSURES FOR THE ST. LOUIS MAIN SITE WHEN INDIVIDUAL AND SURROGATE DATA ARE LACKING

To estimate doses to workers from MED/AEC contamination alone when individual data and surrogate data from records are lacking, use was made of the results of the initial and release Mallinckrodt contamination and dose rate surveys, i.e., those performed before and after the 1959–1961 decontamination (reported in MCW 1958 and MCW 1959 for before decontamination; in MCW 1961a for after). The data taken from these references and used in the calculation of exposure are shown in summary form in Table A-39; it must be stressed that these represents only a small and select subset of data from larger sets of hundreds of data points.

The RESRAD-BUILD computer code (ANL 2003) was used to calculate annual exposures from inhalation of airborne particulates and radon (and its daughters). Separate hand calculations were performed to estimate annual ingestion and external exposures.

Source terms for both types of calculations were derived from the measured data shown in Table A-39. Conservative maximum averages of surface and bulk (volume) contamination were used to produce the inhalation and radon source terms for RESRAD-BUILD and the inhalation RESRAD-BUILD results were used to produce the source term for the ingestion calculations, while the maximum (or average maximum) and typical measured dose rates from gamma and beta radiation were used in the hand calculations to estimate annual external exposures.

For RESRAD-BUILD parameters other than the source term, conservative but Mallinckrodt-suitable values were used, when they could be determined; when no specific or suitable values could be determined, conservative default values given in the RESRAD-BUILD manual (ANL 2003) or other guidance documents were used. These values are considered favorable to claimants.

8.4.1 Assumptions Made in RESRAD-BUILD and Related Internal Exposure Calculations

The principal assumptions made for the RESRAD-BUILD calculations are given below.

1. The inhalation and radon source terms were derived on the basis of the highest average surface and bulk contamination levels, respectively, in each plant, regardless of building or room location. Without regard to the actual correspondence of gamma dose rate, surface contamination, and bulk contamination levels in particular rooms, the room model (work area) was assumed to contain the highest measured average surface contamination concentration, the highest bulk contamination concentration, and the highest spot or average gamma and beta dose rates found anywhere in the respective plant (given in Table A-39). This assumption is favorable to the claimant, since there was no location where all these indicators were simultaneously at the maximum.

2. The room model was assumed to have the measured surface concentration over all wall and floor surfaces and to have the measured bulk concentration extend 6 inches into the walls and floors, which were taken to be concrete. This is reasonable because in MCW 1958 contamination in concrete was measured typically from 4 to 6 inches into the concrete (but much less in steel) and MCW (1958; 1959; 1961a) generally found the overheads to be far less contaminated than the walls and floor and so the overheads would contribute negligibly to the total.

3. Contamination was measured as gross alpha and as either total beta and total gamma separately (MCW 1958; MCW 1959) or total beta-gamma together (MCW 1961a).

4. The worker was assumed to spend his entire work time (8 hours per work day) in the room, i.e., in the most contaminated area of the given plant.

5. The worker was assumed to spend 2,000 hours per year in the one location. The takedown of a building may have been on the order of weeks and decontamination on the order of months; however, continuous decontamination and demolition work over the course of a 50-week year is assumed for such workers.

6. The room size was taken to be about 10' x 20' x 10' (3 m x 6 m x 3 m). There were many process areas that were larger, but they were often partitioned and they were undoubtedly decontaminated in sections. Thus assuming a smaller room would be conservative in terms of concentrating or confining the contamination in the ventilated space.

7. One air change per hour was assumed. While only limited information is available regarding the ventilation systems at Mallinckrodt, it was clear that the process areas had forced ventilation. These were apparently not always used during significantly dusty work, as suggested by MCW (1961b), but in those cases respirators were worn by the workers and enclosures were typically used as well. The enclosures had forced ventilation (MCW 1961b). Thus it is reasonable to assume that either the normal forced ventilation was used in the general area, in which case one air change per hour is a conservative rate, or vented enclosures were used, in which case the air change rate would have been far higher, the worker would have been wearing a respirator, and the calculated exposure would represent a marked overestimate of the likely actual exposure.

8. For the decontamination period and the post-decontamination period, the resuspension factors for the transferable contamination was assumed to be 1×10^{-4}; and 1×10^{-6}, respectively. The latter value is based on NRC (2002) and the former is taken to be a favorable to claimant value for non-respirator work, as is consistent with the discussion and tables in the RESRAD-BUILD manual (ANL 2003).

9. The deposition (settling) velocity was taken to be 0.00075 m/sec, a reasonable value for particles of 5 µm, as shown in Figure J.3 of ANL 2003.

10. The removable fraction for the decontamination period was assumed to be 30%, based on the fact that some early decontamination was done at the end of operations (e.g., rinsing out the process vessels and vacuuming the floors). The removable fraction for the inhalation dose calculation in the post-decontamination period was assumed to be 10%. This should be reasonably favorable to the claimant, since the post-decontamination period followed an extensive decontamination. Default erosion, radon emanation, and associated values were used because they are conservative and thus favorable to the claimant.

11. Three types of exposure levels were used to represent the different exposure potentials of different types of workers. "High" exposure potential represents those working in the most contaminated areas, i.e., the former process areas; such as employees performing decontamination or later working substantial periods of time in the former process areas. "Moderate" exposure potential represents those accessing the less contaminated areas or infrequently accessing the former process areas; such as employees supervising the decontamination on an intermittent basis or those having only occasional need to enter the former process areas. It would also include employees working in the former laboratories. "Low" exposure potential represents employees accessing the slightly contaminated or uncontaminated areas, such as the former office areas.

12. Since the inhalation and radon calculations did not depend on the position of the receptor in the room model and since the radionuclide proportions were taken to be the same at the beginning of the calculation, one wall of the maximally contaminated plant was modeled with the D&D sources for the surface case and similarly for the volume case; the same was done with the post-D&D sources for the surface and volume cases. The results were then ratioed to produce results for the entire wall and floor area for the various plant and exposure potential cases.

13. Because 1959–1962 data for Plants 1 and 2 were not available and because the post-D&D surface and volume data of Plants 1 and 2 were bounded by the Plants 4, 6, 6E, and/or 7 data, as shown by comparisons of the data for all the plants (ORNL 1981), it was assumed that workers in Plants 1 and 2 could be assigned the maximum post-D&D inhalation exposures for the "High" category from calculations for the other plants. Thus it was assumed that it was not necessary to create separate source terms and models for inhalation exposures for Plants 1 and 2.

14. Because 1959–1962 data for Plants 1 and 2 were not available, it was assumed to be appropriate to use the post-D&D calculated radon exposure data for the other plants. While the typical radon measurement data of Plants 1 and 2 (ORNL 1981) were in the same range as the radon measurement data for Plants 4, 6, 6E, and/or 7 (ORNL 1981), there was one high area reading in one building in Plant 1 and one in Plant 2 that far exceeded the other readings. Although the high reading may not be representative of the true exposure, it was assumed that the maximum calculated exposure for the year 1975 (the evaluated year closest to 1977, the year the ORNL survey was done) could be ratioed by the factor or difference seen in the ORNL 1981 data for the respective plants and the calculation. Also, due to the lack of variation in the calculated doses over time, it was assumed that the calculated 1962 post-D&D results, after ratioing, could be extrapolated back to 1959 for Plants 1 and 2 (since they had already been cleaned up and were not in D&D). Thus it was assumed that it was not necessary to create separate source terms and models for radon exposures for Plants 1 and 2.

8.4.2 Results of RESRAD-BUILD Calculations and Conversion to Dosimetrically Useful Quantities

For use in dose reconstruction, the inhalation and radon doses that were the results of computations in RESRAD-BUILD had to be converted back to activity units, in this case to pCi and WLM of intake, respectively. The RESRAD family of codes uses the dose conversion factors for inhalation given in Eckerman et al. (1988), as also listed in the RESRAD-BUILD manual (ANL 2003). The radon conversion is also from the RESRAD-BUILD manual (ANL 2003). Since the conversion factors are applied at the end of the RESRAD-BUILD calculation, it is appropriate to reverse the conversion using the factors. The converted results, assumed to be a constant distribution, are given in Table A-40.

Because of RESRAD-BUILD's limitation on how many yearly printouts can be made, inhalation and radon exposures were calculated for each year for the D&D period but only for the first few years and every five years thereafter for the post-D&D period. This is clearly appropriate since as the output data show, the values change little from year to year. So although multiple years may be indicated in the column headings in Table A-40, the figures below them are for each year and are not the sum for the indicated years. The results are assumed to be a constant distribution.

8.4.3 Assumptions for and Results of Ingestion Calculations

It was assumed that it was appropriate to use the annual inhalation intakes derived from the RESRAD-BUILD inhalation dose results in order to produce source terms for the calculation of bounding ingestion doses according to the methodology of NIOSH (2004).

1. The appropriate inhalation exposures in pCi that were calculated as in Section 8.3.2 from the RESRAD-BUILD results were converted from pCi per year to an effective air concentration in pCi/m^3, assuming a breathing rate of 1.2 m^3/hr and a 2,000-hour work year.

2. The air concentration in pCi/m^3 was multiplied by 0.2 to obtain the pCi ingested per day.

3. The pCi ingested per day was multiplied by 250 work days per year to obtain the pCi ingested per year.

The results, assumed to be a constant distribution, are shown in Table A-40.

8.4.4 Assumptions for and Results of External Exposure Calculations

For the external exposure calculations, separate calculations were performed for gamma and beta radiation. For Plants 4, 6, 6E, and 7, the high maximum average and typical average measured dose rate values in accessible areas were used for the "High" exposure potential case; moderate maximum average and typical average values for the "Moderate" case; and low maximum average and typical average values for the "Low" exposure case. These are defined as in Item 11 of Section 8.4.1 above.

Because exposure (dose) rates were used, the source terms did not have to be translated into activity units. However, while the pre-decontamination survey measured values were given separately as gamma and beta dose rates (MCW 1958; MCW 1959), the final release survey gave values as combined beta-gamma dose rates (MCW 1961a). These were ratioed using the pre-decontamination data in order to produce separate gamma and beta dose rates. The resulting assumed source terms are shown in Table A-39.

In the surveys, the measurement point for betas or mixed beta-gamma radiation was usually a contact or near-contact dose rate for both walls and floors, while for gammas, it was most often a contact or near-distance dose rate for walls and a three-foot measurement for floors. However, the gamma-only measurements with a microrem-reading detector was usually taken in the middle of each survey grid block. It was thus assumed that the measured beta dose rate and the measured mixed beta-gamma dose rate represented all-beta radiation emanating from a wall surface to a receptor point at 1 cm from a wall surface; similarly, the measured gamma dose rate was assumed to represent gamma radiation emanating from a wall surface to a receptor point at 1 meter from a wall surface.

A series of calculations were done to see what size of source (e.g., point, small-radius, and large-radius) was most appropriate for the measured data for each type of radiation. It was found for both beta and gamma that a large-radius source was most appropriate. For the gamma case, it was assumed that the source was of infinite radius (because it was not a very large increase from, e.g., a 4-m radius while the room could be assumed to be on the order of the room used for the RESRAD-

BUILD calculation, or about 3.3 x 6.7 meters for the wall lengths). For the beta case, it was assumed that the source was of essentially infinite radius, i.e., 8.5 m, the range of the most energetic beta emitted from the uranium-daughter source mix.

The dose rates as per Item 2 above were used to determine the areal source strength for beta and gamma separately and then the source strengths were used to calculate the dose rates at 1 foot and 1 meter for beta and at 1 cm and 1 foot for gamma. As per NIOSH direction, the respective dose rates at 1 cm were then considered to be the maximum dose rates, the dose rates at 1 foot the most likely dose rates, and the dose rates at 1 meter the minimum dose rates.

The receptor was assumed to stay in the maximum average location for his exposure potential for two hours per workday and in the typical average location for his exposure potential for six hours per workday, for a total time of 2,000 hours per year. This ignored break time, which was usually spent in areas of very low or no contamination, such as a lunchroom.

For Plants 1 and 2, there were not sufficient data to create the three dose potential categories and there were data for only the one time (i.e., the 1977 ORNL survey data point (ORNL 1981)). Thus there is only a single category of dose potential and the same measured numbers are used for all the post-D&D years. Because the figures were generally mixed beta-gamma and not separate gamma and beta exposure rates, except for one specific gamma measurement, the maximum value was assumed to represent gamma and beta in turn, except for that one gamma measurement. It should be recognized that the exposures calculated in this way for Plants 1 and 2 are likely to be extremely conservative.

Once the annual gamma doses had been calculated for each case from ambient measurement data, the doses had to be converted to photon doses to individual organs. Conversion factors from Appendix B of NIOSH (2007) were used to do this. It was assumed that for gammas, the dose was from photons of energy between 30 and 250 keV. A geometry of 50% AP and 50% ROT was assumed, as seems reasonable from Section 5.4.3.1 above. The results are shown in Table A-41 and represent a triangular dose distribution.

The beta dose rate data given in Table A-39 above was used to calculate electron doses to skin, breast, and testes. To account for attenuation by clothing (see Section 7.6.3), a factor of 0.8 was applied in the calculation of the breast and testes doses. The results are shown in Table A-42 and represent a triangular distribution.

8.5 USE OF DECONTAMINATION AND POST-DECONTAMINATION EXPOSURE DATA FOR ST. LOUIS MAIN SITE DOSE RECONSTRUCTION

As stated above, where urinalysis and film badge data are available for an individual, they should be used to determine the internal and external exposure to the individual; the methodology of Sections 6.0 and 7.0 respectively should be used as guidance for this, as appropriate. Also, for the D&D years it should be assumed that a worker had an annual x-ray (see Sections 8.1 and 7.4 above for the rationale and for guidance, respectively). It should be remembered that as noted in Section 8.1 above, some AEC and Mallinckrodt personnel film badge records for this period may be found in the Weldon Springs site set of records (and not in the Destrehan-St. Louis site set of records) because their badges were issued from Weldon Springs.

Where there is missing dose data in records, the dose reconstructor should identify surrogate worker data from records available in the dose reconstruction project, based on similarity of job title and location. Surrogate data are not provided in this TBD for this time period because of the low number of likely claimants requiring it and because records have not been located.

Where appropriate surrogate data cannot be found for the decontamination period, the data of Table A-37 may be used to provide surrogate data on a group basis. A favorable to claimant value should be assumed. In particular, the default assumption should be "High" exposure, where that choice is available. Where gaps still exist, reference can then be made to the data given in Tables A-40 through A42.

For the post-decontamination period, where individual surrogate data cannot be found, as is likely, the data of Tables A-40 through A-42 should be used. The default assumption should be "High" exposure, where that choice is available.

In both cases, in dose reconstruction using Tables A-40 through A-42, the applicable years of employment for each indicated period should be determined and then the number of years should be multiplied by the annual value.

With regard to determining the exposure potential category in Tables A-40 through A-42, it should most often be possible to determine the degree of exposure of a worker by his job title, e.g., if a worker was a secretary, then the worker should be assigned to the "low" exposure potential category. In cases where it is not possible to determine the category, then the "high" category should be used.

9.0 DOSE RECONSTRUCTION FOR ST. LOUIS AIRPORT SITE WORKERS

NIOSH has determined, and the Secretary of Health and Human Services has concurred, that reconstruction of internal dose is not feasible during the period January 3, 1947, through November 2, 1971, at the St. Louis Airport Site (HHS 2010). Where urinalysis and film badge data are available for an individual, the data should be used to determine the internal and external exposure. The data in Section 5 should be used as guidance for interpreting this data, as appropriate. This is consistent with the SEC recommendation by HHS in which it is stated:

> *Although NIOSH found that it is not possible to completely reconstruct radiation doses for the proposed class, NIOSH intends to use any internal and external monitoring data that may become available for an individual claim (and that can be interpreted using existing NIOSH dose reconstruction processes or procedures). Therefore, dose reconstructions for individuals employed at the St. Louis Airport Storage Site during the period January 3, 1947 through November 2, 1971, but who do not qualify for inclusion in the Special Exposure Cohort, may be performed using these data as appropriate.*

Medical X-ray exposure should be assigned in accordance with ORAUT-OTIB-0006.

9.1 RECONSTRUCTION OF INTERNAL EXPOSURE

Where urinalysis data are available for an individual, the data should be used in the determination of the internal exposure to the individual using the guidance in Section 5.3 and 6, as appropriate. The sections that follow provide guidance on reconstructing internal exposure for claimants during periods for which monitoring data are not available.

9.1.1 January 3, 1947–November 2, 1971

NIOSH has determined, and the Secretary of Health and Human Services has concurred, that reconstruction of internal dose is not feasible for this period. However, internal dose assessments should be completed for any claims that have individual monitoring data in accordance with the guidance in Section 5.3 and 6 for individuals employed at the St. Louis Airport Storage Site during this period, but who do not qualify for inclusion in the Special Exposure Cohort.

9.1.2 November 3, 1971–December 31, 1973

During this period, the site remained undisturbed with a layer of clean fill at the surface. With the exception of potentially increased radon levels, these site conditions provided no potential for internal exposure (NIOSH 2010b). Exposure to radon can be based on measurements conducted during the site remedial investigation (DOE 1979). The maximum recorded radon level (0.99 pCi/L) can be used along with an equilibrium factor of 0.3 to assign potential exposure to radon (Argonne 1993). This yields an annual radon exposure of 0.036 WLM.

9.1.3 January 1, 1984–December 31, 1998

For the period from 1984 to 1998, a potential internal exposure from inhalation and ingestion of airborne particulates can be based on resuspension of soil during work activities. A resuspension factor of 0.080 mg/m^3 is recommended in the *Baseline Risk Assessment* (Argonne 1993) based on a review of ambient dust concentrations in the St. Louis area. The 95% Upper Confidence Limit (UCL) soil concentration values from this same document shown in Table 9-1 can be used in this calculation.

Inhalation intake estimates were obtained by multiplying the resuspension factor mentioned above by the soil concentration, breathing rate (1.2 m^3/hr), exposure duration (hr/d), and number of work days per year. The results of this calculation, based on an exposure duration of 8 hours/day and 250 days/yr are shown below in Table 9-2. Note that ingestion intakes are included as calculated using OCAS-TIB-009 (NIOSH 2004) based on the airborne activity projected using the resuspension rate and soil concentrations cited above.

Material absorption types for uranium should be selected as either M or S, whichever is most favorable to the claimant. Material types for other radionuclides should be consistent with the selection for uranium (i.e., if type M uranium is selected, then type M should be used for the other radionuclides as well). If the ICRP (1998) assigns the nuclide to only one material type (e.g., lead is assigned only to type F), that type should be selected.

Table 9-1. Soil concentrations used to assign internal exposure.

Nuclide	Surface soil concentration (pCi/g)
U-234	39
U-235	1.79
U-238	39
Ra-226	49
Th-232	3
Th-230	670
Ac-227	45.08
Pb-210	83.30
Pa-231	49
Ra-228	0.84
Th-228	2.55

Table 9-2. Inhalation and ingestion intake quantities.

Nuclide	Inhalation	Ingestion	Inhalation	Ingestion
	pCi/yr		pCi/calendar day	
U-234	7.5E+00	1.6E-01	2.1E-02	4.3E-04
U-235	3.4E-01	7.2E-03	9.4E-04	2.0E-05
U-238	7.5E+00	1.6E-01	2.1E-02	4.3E-04

Ra-226	9.4E+00	2.0E-01	2.6E-02	5.4E-04
Th-232	5.8E-01	1.2E-02	1.6E-03	3.3E-05
Th-230	1.3E+02	2.7E+00	3.5E-01	7.3E-03
Ac-227	8.7E+00	1.8E-01	2.4E-02	4.9E-04
Pb-210	1.6E+01	3.3E-01	4.4E-02	9.1E-04
Pa-231	9.4E+00	2.0E-01	2.6E-02	5.4E-04
Ra-228	1.6E-01	3.4E-03	4.4E-04	9.2E-06
Th-228	4.9E-01	1.0E-02	1.3E-03	2.8E-05

The information on radon exposure in Section 9.1 can be used to assign radon exposure during this period as well.

9.2 RECONSTRUCTION OF EXTERNAL EXPOSURE

If external monitoring data are available for an individual, the data should be used in the determination of the external exposure using the guidance in Section 5.4 and 7, as appropriate. The sections that follow provide guidance on reconstructing external exposure for claimants for periods during which monitoring data are not available. A photon energy range of 30 - 250 keV should be used in dose reconstruction.

9.2.1 January 3, 1947–November 2, 1971

Table A-33 provides data on dose rates around the K-65 storage pad, present at SLAPS during the 1947-to-1949 period. During this period, exposures to personnel were well controlled and likely monitored (MCW 1949q). In some cases this monitoring included the use of a self-reading dosimeter for the duration of the work around the storage pad (MCW 1949p). If it is necessary to estimate external dose for an unmonitored individual during this period, consideration should be given to the fact that workers who performed operations involving K-65 materials (i.e., the warehouse/yard workers) were placed on a rigid schedule to keep them from exceeding the tolerance dose (MCW 1949p,q,s, 1950v). For example, MCW (1949s) states that a warehouse worker (including forktruck drivers) could, in 1 week, unload one ore car and make one trip to SLAPS involving K-65 handling and other duties within 50 feet of the K-65/ore pad or he could work loading one railcar with K-65 drums and make one trip to SLAPS for the above reason; an additional restriction was that no more than 2 hours per week could be spent at SLAPS, with only 1 hour in any single day actually working at the pad. Due to the high dose rates associated with the K-65 material (Table A-33 indicates a dose rate of 220 mR/hr at 2 feet from the storage shed), it is not unreasonable to assign the tolerance weekly gamma exposure for individuals working directly with the K-65 material. Weekly tolerance dose values are given in Table 5-1. For other individuals, the data in Table A-33 can be used along with estimated exposure times specific to the tasks likely to be performed. Due to the nature of the exposure from the K-65 material, it is necessary to assign only photon exposure. This is because the material was containerized and the radiation source was primarily photons.

For individuals not working around the K-65 material at SLAPS and for those working at SLAPS after the K-65 material was removed (after 1949), external dose can be estimated using dose rate surveys on the raffinate material that was received in bulk at the site. The dose rates reported in MCW (1949g) for a bulldozer cab and at waist or chest height over the aged piles were used to calculate the exposures from the piles of barium sulfate residue. In addition, the bulldozer cab appeared to be appropriate because the work appeared to consist entirely of processes such as excavation, dumping from trucks, and inspection from trucks. The maximum reported hourly dose rates from fresh raffinate at chest height and in the bulldozer cab were 33 and 2.7 mrep beta and 1.3 and 1.0 mrep gamma, respectively (MCW 1949g). This indicates that the bulldozer provided a beta reduction factor of about

10 and a gamma reduction factor of 1.3. The hourly dose rates reported for the aged barium cake heap were 10.0 mrep beta and 3 to 10.0 mrep gamma. The beta dose rate for dose reconstruction for this period was calculated by dividing 10.0 mrep/hr by the bulldozer reduction factor of 10, which resulted in a beta dose rate of 1 mrad/hr. The gamma dose rate was calculated by averaging the high and low values for the heap and dividing the result by the reduction factor of 1.3, which resulted in a gamma dose rate of 5 mR/hr. These two dose rates (1 mrad/hr beta and 5 mR/hr gamma) can be used to calculate external dose to unmonitored workers during this period. On a calendar year basis, this would be 2000 mrad and 10,000 mR for beta and gamma radiation components, respectively.

9.2.2 November 3, 1971–December 31, 1973

In 1971, the Oak Ridge Operations Office documented (Lenhard 1971) the radiation levels above the surface at SLAPS to be within the criteria previously transmitted to the St. Louis Airport Authority by the Oak Ridge Manager. The levels were characterized as "generally less than 0.05 mrad/h," and none in excess of 1 mrad/hr. The memo stated that a minimum depth of 1 ft of clean fill had been added to the SLAPS area (Lenhard 1971). External photon dose can be based on an assumed dose rate of 1 mrad/hr. On a calendar year basis, this would be 2000 mrad. Based on the thickness of the cover material, no shallow dose needs be assigned.

9.2.3 January 1, 1984–December 31, 1998

A comprehensive radiation survey was completed as part of the site remedial investigation (DOE 1979). The site was divided into 100-foot square grid blocks and gamma dose rates (at 1 m above the ground) and beta/gamma dose rates (at 1 cm above the ground) were collected within each block. In addition, a 47,500 ft^2 area with known elevated activity (due to buried material) was gridded on a finer mesh. The gamma and beta dose rates in the elevated area had maximum values of 300 μR/hr and 4.6 mrad/hr, respectively. The average values were 75 μR/hr and 1 mrad/hr, respectively. For the balance of the site, the maximum gamma and beta dose rate was 80 μR/hr and 0.34 mrad/hr, respectively. The average values were 15μ R/hr and 0.05 mrad/hr, respectively. These data can be used to estimate the external exposure during the 1984–1998 period by averaging the dose rates inside and outside the elevated area (accounting for the difference in area). Using the maximum recorded values, the weighted average beta and gamma dose rates (based on a total area of 915,000 ft^2) are calculated as 0.56 mrad/hr and 92 μR/hr, respectively. On a calendar year basis these exposure rates correspond to 1120 mrad and 184 mR for beta and gamma radiation components, respectively.

10.0 ATTRIBUTIONS AND ANNOTATIONS

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

REFERENCES

ACJ 2002
ACJ & Associates (ACJ) and the UK National Radiological Protection Board. Integrated Modules for Bioassay Analysis (IMBA), Phase 1. Software produced for NIOSH-OCAS as part of the EEOICPA Program. Version 1.0.42; November 2002.

AEC 1947a
Atomic Energy Commission (AEC). Health Hazards at Mallinckrodt Chemical Company's St. Louis Plant. Memorandum to B. S. Wolf from R. E. Hayden. 9 August 1947. [SRDB Ref ID: 10342]

AEC 1947b
Atomic Energy Commission (AEC). Health Physics Program for Plants #6 and #4. Letter to H. E. Thayer of Mallinckrodt Chemical Works from W. E. Kelley of AEC. 19 August 1947. [SRDB Ref ID: 10341]

AEC 1947c
Atomic Energy Commission (AEC). Mallinckrodt Test No. 1, July 25, 1947. Memorandum to "Dr. W. [Dr. Ernest Wollan?]" from "C. B. B.." 5 August 1947. [SRDB Ref ID: 10342]

AEC 1947d
Atomic Energy Commission (AEC). Monthly Status and Progress Report, November 1947, NYOO. Report to C. L. Wilson from W. E. Kelley. 8 December 1947. [SRDB Ref ID: 6292]

AEC 1947e
Atomic Energy Commission (AEC). Review of AEC Operations at the Mallinckrodt Chemical Company, St. Louis, Mo., July 22–25, 1947. Memorandum to B. S. Wolf from W. H. Ray (health physics consultant to AEC). 18 August 1947. [SRDB Ref ID: 10344]

AEC 1947f
Atomic Energy Commission (AEC).Visit to Mallinckrodt, St. Louis, Missouri. Memorandum to G. W. Beeler from R. V. Randall, 17 February 1947. [SRDB Ref ID: 10350]

AEC 1948a
Atomic Energy Commission (AEC). Dust Samples Taken at Mallinckrodt Chemical Works, St. Louis. Memorandum to B. S. Wolf from P. B. Klevin. 18 March 1948. [SRDB Ref ID: 10841]

AEC 1948b
Atomic Energy Commission (AEC). Dust Samples Taken at Mallinckrodt Chemical Works, St. Louis. Memorandum to B. S. Wolf from P. B. Klevin. 26 March 1948. [SRDB Ref ID: 10841]

AEC 1948c
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works' Badge System. Letter to H. E. Thayer of Mallinckrodt Chemical Works from C. L. Karl of AEC. 18 February 1948. [SRDB Ref ID: 6513]

AEC 1948d
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Proposal for Improvement in the Method of Feinc Filtrate Clarification. Memorandum to W. E. Kelley from B. S. Wolf; 24 September 1948. [SRDB Ref ID: 3872, p. 8]

AEC 1948e
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works, St. Louis, Missouri. Memorandum to F. M. Belmore from B. S. Wolf; 16 March 1948. [SRDB Ref ID: 3926]

AEC 1948f
Atomic Energy Commission (AEC). Monthly Status and Progress Report for February 1948, NYOO. Report by W. E. Kelley. 5 March 1948. [SRDB Ref ID: 6287]

AEC 1948g
Atomic Energy Commission (AEC). Monthly Status and Progress Report for March 1948, NYOO. Report by W. E. Kelley. 6 April 1948. [SRDB Ref ID: 6287]

AEC 1948h
Atomic Energy Commission (AEC). Off Area Repair of Contaminated Equipment. Letter to K. J. Caplan of Mallinckrodt Chemical Works from M. Eisenbud of AEC. 10 June 1948. [SRDB Ref ID: 11179, p. 11]

AEC 1948i
Atomic Energy Commission (AEC). Radium Standard R-515. Letter to Mallinckrodt Chemical Works from C. B. Braestrup, Consultant to AEC. 17 June 1948. [SRDB Ref ID: 11179, p. 10]

AEC 1948j
Atomic Energy Commission (AEC). Radon Samples Taken in Airport Area, Robertson, Missouri. Memorandum to B. S. Wolf from P. B. Klevin. 29 March 1948. [SRDB Ref ID: 11180]

AEC 1948k
Atomic Energy Commission. Urinalysis Procedure for Plant 6. Memorandum from B. S. Wolfe of AEC-NY to J. J. Koenig of AEC-St. Louis; 13 January 1948. [SRDB Ref ID: 16852]

AEC 1948l
Atomic Energy Commission (AEC). Occupational Exposure to Radioactive Dust. Report for Plants 4 and 6. 23 June 1948. [SRDB Ref ID: 20665]

AEC 1949–1956
Atomic Energy Commission (AEC). Health and Safety Division Sample Analysis Sheets. Radon Breath Analyses. [SRDB Ref ID: 9207]

AEC 1949a
Atomic Energy Commission (AEC). Beta Calibration of Zeus. Letter to K. J. Caplan of Mallinckrodt Chemical Works from B. S. Wolf of AEC. 9 March 1949. [SRDB Ref ID: 3904]

AEC 1949b
Atomic Energy Commission (AEC). Health Hazards in NYOO Facilities Producing and Processing Uranium. Report by the New York Operations Office Medical Division.18 April 1949. [SRDB Ref ID: 3931]

AEC 1949c
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works, Plant 4. Memorandum to F. M. Belmore from B. S. Wolf. 24 January 1949. [SRDB Ref ID: 10339]

AEC 1949d
Atomic Energy Commission (AEC). Monthly Status and Progress Report for April 1949, NYOO. Report by W. E. Kelley. 10 May 1949. [SRDB Ref ID: 6291]

AEC 1949e
Atomic Energy Commission (AEC). Monthly Status and Progress Report for February 1949, NYOO. Report by W. E. Kelley. 7 April 1949. [SRDB Ref ID: 6291]

AEC 1949f
Atomic Energy Commission (AEC). Monthly Status and Progress Report for January 1949, NYOO. Report by W. E. Kelley. 7 February 1949. [SRDB Ref ID: 6291]

AEC 1949g
Atomic Energy Commission (AEC). No subject. Letter to K. J. Caplan of Mallinckrodt Chemical Works from A. R. Piccot of AEC. 29 June 1949. [SRDB Ref ID: 10331]

AEC 1949h
Atomic Energy Commission (AEC). No subject. Letter to K. J. Caplan of Mallinckrodt Chemical Works from B. S. Wolf of AEC. 19 August 1949.

AEC 1949i
Atomic Energy Commission (AEC). No subject. Letter to K. J. Caplan of Mallinckrodt Chemical Works from H. D. Levine of AEC(?). 30 April 1948. [SRDB Ref ID: 10841, p. 62]

AEC 1949j
Atomic Energy Commission (AEC). Radon Samples, Airport Area, St. Louis. Memorandum to M. Eisenbud from W. Harris. 7 February 1949. [SRDB Ref ID: 11173, p. 6]

AEC 1949k
Atomic Energy Commission (AEC). Visit to Mallinckrodt Chemical Company January 25 and 26, 1949. Memorandum to B. S. Wolf from W. H. Ray, Health Physics Consultant to AEC. 3 February 1949. [SRDB Ref ID: 11173, p. 20]

AEC 1949l
Atomic Energy Commission (AEC). Visit to Mallinckrodt Chemical Works, St. Louis, Missouri. Memorandum to Files from H. Blatz. 1 March 1949. [SRDB Ref ID: 10337, p. 4]

AEC 1949m
Atomic Energy Commission (AEC). Waste Disposal, Mallinckrodt Plants. Memorandum to File from D. E. Lynch. 9 February 1949. [SRDB Ref ID: 11173, p. 2]

AEC 1950a
Atomic Energy Commission (AEC). An Estimate of Cumulative Multiple Exposures to Radioactive Materials, Mallinckrodt Chemical Works, Plants 4 and 6. Report covering July 1942 to October 1949. allinckrodt-5; 20 November 1950. [SRDB Ref ID: 17013]

AEC 1950b
Atomic Energy Commission (AEC). Conference on Radiation Exposure at Mallinckrodt Chemical Works. Memorandum to M. Eisenbud from W. B. Harris; 11 July 1950. [SRDB Ref ID: 4020]

AEC 1950c
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 4 Occupational Exposure to Radioactive Dust. Mallinckrodt-3; 26 July 1950. [SRDB Ref ID: 20667]

AEC 1950d
Atomic Energy Commission (AEC). Monthly Report of Field Activities, September 1950, Health and Safety Division. 19 October 1950. [SRDB Ref ID: 13632]

AEC 1950e
Atomic Energy Commission (AEC). No subject. Letter to H. E. Thayer of Mallinckrodt from M. Eisenbud of AEC. 27 October 1950. [SRDB Ref ID: 10323]

AEC 1950f
Atomic Energy Commission (AEC). No subject. Letter to K. J. Caplan of Mallinckrodt Chemical Works from H. Blatz of AEC; 7 August 1950. [SRDB Ref ID: 4020]

AEC 1950g
Atomic Energy Commission (AEC). No subject. Letter to K. J. Caplan of Mallinckrodt Chemical Works from H. Blatz of AEC; 25 August 1950. [SRDB Ref ID: 4020, p. 15]

AEC 1950h
Atomic Energy Commission (AEC). No subject. Letter to K. J. Caplan of Mallinckrodt Chemical Works from H. Blatz of AEC; 11 September 1950. [SRDB Ref ID: 4020, p. 16]

AEC 1950i
Atomic Energy Commission (AEC). No subject. Letter to K. J. Caplan of Mallinckrodt Chemical Works from H. Blatz of AEC; 12 October 1950. [SRDB Ref ID: 4020, p. 13]

AEC 1950j
Atomic Energy Commission (AEC). No subject. Letter to K. J. Caplan of Mallinckrodt Chemical Works from M. Eisenbud of AEC; 10 July 1950. [SRDB Ref ID: 3967, p. 5]

AEC 1950k
Atomic Energy Commission (AEC). No subject. Letter to M. G. Mason of Mallinckrodt Chemical Works from H. Blatz of AEC. 26 April 1950. [SRDB Ref ID: 3976, p. 8]

AEC 1950l
Atomic Energy Commission (AEC). Urinary Uranium Analyses for Mallinckrodt Chemical Works. Memorandum to M. Eisenbud from J. Harley. 7 February 1950. [SRDB Ref ID: 3976, p. 17]

AEC 1950m
Atomic Energy Commission (AEC). Visit to Mallinckrodt Chemical Works -- May 24–25, 1950. Memorandum to Files from J. A. Quigley; 6 June 1950. [SRDB Ref ID: 3967, p. 3]

AEC 1950n
Atomic Energy Commission (AEC). Visit to Mallinckrodt Chemical Works, St. Louis, Missouri, September 27 and 28, 1950. Memorandum to M. Eisenbud from H. Blatz; 3 October 1950. [SRDB Ref ID: 4020, p. 17]

AEC 1950o
Plant 6 Surveys at Mallinckrodt Chemical Works. Memorandum to W. B. Harris from A. R. Piccot. 22 September 1950. [SRDB Ref ID: 10325]

AEC 1951a
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 7 Occupational Exposure to Radioactive Dust. Mallinckrodt-7; 21 December 1951. [SRDB Ref ID: 20682]

AEC 1951b
Atomic Energy Commission (AEC). The Production of Uranium Feed Materials. Report to the Commission by the AEC Director of Production, with note by Secretary R. B. Snapp. 22 May 1951. [SRDB Ref ID: 4125]

AEC 1951c
Atomic Energy Commission (AEC). Urine Samples. Memorandum to C. L. Karl from W. B. Harris. 20 September 1951.

AEC 1952a
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 7 Occupational Exposure to Radioactive Dust. Mallinckrodt-9; 22 December 1952. [SRDB Ref ID: 20683]

AEC 1952b
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works -- Routine Inspection. Memorandum from W. B. Harris to files; 26 March 1952. [SRDB Ref ID: 9236, p. 120]

AEC 1953
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 6 -- Ore Room Addition -- Occupational Exposure to Airborne Contamination. 22 May 1953. [SRDB Ref ID: 9367]

AEC 1954–1955
Atomic Energy Commission (AEC). Health and Safety Division Sample Analysis Sheets. [SRDB Ref ID: 9436]

AEC 1954a
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 4 Occupational Exposure to Airborne Contamination. [HASL-]MCW-17; 11 February 1954. [SRDB Ref ID: 20656]

AEC 1954b
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 6 Occupational Exposure to Airborne Contamination. [HASL-]MCW-15; January 1954. [SRDB Ref ID: 20652]

AEC 1954c
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 6 Occupational Exposure to Airborne Contaminants. HASL-MCW-19; 13 August 1954. [SRDB Ref ID: 20634]

AEC 1954d
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 6E Occupational Exposure to Airborne Contamination. [HASL-]MCW-18; February 1954. [SRDB Ref ID: 20657]

AEC 1954e
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 6E Occupational Exposure to Airborne Contaminants. HASL-MCW-20; November 1954. [SRDB Ref ID: 20639]

AEC 1954f
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 7 Occupational Exposure to Airborne Contamination. [HASL-]MCW-16; February 1954. [SRDB Ref ID: 20654]

AEC 1954g
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 7 Occupational Exposure to Airborne Contamination. HASL-MCW-21; October 1954. [SRDB Ref ID: 15597]

AEC 1954h
Atomic Energy Commission (AEC). Production Requirements for the First Third of Calendar Year. Letter to C. D. Harrington of Mallinckrodt from J. P. Morgan of AEC; 9 February 1954. [SRDB Ref ID: 3835, p. 17]

AEC 1955a
Atomic Energy Commission (AEC). Code Words Used in Contract No. W-14-108-ENG-8. Memorandum to F. P. Callaghan from R. A. Foor; 25 April 1955. [SRDB Ref ID: 3835, p. 9]

AEC 1955b
Atomic Energy Commission (AEC). Design Criteria for SLPC Expansion. Memorandum to M. Eisenbud from W. B. Harris. 18 January 1955. [SRDB Ref ID: 4338, p. 4]

AEC 1955c
Atomic Energy Commission (AEC). Discussion of Ionium Toxicology at Rochester, July 14, and Mallinckrodt, July 15. Memorandum to C. L. Dunham from R. E. Albert. 19 July 1955. [SRDB Ref ID: 14037]

AEC 1955d
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 7 Occupational Exposure to Airborne Contamination. HASL-MCW-23; 27 May 1955. [SRDB Ref ID: 20641]

AEC 1955e
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plants 6E & 7E Occupational Exposure to Airborne Contamination. HASL-MCW-24; 22 June 1955. [SRDB Ref ID: 20643]

AEC 1956a
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 4 Occupational Exposure to Airborne Contamination. HASL-MCW-26; 24 September 1956. [SRDB Ref ID: 20644]

AEC 1956b
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 6 Occupational Exposure to Airborne Contamination. HASL-MCW-27; 12 October 1956. [SRDB Ref ID: 20646]

AEC 1956c
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 6E Occupational Exposure to Airborne Contamination. HASL-MCW-25; 21 September 1956. [SRDB Ref ID: 15618]

AEC 1956d
Atomic Energy Commission (AEC). Mallinckrodt Chemical Works Plant 7 and Slag Separation Plant Occupational Exposure to Airborne Contamination. HASL-MCW-28; 25 October 1956. [SRDB Ref ID: 20650]

AEC 1956e
Atomic Energy Commission (AEC). Pitchblende AM-7 Raffinate at St. Louis Airport. Memorandum from F. R. Dowling of the Feed Materials Division, Oak Ridge Operations Office, to S. W. Bistyga, Division of Raw Materials, Washington; 15 June 1956. [SRDB Ref ID: 10301]

AEC 1958
Atomic Energy Commission (AEC). Environmental Hazards Associated with the Milling of Uranium Ore. HASL-40; Revised, 14 November 1958. [SRDB Ref ID: 10733]

AEC 1959
Atomic Energy Commission (AEC)?. St. Louis Airport Site, Summary. Report regarding types and inventories of wastes stored [MO.1-2]; 11 April 1959. [SRDB Ref ID: 10300]

AEC 1960
Atomic Energy Commission (AEC). Request for Proposals for the Purchase and Removal of Uranium-Contaminated Residues. Draft: 3 June 1960. [SRDB Ref ID: 4342, p. 4]

AEC 1964
Atomic Energy Commission (AEC). Disposal of AEC Storage Site at Middlesex, New Jersey, and St. Louis Airport Site. Memorandum to F. P. Barnowski from S. R. Sapirie. 13 August 1964. [SRDB Ref ID: 6594]

AEC 1967
Atomic Energy Commission (AEC). Historical Review of the Mallinckrodt Airport Cake. Report (transmitted with cover letter from J. R. Katz, legislative assistant to Missouri Congressman Robert A. Young, to Dr. W. E. Mott, Director, Division of Environmental Control Technology, Department of Energy, 26 July 1978). 1967. [SRDB Ref ID: 9485]

AEC 1969
Atomic Energy Commission (AEC). Procedures for Monitoring Radioactivity by St. Louis Health Department of AEC Storage Site. Attachment to a letter to D. E. Leigh from S. R. Sapirie. 23 October 1969.

AEC 1972
Atomic Energy Commission (AEC). No subject. Letter to D. E. Leigh from S. R. Sapirie. 17 January 1972. [SRDB Ref ID: 6875]

AEC 1979
Atomic Energy Commission (AEC). Remedial Action Program -- St. Louis Airport. Memorandum to the AEC-NE Deputy Undersecretary from S. Meyers of the Office of Nuclear Waste Management. 13 November 1979. [SRDB Ref ID: 10244, p. 35]

Applied Nuclear Safety 1986
Applied Nuclear Safety. St. Louis Plant Rn-222 Gas Monitoring. 1986. [SRDB Ref ID: 3995]

Applied Nuclear Safety 1991
Applied Nuclear Safety. St Louis Plant Rn-222 Gas Monitoring -- 3rd Quarter 1990. Memorandum to T. Byrd from D. Soldan. 28 January 1991. [SRDB Ref ID: 3995]

ANL 2003
Argonne National Laboratory (ANL). "User's Manual for RESRAD-BUILD Version 3." Manual for code maintained by the ANL Environmental Assessment Division. June 2003.

Argonne 1993
Baseline Risk Assessment for Exposure to Contaminants at the St. Louis Site, St. Louis, Missouri, DOE/OR/23701-41.1; Environmental Assessment Division of Argonne National Laboratory (Argonne); November 1993. [SRDB Ref ID: 62450]

Bailey 1958
Bailey JC. Personnel Contamination as a Uranium Hazard. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 157-161. [SRDB Ref ID: 7886, p. 165]

Baker 1958
Baker RC. Beta Exposure during Uranium Processing. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 189-194. [SRDB Ref ID: 7886, p. 195]

Becher 1958
Becher AF. The Development of Surface Alpha Contamination Limits. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 151-156. [SRDB Ref ID: 7886, p. 159]

Bechtel 1987
Bechtel National Incorporated (Bechtel). St. Louis Airport Site Annual Site Environmental Report, Calendar Year 1986. Report prepared by Bechtel for the US Department of Energy. DOE/OR/20722-145; Draft. May 1987. [SRDB Ref ID: 10244, p. 72]

BRH 1970
Bureau of Radiological Health (BRH). Radiological Health Handbook. Revised Edition. U. S. Department of Health, Education and Welfare, Public Health Service, Food and Drug Administration. Rockville, Maryland. January 1970.

Breslin 1958
Breslin AJ. Occupational Exposures to Uranium Air Contamination in Feed Materials Production Facilities, 1948–1956. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958:10-15. [SRDB Ref ID: 7886, p. 24]

Brobst 1958
Brobst WA. Session IV Discussion. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 185. [SRDB Ref ID: 7886, p. 193]

Caplan 1952
Caplan KJ, Mason MG. Efficiency of Reverse-Jet Filters on Uranium Refining Operations. In: Proceedings of the Second AEC Air-Cleaning Seminar for AEC Personnel. Proceedings of a United States Atomic Energy Commission conference. Ames, Iowa: United States Atomic Energy Commission; WASH-149; 1952: 77-85. [SRDB Ref ID: 14849]

DOE 1979
Department of Energy (DOE). *Formerly Utilized MED/AEC Sites Remedial Action Program, Radiological Survey of the St. Louis Airport Storage Site, St. Louis, Missouri*, final report DOE/EV-0005/16 UC-70; U.S. Department of Energy (DOE); September 1979. [SRDB Ref ID: 10302]

DOE 1981
Department of Energy (DOE). US DOE/EV-0097A, excerpted in Information on FUSRAP and Surplus Facility Sites in Missouri, R. Cooperstein of US DOE-RP to J. Counts of US DOE-EP; 10 November 1981. [SRDB Ref ID: 3940]

DOE 1986
Department of Energy (DOE). Fact Sheet, DOE Remedial Action Sites in Missouri. Prepared by NE-20. 6 October 1986. [SRDB Ref ID: 10244, p. 69]

DOE 1997
Department of Energy (DOE), Office of Environmental Management. Linking Legacies: Connecting the Cold War Nuclear Weapons Production Processes to Their Environmental Consequences. DOE/EM-3019; Appendix B; January 1997. [SRDB Ref ID: 11930]

DOE 2000
Department of Energy (DOE), Richland Operations Office. Review of Generation and Flow of Recycled Uranium at Hanford. Department of Energy; DOE/RL-2000-43; 30 June 2000. [SRDB Ref ID: 4971]

DOE 2001a
Department of Energy (DOE). Guide of Good Practices for Occupational Radiation Protection in Uranium Facilities. DOE-STD-1136-2000; Change Notice No. 3. December 2001. [SRDB Ref ID: 4617]

DOE 2002
Department of Energy (DOE). Processes and Characteristics of Major Isotopes Handled at Mound. Technical Document attached to the Miamisburg Closure Project Prime Contract Solicitation. Available at http://www.ohio.doe.gov/oh_seb/does/isotopes.pdf. Accessed 28 March 2003. Issued 5 August 2002. [SRDB Ref ID: 12328]

DOE 2003
Department of Energy (DOE). Lowman Mill and Disposal Site. Fact sheet. Available at http://www.eia.doe.gov/cneaf/nuclear/page/umtra/lowman_title1.html. Accessed 17 March 2003. [SRDB Ref ID: 12329]

DOE 2004b
Formerly Used Sites Remedial Action Program (FUSRAP), Army Corps of Engineers. Re: SLAPS Status. Follow-up E-mail message from J. Mattingly of FUSRAP to J. L. Westbrook of MJW Corporation. 20 July 2004. [SRDB Ref ID: 24423]

DOE 2009
Department of Energy (DOE). Worker Advocacy Facility List, available at http://www.hss.energy.gov/healthsafety/FWSP/Advocacy/faclist/showfacility.cfm. Accessed 9 September 2010.

Dupree-Ellis 1998
Dupree-Ellis E, Watkins JP, Ingle JN, Phillips JA. External Radiation Exposure and Mortality in a Cohort of Uranium Processing Workers. US Department of Health and Human Services. 1998. [SRDB Ref ID: 3862]

Dupree-Ellis 2000
Dupree-Ellis E, Watkins J, Ingle JN, Phillips J. External Radiation Exposure and Mortality in a Cohort of Uranium Processing Workers. Am J Epidem, 152(1): 91-95; 2000. [SRDB Ref ID: 9486]

Eckerman 1988
Eckerman KF, Wolbarst AB, Richardson ACB. Limiting Values of Radionuclide Intake and Air Concentrations and Dose Conversion Factors for Inhalation, Submersion, and Ingestion -- Federal Guidance Report No. 11. Report prepared by Oak Ridge National Laboratory for the US Environmental Protection Agency. EPA-520/1-88-020; 1988. [SRDB Ref ID: 8251]

Eckerman 1993
Eckerman KF, Ryman JC. External Exposure to Radionuclides in Air, Water, and Soil, Exposure-to-Dose Coefficients for General Application -- Federal Guidance Report No. 12. Report prepared by Oak Ridge National Laboratory for the US Environmental Protection Agency. 1993. [SRDB Ref ID: 11997]

Eisenbud 1958
Eisenbud M. Discussion of Apparent Anomalies in Lung Retention of Uranium. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 212-213. [SRDB Ref ID: 7886, p. 218]

Eisenbud 1975
Eisenbud M. Early Occupational Exposure Experience with Uranium Processing. In: Occupational Health Experience with Uranium. Proceedings of a United States Atomic Energy Commission conference. Arlington, Virginia: ERDA-93; 1975: 9-24. [SRDB Ref ID: 10629]

Figgins 1962
Figgins PE and Kirby HW. Survey of Sources of Ionium (Thorium-230). AEC Research and Development Report; MLM-1349; 1962(?). [SRDB Ref ID: 14987]

Fleishman-Hilliard 1967
Fleishman-Hilliard, Inc. Fuel for the Atomic Age. Completion report on St. Louis area uranium processing operations, prepared for Mallinckrodt Chemical Works to document performance under AEC Contract No. W-14-108-Eng-8. 30 September 1967. [SRDB Ref ID: 6538]

FUSRAP undated a
Formerly Utilized Sites Remedial Action Program (FUSRAP), Army Corps of Engineers. History of Material Storage at the St. Louis Airport. Undated. [SRDB Ref ID: 10244]

FUSRAP undated b
Formerly Utilized Sites Remedial Action Program (FUSRAP), US Department of Energy. Mallinckrodt, Inc. Site description of St. Louis Downtown Site; undated. [SRDB Ref ID: 9442]

FUSRAP 2002
Formerly Utilized Sites Remedial Action Program (FUSRAP), Army Corps of Engineers. St. Louis Sites Contamination Chronology. Fact Sheet. Available at: http://www.mvs.usace.army.mil/engr/fusrap/Chronology.htm. Accessed 2 January 2003. Last update: 22 June 2002. [SRDB Ref ID: 16514]

FUSRAP 2003a
Formerly Utilized Sites Remedial Action Program (FUSRAP), Army Corps of Engineers. Original Drawing No. 2211-1, Mallinckrodt Chemical Works, St. Louis (7/24/1958); modification drawn by Woodward-Clyde Consultants for Mallinckrodt Specialty Chemicals Company (1983); provided to J. L. Westbrook of MJW Corporation by D. Chambers of FUSRAP; 2003. [SRDB Ref ID: 14996]

FUSRAP 2003b
Formerly Utilized Sites Remedial Action Program (FUSRAP), Army Corps of Engineers. Personal Communication; J. Mattingly of FUSRAP to J. L. Westbrook of MJW Corporation, based on Drawing No. 3517-2; 2003. [SRDB Ref ID: 14989]

FUSRAP 2003c
Formerly Utilized Sites Remedial Action Program (FUSRAP), Army Corps of Engineers. St. Louis Downtown Site (SLDS). Fact Sheet. Available at: http://www.mvs.usace.army.mil/engr/fusrap/SLDS.htm. Accessed 2 January 2003. [SRDB Ref ID: 12423]

FUSRAP 2004a
Formerly Used Sites Remedial Action Program (FUSRAP), Army Corps of Engineers. Re: SLAPS Status. E-mail message from J. Mattingly of FUSRAP to J. L. Westbrook of MJW Corporation. 20 July 2004. [SRDB Ref ID: 24421]

Glauberman 1958
Glauberman H, Harris WB. Air Sampling Procedures in Evaluating Exposures. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 208-211. [SRDB Ref ID: 7886]

Harris 1953
Harris WB, Mason MG. Operating Economics of Air-Cleaning Equipment Utilizing the Reverse Jet Principle. In: Proceedings of the Third AEC Air-Cleaning Conference. Proceedings of a United States Atomic Energy Commission conference. Los Alamos: United States Atomic Energy Commission; WASH-170; 1953: 68-78. [SRDB Ref ID: 14848]

Harris 1958
Harris WB. Introduction. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: vi-xi. [SRDB Ref ID: 7886, p. 10]

Harshaw 1946
Harshaw Chemical Company (Harshaw). Operating Manual [for] The Manufacture of Uranium Hexafluoride. A-4003; 22 October 1946. [SRDB Ref ID: 10484]

Heatherton 1975
Heatherton RC. Discussion accompanying his paper Occupational Health Experience with a Contractor Uranium Refinery. In: Occupational Health Experience with Uranium. Proceedings of a United States Atomic Energy Commission conference. Arlington, Virginia: ERDA-93; 1975: 148-159. [SRDB Ref ID: 4613, p. 157]

HHS 2005a
Health and Human Services (HHS). Designating a Class of Employees from the Uranium Division of Mallinckrodt Chemical Works, Destrehan Street Facility, St. Louis Missouri. April 11, 2005 (http://www.cdc.gov/niosh/ocas/pdfs/sec/malink/hhsd4248.pdf)

HHS 2005b
Health and Human Services (HHS). Designating a Class of Employees from the Uranium Division of Mallinckrodt Chemical Works, Destrehan Street Facility, St. Louis Missouri. October 14, 2005 (http://www.cdc.gov/niosh/ocas/pdfs/sec/malink/hhsd4957.pdf)

HHS 2009
Health and Human Services (HHS). Designating a Class of Employees from Mallinckrodt Chemical Co., Destrehan Street Facility, St. Louis Missouri. January 16, 2009 (http://www.cdc.gov/niosh/ocas/pdfs/sec/malink/hhsd58.pdf)

HHS 2010
Health and Human Services (HHS). Designating a Class of Employees from St. Louis Airport Storage Site, St. Louis, Missouri. July 14, 2010 (http://www.cdc.gov/niosh/ocas/pdfs/sec/slaps/slapsdes-150.pdf)

Hickey and Dupree 1984
Hickey JLS and Dupree EA Occupational Exposures of Workers to Chemicals During Uranium Processing, 1942–1966. Report prepared for Oak Ridge Associated Universities. Draft; September 1984. [SRDB Ref ID: 11664]

Hursh 1975
Hursh JB. Origin and Basis of Present Standards for Uranium. In: Occupational Health Experience with Uranium. Proceedings of a United States Atomic Energy Commission conference. Arlington, Virginia: ERDA-93; 1975: 26-34. [SRDB Ref ID: 4613, p. 35]

ICRP 1982
International Commission on Radiation Protection (ICRP). Protection of the Patient in Diagnostic Radiology. ICRP Publication 34, Annals of the ICRP, Vol. 9/2. ICRP;1982.

ICRP 1994
International Commission on Radiation Protection (ICRP). Human Respiratory Tract Model for Radiological Protection. ICRP Publication 66, Annals of the ICRP, Vol. 24/1-3. ICRP;1994.

ICRP 1995a
International Commission on Radiological Protection (ICRP). Age-Dependent Doses to Members of the Public from Intake of Radionuclides: Part 4 Inhalation Dose Coefficients. ICRP Publication 71; 1995.

ICRP 1995b
International Commission on Radiological Protection (ICRP). Dose Coefficients for Intakes of Radionuclides by Workers. A report of a task group of Committee 2 of the International Commission on Radiological Protection. ICRP Publication 68; 1995.

ICRP 1996
International Commission on Radiological Protection (ICRP). Conversion Coefficients for Use in Radiological Protection against External Radiation. ICRP Publication 74, Annals of the ICRP, Vol. 26/3. ICRP; 1996.

Kuhlman 1955
Kuhlman CW, Knecht WS, and Piper RD. Production of Ionium from a Pitchblende Residue. AEC Research and Development Report, MCW-1379; 1955. [SRDB Ref ID: 41105]

LASL 1955
Los Alamos Scientific Laboratory (LASL). The Determination of Plutonium in Urine. LASL procedure obtained by Mallinckrodt's M. G. Mason in early 1955 (apparently for potential use in urinalysis for thorium). Circa 1955. [SRDB Ref ID: 15633]

Lenhard 1971
Lenhard, J. A., 1971. "Final Radiation Survey of St. Louis Airport Site," correspondence to Thomas H. Hardin with attachment regarding procedures for monitoring radioactivity; Joseph A. Lenhard; November 17, 1971. [SRDB Ref ID: 6871]

Lippmann 1958
Lippmann M. Correlation of Urine Data and Medical Findings with Environmental Exposure to Uranium Compounds. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 103-114. [SRDB Ref ID: 7886, p. 113]

Mallinckrodt 1994
Mallinckrodt, Inc. (Mallinckrodt). Columbium-Tantalum Plant Characterization Plan. Plan for the St. Louis, Missouri plant; 19 January 1994. [SRDB Ref ID: 3840]

MCW undated
Mallinckrodt Chemical Works (MCW). Mallinckrodt Radiation Summary APR 46 TO MAR 48. Author unknown, date unknown. From electronic file "Mallinckrodt_1946.pdf" in scanned records. [SRDB Ref ID: 6586]

MCW 1946a
Mallinckrodt Chemical Works (MCW). Health Report for Plant #6. No author. Radiation summaries for 7/46 and 8/46 (direct radiation). 1946. [SRDB Ref ID: 15575, pp. 19-26]

MCW 1946b
Mallinckrodt Chemical Works (MCW). No subject. Letter to the St. Louis Area Engineer, MED, from W. F. Bale of MCW. 3 January 1946. [SRDB Ref ID: 7711, p. 3]

MCW 1946c
Mallinckrodt Chemical Works (MCW). No subject. Letter to the St. Louis Area Engineer, MED, from W. F. Bale of MCW. 16 January 1946. [SRDB Ref ID: 7711, p. 14]

MCW 1946d
Mallinckrodt Chemical Works (MCW). No subject. Letter to the St. Louis Area Engineer, MED, from W. F. Bale of MCW. 24 January 1946. [SRDB Ref ID: 7711, p. 8]

MCW 1946e
Mallinckrodt Chemical Works (MCW). No subject. Letter to the St. Louis Area Engineer, MED, from W. F. Bale of MCW. 28 January 1946. [SRDB Ref ID: 7711, p. 18]

MCW 1946f
Mallinckrodt Chemical Works (MCW). No subject. Letter to the St. Louis Area Engineer, MED, from W. F. Bale of MCW. 1 February 1946. [SRDB Ref ID: 7711, p. 21]

MCW 1946g
Mallinckrodt Chemical Works (MCW). No subject. Letter to W. D. Fleming of the Manhattan Engineer District from S. H. Anonsen of Mallinckrodt. 9 November 1946. [SRDB Ref ID: 9123]

MCW 1947
Mallinckrodt Chemical Works (MCW). Health Protection for Ore Refinery Employees. Letter to D. Duffey of AEC from H. E. Thayer of MCW. 20 March 1947. [SRDB Ref ID: 6513, p. 150]

MCW 1947–1957
Mallinckrodt Chemical Works (MCW). MZ Reports. Periodic reports of radon measurements. 1947–1957. [SRDB Ref ID: 9357, p. 36]

MCW 1948a
Mallinckrodt Chemical Works (MCW). Beta Radiation at Plant Four. Letter to J. F. Hubbell of Singmaster & Breyer from K. J. Caplan of MCW. 13 November 1948. [SRDB Ref ID: 10340]

MCW 1948b
Mallinckrodt Chemical Works (MCW). Beta Radiation Problem at Plant Four. Letter to [J. F.] Hubbell of Singmaster & Breyer from K. J. Caplan of MCW. 2 August 1948. [SRDB Ref ID: 15587]

MCW 1948c
Mallinckrodt Chemical Works (MCW). Bldg 101 Changes. Memorandum to All Personnel. About 12 April 1948. [SRDB Ref ID: 11179, p. 13]

MCW 1948d
Mallinckrodt Chemical Works (MCW). Change of Film Badge on Week Ends. Memorandum to (Guard) Chief Gerk from K. J. Caplan. 1 November 1948. [SRDB Ref ID: 6513, p. 120]

MCW 1948e
Mallinckrodt Chemical Works (MCW). Health Evaluation of the Feinc Platform Area. Letter to J. J. Koenig of the Atomic Energy Commission from K. J. Caplan of MCW. 8 October 1948. [SRDB Ref ID: 12397, p. 27]

MCW 1948f
Mallinckrodt Chemical Works (MCW). Mz Study of Centrifuge Bays, Full Drums in Bays. Memorandum to K. J. Caplan from R. E. Youtzy. 18 January 1950. [SRDB Ref ID: 12397, p. 5]

MCW 1948g
Mallinckrodt Chemical Works (MCW). No subject. Letter to R. Hayes of the University of Rochester from K. J. Caplan of Mallinckrodt. 5 June 1948. [SRDB Ref ID: 6513, p. 137]

MCW 1948h
Mallinckrodt Chemical Works (MCW). Radon and Radiation Problem of the "New" Ore Cars. Memorandum to S. H. Aronsen from K. J. Caplan. 14 October 1948. [SRDB Ref ID: 12397, p. 18]

MCW 1948i
Mallinckrodt Chemical Works (MCW). Radon Concentrations in K-65 Centrifuge Platform. Memorandum to H. E. Thayer from K. J. Caplan. 31 December 1948. [SRDB Ref ID: 12397, p. 6]

MCW 1948j
Mallinckrodt Chemical Works (MCW). Scale House and Scale House Sample Room. Memorandum to H. E. Thayer from K. J. Caplan. 12 June 1948. [SRDB Ref ID: 12369, p. 8]

MCW 1948k
Mallinckrodt Chemical Works (MCW). Weekly Badge Summary. Memorandum to H. E. Thayer et al. from K. J. Caplan. 29 June 1948. [SRDB Ref ID: 6513, p. 130]

MCW 1948l
Mallinckrodt Chemical Works (MCW). Health Physics Survey of the Airport K-65 Storage Shed and Area. No author listed. 25 February 1948. [SRDB Ref ID: 11184]

MCW 1948m
Mallinckrodt Chemical Works (MCW). Health Physics Survey of the Airport K-65 Storage Area; Gamma Summary. No author listed. 03 March 1948. [SRDB Ref ID: 11184]

MCW 1949a
Mallinckrodt Chemical Works (MCW). Beta Radiation -- Metal Plant. Letter to B. S. Wolf of AEC from H. E. Thayer of Mallinckrodt Chemical Works. 9 February 1949. [SRDB Ref ID: 10337, p. 10]

MCW 1949b
Mallinckrodt Chemical Works (MCW). Dust and HF Study in Plant 4 Furnace Room, July 1949. Memorandum to H. E. Thayer from K. J. Caplan. 21 July 1949. [SRDB Ref ID: 10912]

MCW 1949c
Mallinckrodt Chemical Works (MCW). Dust Study at MCW Plant 4, 26 January 1949. Report transmitted by memorandum, Dust Study at MCW Plant 4, to H. H. Thayer from K. J. Kaplan. 2 February 1949. [SRDB Ref ID: 11553]

MCW 1949d
Mallinckrodt Chemical Works (MCW). Dust Study of Plant Six, October-November 1948. Memo and report to H. E. Thayer from K. J. Caplan; 21 April 1949. [SRDB Ref ID: 10917]

MCW 1949e
Mallinckrodt Chemical Works (MCW). Hand Gamma Exposure at K-65 Drum Opening Operation. Memorandum to H. E. Thayer from K. J. Caplan. 31 January 1949. [SRDB Ref ID: 11173, p. 17]

MCW 1949g
Mallinckrodt Chemical Works (MCW). Health Problems at the Airport Properties. Memorandum to H. E. Thayer from K. J. Caplan. 11 August 1949.[SRDB Ref ID: 11193]

MCW 1949h
Mallinckrodt Chemical Works (MCW). New Type Plant Badge -- Plant 4 and 6. Memorandum to J. A. Gerk from K. J. Caplan. 8 April 1949. [SRDB Ref ID: 6513, p. 100]

MCW 1949i
Mallinckrodt Chemical Works (MCW). No subject. Letter to B. S. Wolf of AEC from K. J. Caplan of Mallinckrodt Chemical Works. 23 March 1949. [SRDB Ref ID: 3904, p. 23]

MCW 1949j
Mallinckrodt Chemical Works (MCW). No subject. Letter to J. H. Harley of AEC from K. J. Caplan of Mallinckrodt. 26 October 1949. [SRDB Ref ID: 3976, p. 28]

MCW 1949k
Mallinckrodt Chemical Works (MCW). No subject. Letter to M. Eisenbud of AEC from K. J. Caplan of Mallinckrodt Chemical Works. 6 May 1949. [SRDB Ref ID: 3904, p. 17]

MCW 1949l
Mallinckrodt Chemical Works (MCW). Production of Uranium Metal for Commercial Uses. Letter to W. E. Kelley of the Atomic Energy Commission from J. Fistere of Mallinckrodt; 25 April 1949. [SRDB Ref ID: 9205]

MCW 1949m
Mallinckrodt Chemical Works (MCW). Radon Concentrations in Ore Room. Memorandum to E. Miller from K. J. Caplan. 1 July 1949. [SRDB Ref ID: 12369, p. 3]

MCW 1949n
Mallinckrodt Chemical Works (MCW). Radon in General Yard Area of Plant Six. Memorandum to H. E. Thayer from K. J. Caplan. 11 August 1949. [SRDB Ref ID: 10848]

MCW 1949o
Mallinckrodt Chemical Works (MCW). Radon in Warehouse Ore Drying Oven. Memorandum to H. E. Thayer from K. J. Caplan. 4 May 1949. [SRDB Ref ID: 12397, p. 10]

MCW 1949p
Mallinckrodt Chemical Works (MCW). Revised Work Time Schedule for Warehouse Operations. Memorandum to J. Lang from K. J. Caplan. 13 July 1949. [SRDB Ref ID: 11640, p. 3]

MCW 1949q
Mallinckrodt Chemical Works (MCW). Use of Film Badge during Off-Plant Work. Memorandum to Mr. Anonsen et al. from K. J. Caplan. 21 April 1949. [SRDB Ref ID: 6513, p. 99]

MCW 1949r
Mallinckrodt Chemical Works (MCW). Use of Rubber Gaskets on K-65 Drums to Prevent Escape of Radon. Memorandum to H. E. Thayer from D. J. Huelster. 8 March 1949. [SRDB Ref ID: 12397, p. 25]

MCW 1949s
Mallinckrodt Chemical Works (MCW). Work Time Permits for Warehouse Operations. Memorandum to J. Lang from K. J. Caplan. 28 February 1949. [SRDB Ref ID: 11640, p. 2]

MCW 1950a
Mallinckrodt Chemical Works (MCW). Badge Numbers and Clock Numbers. Memorandum to M. G. Mason et al. from K. J. Caplan. 3 January 1950. [SRDB Ref ID: 6513, p. 94]

MCW 1950b
Mallinckrodt Chemical Works (MCW). Changing and Cleaning of Feinc Niagara Press Plates. Memorandum to K. J. Caplan from unspecified author. 3 May 1950. [SRDB Ref ID: 11638, p. 8]

MCW 1950c
Mallinckrodt Chemical Works (MCW). Evaluation of Past Dust Exposures at Plant 4 and Plant 6. Letter to M. Eisenbud of AEC from K. J. Caplan of Mallinckrodt. 16 January 1950. [SRDB Ref ID: 3976, p. 20]

MCW 1950d
Mallinckrodt Chemical Works (MCW). Hand Loading of Raw Ore into Secondary Elevator. Memorandum to K. J. Caplan from M. G. Mason. 23 February 1950. [SRDB Ref ID: 12368]

MCW 1950e
Mallinckrodt Chemical Works (MCW). Health Physics Program for Plant Six and Plant Four. Letter to J. J. Koenig of the Atomic Energy Commission from K. J. Caplan of MCW. 14 April 1950. [SRDB Ref ID: 10327, p. 2]

MCW 1950f
Mallinckrodt Chemical Works (MCW). Health Physics Survey of the Airport K-65 Storage Area. No author listed. 16 January 1950.

MCW 1950g
Mallinckrodt Chemical Works (MCW). Health Problems of Special Ore Inventory, February 1, 1950. Memorandum to Dr. C. M. Walden from K. J. Caplan. 10 February 1950. [SRDB Ref ID: 12397, p. 13]

MCW 1950h
Mallinckrodt Chemical Works (MCW). Investigation of Uranium Analysis Results from Barnes Hospital. Memorandum to K. J. Caplan from M. G. Mason. 2 February 1950. [SRDB Ref ID: 3967, p. 12]

MCW 1950i
Mallinckrodt Chemical Works (MCW). No subject. Letter to H. I. Blatz of AEC from K. J. Caplan of MCW. 18 January 1950. [SRDB Ref ID: 3976, p. 18]

MCW 1950k
Mallinckrodt Chemical Works (MCW). No subject. Letter to H. I. Blatz of AEC from M. G. Mason of MCW. 6 April 1950. [SRDB Ref ID: 9433, p. 63]

MCW 1950l
Mallinckrodt Chemical Works (MCW). No subject. Letter to H. I. Blatz of AEC from M. G. Mason of Mallinckrodt. 20 April 1950. [SRDB Ref ID: 3976, p. 9]

MCW 1950m
Mallinckrodt Chemical Works (MCW). No subject. Letter to J. H. Harley of AEC from K. J. Caplan of Mallinckrodt. 15 May 1950. [SRDB Ref ID: 3976, p. 3]

MCW 1950n
Mallinckrodt Chemical Works (MCW). No subject. Letter to J. J. Koenig of the Atomic Energy Commission from M. G. Mason of MCW. 16 November 1950. [SRDB Ref ID: 11661]

MCW 1950o
Mallinckrodt Chemical Works (MCW). No subject. Letter to M. Eisenbud of AEC from K. J. Caplan of MCW. 13 July 1950. [SRDB Ref ID: 4020, p. 7]

MCW 1950p
Mallinckrodt Chemical Works (MCW). No subject. Letter to M. Eisenbud of AEC from K. J. Caplan of Mallinckrodt. 18 August 1950. [SRDB Ref ID: 4020, p. 12]

MCW 1950q
Mallinckrodt Chemical Works (MCW). No subject. Letter to M. Eisenbud of AEC from K. J. Caplan of Mallinckrodt. 4 October 1950. [SRDB Ref ID: 3967, p. 10]

MCW 1950r
Mallinckrodt Chemical Works (MCW). No subject. Memorandum to K. J. Caplan from M. G. Mason. 23 February 1950. [SRDB Ref ID: 15578, p. 20]

MCW 1950s
Mallinckrodt Chemical Works (MCW). Plant Six Dust Study, August 1950. Report; 21 August 1950. [SRDB Ref ID: 9347]

MCW 1950t
Mallinckrodt Chemical Works (MCW). Radiation Exposure of MCW Plant Six Employees. Letter to C. L. Karl of the Atomic Energy Commission from H. E. Thayer of MCW. 5 May 1950. [SRDB Ref ID: 10327, p. 24]

MCW 1950u
Mallinckrodt Chemical Works (MCW). Recheck of Dust Survey in the Ore Room and Ore Room Addition. Memorandum to M. G. Mason from R. E Youtzy. 29 September 1950. [SRDB Ref ID: 10324]

MCW 1950v
Mallinckrodt Chemical Works (MCW). Revised Warehouse Work-Time Schedule. Memorandum to J. Lang from K. J. Caplan. 21 June 1950. [SRDB Ref ID: 11640, p. 5]

MCW 1950w
Mallinckrodt Chemical Works (MCW). Termination Physical Examinations for MCW Employees on AEC Project. Letter to C. L. Karl of the Atomic Energy Commission from H. E. Thayer of MCW. 17 May 1950. [SRDB Ref ID: 10327, p. 14]

MCW 1950x
Mallinckrodt Chemical Works (MCW). The Role of Primary Beta Radiation in Area Radiation Dose Rates, Plant Six Digest Area. Report by R. F. Nagel of (presumably) Mallinckrodt. 17 November 1950. [SRDB Ref ID: 9362, p. 195]

MCW 1950y
Mallinckrodt Chemical Works (MCW). Mallinckrodt Chemical Works Plant Four Dust Study. Memorandum report to K. H. Caplan from D. J. Huelster. 1 March 1950. [SRDB Ref ID: 9340]

MCW 1951a
Mallinckrodt Chemical Works (MCW). Beta and Gamma Radiation Exposure Study -- Filter Cloth Operators. Mallinckrodt report, no author listed. 13 February 1951. [SRDB Ref ID: 12391, p. 9]

MCW 1951b
Mallinckrodt Chemical Works (MCW). Dust Study of MgX Process. Memorandum to H. E. Thayer from K. J. Caplan. 12 March 1951. [SRDB Ref ID: 11638, p. 14]

MCW 1951c
Mallinckrodt Chemical Works (MCW). Health Group Monthly Report for December 1950. Memorandum and report to H. E. Thayer from K. J. Kaplan, 29 January 1951. [SRDB Ref ID: 9362]

MCW 1951d
Mallinckrodt Chemical Works (MCW). No subject. Letter to C. L. Karl of the Atomic Energy Commission from H. S. Thayer of MCW. 23 February 1951. [SRDB Ref ID: 15606, p. 6]

MCW 1951e
Mallinckrodt Chemical Works (MCW). No subject. Letter to W. B. Harris of the Atomic Energy Commission from K. J. Caplan of MCW. 19 January 1951.

MCW 1951f
Mallinckrodt Chemical Works (MCW). Badge Reading Reports. Memorandum to K. J. Caplan from E. Miller. 5 April 1951. [SRDB Ref ID: 6513, p. 83]

MCW 1951g
Mallinckrodt Chemical Works (MCW). Radiation Exposure of Feinc Cloth Operators. Memorandum to H. E. Thayer from K. J. Caplan. 5 March 1951. [SRDB Ref ID: 12391, p. 3]

MCW 1951h
Mallinckrodt Chemical Works (MCW). Radon Survey Downwind from East End of Manufacturing Building Early Monday after Week-end Shutdown. Memorandum to M. G. Mason from R. E. Youtzy. 15 January 1951. [SRDB Ref ID: 3962]

MCW 1951i
Mallinckrodt Chemical Works (MCW). Techniques of Breath Radon Sampling. Letter to W. B. Harris of the Atomic Energy Commission from K. J. Caplan of MCW. 8 January 1951.

MCW 1953a
Mallinckrodt Chemical Works (MCW). Dust Study of the New K-65 Ledoux Laboratory Installation. Memo and report to C. D. Harrington from M. G. Mason, 10 August 1953. [SRDB Ref ID: 14137]

MCW 1953b
Mallinckrodt Chemical Works (MCW). Dust Study of the K-65 Ledoux Laboratory. Report by R. E. Youtzy of MCW. June 1953. [SRDB Ref ID: 14137, p. 3]

MCW 1953c
Mallinckrodt Chemical Works (MCW). First Third 1954 Cost Estimates. Letter to J. P. Morgan of AEC from S. A. Anonsen of Mallinckrodt; 7 December 1953. [SRDB Ref ID: 3835, p. 12]

MCW 1953d
Mallinckrodt Chemical Works (MCW). Health Conditions in the MgX Area. Memorandum to E. I . Miller from M. G. Mason. 23 August 1953. [SRDB Ref ID: 11638, p. 17]

MCW 1953e
Mallinckrodt Chemical Works (MCW). Plant 4 Recast Operation. Report by J. R. Fields. Circa November 1953. [SRDB Ref ID: 12390]

MCW 1954a
Mallinckrodt Chemical Works (MCW). K-65 Sampling Lab. Report by (apparently) E. Roddy. Circa 5 January 1954. [SRDB Ref ID: 11650]

MCW 1954b
Mallinckrodt Chemical Works (MCW). Plant 6 Laboratory Sample Room Radioactive Dust Concentrations. Report by E. Roddy. 5 January 1954. [SRDB Ref ID: 11647]

MCW 1954c
Mallinckrodt Chemical Works (MCW). Plant 6. Report by (apparently) E. Roddy. 11 February 1954. [SRDB Ref ID: 11647, p. 8]

MCW 1954d
Mallinckrodt Chemical Works (MCW). Plant Four Film Badges. Memorandum to M. G. Mason et al. from J. R. Messerli. 10 September 1954. [SRDB Ref ID: 6513, p. 73]

MCW 1954e
Mallinckrodt Chemical Works (MCW). Report on Medical and Industrial Hygiene Talks Between Representatives of MCW and NYOO AEC Health Departments. Memo to C. D. Harrington from M. G. Mason, 24 February 1954. [SRDB Ref ID: 9362, p. 24]

MCW 1955a
Mallinckrodt Chemical Works (MCW). Expansion Group Personnel Film Monitors. Memorandum to J. C. Graham from M. G. Mason. 11 August 1955. [SRDB Ref ID: 6513, p. 54]

MCW 1955b
Mallinckrodt Chemical Works (MCW). Film Badge Program. Memorandum to C. D. Harrington et al. from M. G. Mason. 31 January 1955. [SRDB Ref ID: 6513, p. 65]

MCW 1955c
Mallinckrodt Chemical Works (MCW). Film Badge Reports, Mallinckrodt Chemical Works Uranium Division. Letter to H. J. McAlduff, Jr. of AEC from M. G. Mason of MCW. 5 April 1955. [SRDB Ref ID: 4338, p. 3]

MCW 1955d
Mallinckrodt Chemical Works (MCW). Health Inspection of Plant Six on October 17, 1955. Memorandum to E. L. Ball from M. G. Mason. 18 October 1955. [SRDB Ref ID: 12370]

MCW 1955e
Mallinckrodt Chemical Works (MCW). Interim Report on Film Badge Exposures in the Shotgun Laboratory. Memorandum to M. G. Mason from E. M. Wilcox. 13 October 1955. [SRDB Ref ID: 12361]

MCW 1955f
Mallinckrodt Chemical Works (MCW). Mallinckrodt Chemical Works Health Program: Policies, Status, and Summary. Report by M. G. Mason of Mallinckrodt. 21 February 1955. [SRDB Ref ID: 13180]

MCW 1955g
Mallinckrodt Chemical Works (MCW). Maximum Emergency Non-Survey Time [for] Cells, Dust Collectors, and Tanks. 1 March 1955. [SRDB Ref ID: 12369, p. 7]

MCW 1955h
Mallinckrodt Chemical Works (MCW). Meter Readings (Gamma) at Plant Monitoring Film Badge Locations. Memorandum to M. G. Mason from E. M. Wilcox. 15 December 1955. [SRDB Ref ID: 6513, p. 46]

MCW 1955i
Mallinckrodt Chemical Works (MCW). No subject. Letter to C. H. Bingham of National Lead Company of Ohio from H. A. Schlueter of MCW. 11 February 1955. [SRDB Ref ID: 6513, p. 57]

MCW 1955j
Mallinckrodt Chemical Works (MCW). Plant 6 Cloth Storage Room Radon Concentration. Memorandum to M. G. Mason from D. J. Huelster. 14 January 1955. [SRDB Ref ID: 12397, p. 3]

MCW 1955k
Mallinckrodt Chemical Works (MCW)(?). Procedure for Sampling and Determination of Radon. No author, no date. Procedure No. C-02-04-01. Circa 1955? [SRDB Ref ID: 3857]

MCW 1955l
Mallinckrodt Chemical Works (MCW). Radioactive Dust Concentrations, U-Con Grinding in the Shotgun Laboratory. Report by J. M. Horner of Mallinckrodt. 9 November 1955. [SRDB Ref ID: 12365, p. 3]

MCW 1955m
Mallinckrodt Chemical Works (MCW). Sampling of Feed Materials. Memorandum to M. G. Mason et al. from W. J. Shelley. 13 October 1955.

MCW 1955n
Mallinckrodt Chemical Works (MCW). Scalehouse Sample Room Study [of] Occupational Exposure to Radioactive Dust. Report by E. L. Roddy. 23 June 1955. [SRDB Ref ID: 12371]

MCW 1955o
Mallinckrodt Chemical Works (MCW). Investigation of Dust Problem in Cage Area of Plant 6E. Memorandum to M. G. Mason from J. W. Miller. 7 July 1955. [SRDB Ref ID: 15616, p. 4]

MCW 1955p
Mallinckrodt Chemical Works (MCW). Plant 6E Derby Brushing Station. Report by W. Linenweber. 5 December 1955. [SRDB Ref ID: 15616, p. 27]

MCW 1955q
Mallinckrodt Chemical Works (MCW). Plant 6E -- Grinding Station Radioactive Dust Concentrations. Report by J. M. Horner of MCW. 16 September 1955. [SRDB Ref ID: 15616, p. 84]

MCW 1955r
Mallinckrodt Chemical Works (MCW). Study of Plant 6 Pot Room and Orange Packing Station. Report by E. Roddy of MCW. 20 August 1955. [SRDB Ref ID: 15616, p. 46]

MCW 1955s
Mallinckrodt Chemical Works (MCW). Radiation in the Upper YM-5 Furnace Area, Plant Six-E. Report by E. L. Roddy. 11 November 1955. [SRDB Ref ID: 17244]

MCW 1956a
Mallinckrodt Chemical Works (MCW). Commentary on the Records and Reports Resulting from the Film Badge Program at Mallinckrodt Chemical Works. Memorandum to J. W. Miller from K E. Brandner. 14 June 1956. [SRDB Ref ID: 6513, p. 3]

MCW 1956b
Mallinckrodt Chemical Works (MCW). Film Badge Procedures for Transfers to Weldon Spring and New Hires for Weldon Spring. Memorandum to M. G. Mason from K E. Brandner. 26 October 1956. [SRDB Ref ID: 6513, p. 33]

MCW 1956c
Mallinckrodt Chemical Works (MCW). Hand Scooping of QM-2 from the Pots in the Pot Room at Plant Six. Report by W. F. Bushman. 29 December 1956. [SRDB Ref ID: 11641]

MCW 1956d
Mallinckrodt Chemical Works (MCW). No subject. Letter to C. H. Walden of National Lead Company of Ohio from H. J. Schaeffer of MCW. 16 April 1956. [SRDB Ref ID: 8649]

MCW 1956e
Mallinckrodt Chemical Works (MCW). No subject. Letter to L. Johnson of the US Atomic Energy Commission from F. M. Belmore of Mallinckrodt. 18 June 1956. [SRDB Ref ID: 3987, p. 23]

MCW 1956f
Mallinckrodt Chemical Works (MCW). Pickling of Hi-Carbon Scrap Metal. Memorandum to M. G. Mason from J. Horner. 23 October 1956. [SRDB Ref ID: 12365, p. 13]

MCW 1956g
Mallinckrodt Chemical Works (MCW). Quarterly Film Badge Summary -- Second Quarter, 1954. Memorandum to C. M. Harrington from R. J. Marschner. 17 August 1956. [SRDB Ref ID: 9432, p. 6]

MCW 1956h
Mallinckrodt Chemical Works (MCW). Radioactive Airborne Dust Study of Sampling of Feed Materials for Oil Analysis. Report by D. Darr of Mallinckrodt. 4 December 1956. [SRDB Ref ID: 12364]

MCW 1956i
Mallinckrodt Chemical Works (MCW). Summary of the Mallinckrodt Chemical Works Film Badge Program. Memorandum to J. W. Miller from K E. Brandner. May 1956. [SRDB Ref ID: 6513, p. 35]

MCW 1956j
Mallinckrodt Chemical Works (MCW). Weekly Report -- Radiation Exposures. Memorandum to J. W. MIller from K. E. Brandner. 17 August 1956. [SRDB Ref ID: 15571, p. 11]

MCW 1956k
Mallinckrodt Chemical Works (MCW). Radiation Exposures. Memorandum to M. G. Mason from K. E. Brandner. 21 December 1956.

MCW 1956l
Mallinckrodt Chemical Works (MCW). Radiation Study of the Shotgun Laboratory Operations, April 27, 1956. Report by E. L. Roddy. 16 May 1956. [SRDB Ref ID: 15581]

MCW 1956m
Mallinckrodt Chemical Works (MCW). Weekly Report -- Radiation Exposures. Memorandum to J. W. MIller from K. E. Brandner. 14 September 1956. [SRDB Ref ID: 15571, p. 8]

MCW 1956n
Mallinckrodt Chemical Works (MCW). Weekly Report -- Radiation Exposures. Memorandum to J. W. MIller from K. E. Brandner. 24 August 1956.

MCW 1957
Mallinckrodt Chemical Works (MCW). Radon and Gamma Levels in the Plant 6 Cloth Storage Room. Report by D. G. Darr. 18 January 1957. [SRDB Ref ID: 12397, p. 35]

MCW 1958
Mallinckrodt Chemical Works (MCW). Radioactive Contamination Survey, Mallinckrodt Chemical Works -- Uranium Division, Plant 4 Site. Report of a survey by the MCW Health and Safety Department; 26 November 1958. [SRDB Ref ID: 4023, p. 115]

MCW 1959
Mallinckrodt Chemical Works (MCW). Radioactive Contamination Survey, Mallinckrodt Chemical Works -- Uranium Division, Destrehan Plant. Report of a survey by the MCW Health and Safety Department; 24 August 1959. [SRDB Ref ID: 4023]

MCW 1961a
Mallinckrodt Chemical Works (MCW). Activity Levels, Final Radioactivity Survey, Destrehan Street Facilities. Report by the Health and Safety Department; 30 November 1961. [SRDB Ref ID: 3816]

MCW 1961b
Mallinckrodt Chemical Works (MCW). Disposal of Destrehan Street Facilities and Restoration of Site. Report of service (work) provided under contract to AEC. Circa 1961. [SRDB Ref ID: 3936]

MED undated a
Manhattan Engineer District (?) (MED). Supplemental Report To Complete Preliminary Survey of Plants Engaged in Production of Materials. Undated (1942–1944 vintage). [SRDB Ref ID: 3996]

MED undated b
Manhattan Engineer District (?) (MED).Supplementary Report on the Explosion in the Ether Building on 4 May 1946 at the New Process Plant, St. Louis Area. Memorandum from S. H. Brown of MED(?). Undated. [SRDB Ref ID: 4024, p. 34]

MED 1942
Manhattan Engineer District(?) (MED). Supplemental Report To Complete Preliminary Survey of Plants Engaged in Production of Materials. Report by H. L. Friedell of the Corps of Engineers (MED). 23 December 1942. [SRDB Ref ID: 3996]

MED 1943a
Manhattan Engineer District (?) (MED). Fire in Oxide Plant (Buildings 51 and 52). Memorandum from J. H. McKinley; 14 July 1943. [SRDB Ref ID: 4024, p. 16]

MED 1943b
Manhattan Engineer District (MED). Fire in Rubbish Truck -- Plant 4, July 3, 1943. Memorandum to the St. Louis Area Engineer from J. R. Ruhoff of the St. Louis(?) Area Engineer. 27 July 1943. [SRDB Ref ID: 4024, p. 33]

MED 1943c
Manhattan Engineer District (MED). No subject. Letter to J. A. Kyger of Mallinckrodt Chemical Works from H. L. Friedell of the Corps of Engineers. 16 June 1943. [SRDB Ref ID: 5885, p. 5]

MED 1943d
Manhattan Engineer District (MED). No title. Air sampling data sheets series for measurements taken 8 April–16 June 1943. 1943. [SRDB Ref ID: 10838]

MED 1943e
Manhattan Engineer District (MED). Radiation Hazards -- Mallinckrodt Plant. Memorandum to H. L. Friedell of the Chicago Area Engineer from T. T. Crenshaw, 22 January 1943. [SRDB Ref ID: 3996, p. 7]

MED 1944a
Manhattan Engineer District (MED). No subject. Letter to E. V. Thayer of Mallinckrodt Chemical Works from R. A. Tybout of the Corps of Engineers. 15 July 1944. [SRDB Ref ID: 9136, p. 5]

MED 1944b
Manhattan Engineer District (MED). No subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from J. L. Ferry of the Corps of Engineers. 4 March 1944. [SRDB Ref ID: 5823, p. 10]

MED 1944c
Manhattan Engineer District (MED). No subject. Letter to J. A Kyger of Mallinckrodt Chemical Works from J. L. Ferry of the Corps of Engineers. 31 March 1944. [SRDB Ref ID: 5888]

MED 1944d
Manhattan Engineer District (MED). No subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from J. L. Ferry of the Corps of Engineers. 11 May 1944. [SRDB Ref ID: 9134]

MED 1944e
Manhattan Engineer District (MED). No subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from J. L. Ferry of the Corps of Engineers. 9 June 1944. [SRDB Ref ID: 9144, p. 3]

MED 1944f
Manhattan Engineer District (MED). No subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from R. A. Tybout of MED. 26 June 1944. [SRDB Ref ID: 9144, p. 6]

MED 1944g
Manhattan Engineer District (MED). No subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from R. A. Tybout of the Corps of Engineers. 6 July 1944. [SRDB Ref ID: 9130]

MED 1944h
Manhattan Engineer District (MED). No subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from R. A. Tybout of MED. 14 July 1944. [SRDB Ref ID: 9144, p. 13]

MED 1944i
Manhattan Engineer District (MED). No subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from R. A. Tybout of MED. 21 October 1944. [SRDB Ref ID: 9136, p. 11]

MED 1944j
Manhattan Engineer District (MED). Progress Report of the Special Materials Division of the Medical Section. Memorandum to S. L. Warren from J. L. Ferry. 3 January 1944. [SRDB Ref ID 14490]

MED 1944k
Manhattan Engineer District (MED). Report of Visit to Mallinckrodt Chemical Company, 17 and 18 July 1944. Memorandum to the Madison Square Area Engineer from R. A. Tybout. 22 July 1944. [SRDB Ref ID: 5885]

MED 1944l
Manhattan Engineer District (MED). Security Survey Report, Mallinckrodt Chemical Works, St. Louis, Missouri. Memorandum to The District Engineer, Oak Ridge Office, from E. M. Velten of the St. Louis Area Office; 21 December 1944. [SRDB Ref ID: 4024]

MED 1944m
Manhattan Engineer District (MED). Visit to Mallinckrodt Chemical Company -- 20 September 1944. Memorandum to The Madison Square Area Engineer from R. A. Tybout. 22 September 1944. [SRDB Ref ID: 9144, p 27]

MED 1944n
Manhattan Engineer District (MED). Visit to Mallinckrodt Chemical Works -- 6 September 1944. Memorandum to the New York Area Engineer from R. A. Tybout. 8 September 1944. [SRDB Ref ID: 5885, p. 9]

MED 1944o
Manhattan Engineer District (MED). Safeguarding of Metal. Memorandum to the New York Area Engineer, Attn C. Hadlock, from F. Huke, 27 January 1944. [SRDB Ref ID: 3996, p. 9]

MED 1944p
Manhattan Engineer District (MED). Security Survey Report, Mallinckrodt Chemical Works. Form submitted by the Chicago Branch Intelligence Office; 22 November 1944. [SRDB Ref ID: 4024, p. 19]

MED 1945a
Manhattan Engineer District (MED). Installation of Dust Control System in the Reduction Step, Mallinckrodt Chemical Works. Memorandum to the New York Area Engineer from E. M. Velten of the St. Louis Area Engineer. 14 May 1945. [SRDB Ref ID: 3996, p. 19]

MED 1945b
Manhattan Engineer District (MED). No subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from R. A. Tybout of MED. 12 January 1945. [SRDB Ref ID: 9144, p. 10]

MED 1945c
Manhattan Engineer District (MED). No Subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from R. A. Tybout. 19 January 1945. [SRDB Ref ID: 9136, p. 22]

MED 1945d
Manhattan Engineer District (MED). No subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from R. A. Tybout of MED. 26 February 1945. [SRDB Ref ID: 9127]

MED 1945e
Manhattan Engineer District (MED). No subject. Letter to S. H. Anonsen of Mallinckrodt Chemical Works from B. J. Mears of MED. 9 July 1945. [SRDB Ref ID: 10837]

MED 1945f
Manhattan Engineer District (MED). No subject. Letter to S. H. Anonsen of Mallinckrodt Chemical Works from B. J. Mears of MED. 1 August 1945. [SRDB Ref ID: 9144, p. 15]

MED 1945g
Manhattan Engineer District (MED). No subject. Memorandum to the St. Louis Area Engineer from W. F. Bale. 15 November 1945. [SRDB Ref ID: 9144, p. 43]

MED 1945h
Manhattan Engineer District (MED). No subject. Memorandum to the St. Louis Area Engineer from W. F. Bale. 20 November 1945. [SRDB Ref ID: 9144, p. 50]

MED 1945i
Manhattan Engineer District (MED). No subject. Memorandum to the St. Louis Area Engineer from W. F. Bale. 26 November 1945. [SRDB Ref ID: 9144, p. 59

MED 1945j
Manhattan Engineer District (MED). No subject. Memorandum to the St. Louis Area Engineer from W. F. Bale. 6 December 1945. [SRDB Ref ID: 9144, p. 71]

MED 1945k
Manhattan Engineer District (MED). No subject. Memorandum to the St. Louis Area Engineer from W. F. Bale. 11 December 1945. [SRDB Ref ID: 9144, p. 65]

MED 1945l
Manhattan Engineer District (MED). No subject. Memorandum to the St. Louis Area Engineer from W. F. Bale. 21 December 1945. [SRDB Ref ID: 9146, p. 122]

MED 1945m
Manhattan Engineer District (MED). No subject. Memorandum to the St. Louis Area Engineer from W. F. Bale. 26 December 1945. [SRDB Ref ID: 9144, p. 79]

MED 1945n
Manhattan Engineer District (MED). Shipment Security Survey at Mallinckrodt Chemical Works. Memorandum to the Officer in Charge from Lt. F. W. Simmons, Shipment Security Control Officer of the Intelligence and Security Division; 15 February 1945. [SRDB Ref ID: 9161]

MED 1945o
Manhattan Engineer District (MED). No subject. Letter to S. H. Anonsen of Mallinckrodt Chemical Works from B. J. Mears of MED. 17 July 1945. [SRDB Ref ID: 13853]

MED 1946a
Manhattan (Engineer) District (MED), (Army) Corps of Engineers, Office of the District Engineer. Description of Uranium Producing Processes. Memorandum from Major W. E. Gates to the Area Engineer (Madison Square Area); 17 October 1946. [SRDB Ref ID: 9442, p. 16]

MED 1946b
Manhattan Engineer District (MED). No subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from W. F. Bale of MED. 6 February 1946. [SRDB Ref ID: 9124]

MED 1946c
Manhattan Engineer District (MED). No subject. Letter to H. E. Thayer of Mallinckrodt Chemical Works from W. F. Bale of MED. 18 November 1946. [SRDB Ref ID: 7709]

MED 1946d
Manhattan Engineer District (MED). No subject. Letter to the St. Louis Area Engineer from J. W. Howland of the Medical Corps. 9 September 1946. [SRDB Ref ID: 7711, p. 25]

MED 1946e
Manhattan Engineer District (MED). No subject. Letter to the St. Louis Area Engineer from J. W. Howland of the Medical Corps. 14 November 1946. [SRDB Ref ID: 7711, p. 29]

MED 1946f
Manhattan Engineer District (MED). Uranium Content of Subsoil of Mallinckrodt's Buildings 51 and 52 -- Former Brown Oxide Plant. Memorandum to the New York Area Engineer from E. M. Velten of the St. Louis Area Engineer. 15 October 1946. [SRDB Ref ID: 4024, p. 9]

MED 1948
Manhattan Engineer District (MED). Explosion at Mallinckrodt Chemical Works. Memorandum to K. D. Nichols from G. W. Beeler; 13 June 1948. [SRDB Ref ID: 4024, p. 15]

MED 1949a
Manhattan Engineer District (MED), Division of Technical Advisors. Uranium Metal Production. Memorandum from F. G. Stroke to Manhattan Engineer District Files; 4 March 1949. [SRDB Ref ID: 9442. p. 11]

MED 1949b
Manhattan Engineer District (MED), Division of Technical Advisors. Uranium Technology. Memorandum from F. G. Stroke to Manhattan Engineer District Files; 3 March 1949. [SRDB Ref ID: 9442, p. 12]

Mason 1958a
Mason MG. A Summary of Fifteen Years of Experience with Dust Problems in the Refining and Fabrication of Uranium. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 3-9. [SRDB Ref ID: 7886, p. 12]

Mason 1958b
Mason MG. Session I Discussion. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 47-48. [SRDB Ref ID: 7886, p. 61]

Mason 1977
M. G. Mason. History & Background Relative to the Radiological Remonitoring of Mallinckrodt by the Energy Research & Development Administration. Report prepared for Mallinckrodt, Inc. (later shared with Oak Ridge Associated Universities for use in their study of Mallinckrodt workers). 19 August 1977. [SRDB Ref ID: 15283]

Mercer 1975
Mercer TT. The Role of Particle Size in the Evaluation of Uranium Hazards. In: Occupational Health Experience with Uranium. Proceedings of a United States Atomic Energy Commission conference. Arlington, Virginia: ERDA-93; 1975: 402-418. [SRDB Ref ID: 4613, p. 410]

Miller 1953
Miller HI, Jr. Ventilation and Dust Control in Refining Uranium Ores and Concentrates. In: Proceedings of the Third AEC Air-Cleaning Conference. Proceedings of a United States Atomic Energy Commission conference. Los Alamos: United States Atomic Energy Commission; WASH-170; 1953: 79-86. [SRDB Ref ID: 14850]

Mlekodaj 2002
Mlekodaj, RL. Answer to Question #2041 Submitted to "Ask The Experts." Response posted on the Health Physics Society Web Site to a question on neutron shielding requirements for thorium fluorides. http://hps.org/publicinformation/ate/q2041.html. Accessed 3/22/2004. 1 July 2002. [SRDB Ref ID: 14855]

NBS 1941
National Bureau of Standards (NBS). Safe Handling of Radioactive Luminous Compounds. NBS Handbook H27; recommendations of the Advisory Committee on X-Ray and Radium Protection; 1941.

NCRP 1974
National Committee on Radiation Protection and Measurements (NCRP). Specification of Units for Natural Uranium and Natural Thorium. NCRP: Statement No. 4;1974. Available at: http://www.ncrp.com/4statem.htm. Accessed 6 February 2003. [SRDB Ref ID: 14851]

NCRP 1989
National Committee on Radiation Protection and Measurements (NCRP). Medical X-Ray, Electron Beam, and Gamma-Ray Protection for Energies Up to 50 MeV (Equipment, Design, Performance, and Use). NCRP 102: 1989.

Neton 2007
Neton, J. e-mail to C. Bloom. Mallinckrodt Special Exposure Cohort 1942–1948, April 20, 2007. [SRDB Ref ID: 31509]

NIOSH 2002a
National Institute for Occupational Safety and Health (NIOSH). Internal Dose Reconstruction Implementation Guideline. OCAS-IG-002. Rev. 0; August 2002.

NIOSH 2002b
National Institute for Occupational Safety and Health (NIOSH). NIOSH-Interactive RadioEpidemiological Program (NIOSH-IREP) Technical Documentation, Final Report. National Institute for Occupational Safety and Health, Office of Compensation Analysis and Support; Cincinnati, Ohio; June 2002.

NIOSH 2004
National Institute for Occupational Safety and Health (NIOSH). Estimation of Ingestion Intakes, Office of Compensation Analysis and Support, Technical Information Bulletin, OCAS-TIB-009. Rev. 0; 13 April 2004.

NIOSH 2006
National Institute for Occupational Safety and Health (NIOSH). Special External Dose Reconstruction Considerations for Mallinckrodt Workers, Office of Compensation Analysis and Support, Technical Information Bulletin, OCAS-TIB-013. Rev. 0; 26 October 2006.

NIOSH 2007
National Institute for Occupational Safety and Health (NIOSH). External Dose Reconstruction Implementation Guideline. OCAS-IG-001. Rev. 3; 21 November 2007.

NIOSH 2010a
National Institute for Occupational Safety and Health (NIOSH). Radiation Exposures Covered for Dose Reconstructions Under Part B of the Energy Employees Occupational Illness Compensation Program Act, DCAS-IG-003, Rev. 01, Division of Compensation Analysis and Support, Cincinnati, Ohio, October 2010.

NIOSH 2010b
National Institute for Occupational Safety and Health (NIOSH). Special Exposure Cohort Petition Evaluation Report Petition SEC-00150, Division of Compensation Analysis and Support, Cincinnati, Ohio.

NRC 1994
Nuclear Regulatory Commission (NRC). Inspection on September 15-16, 1993, Contemporary Metals Corporation and Continental Mining and Milling, Report No. 999-900003/93030(DRSS), Region III, Illinois. [SRDB Ref ID: 3907]

NRC 2002
Nuclear Regulatory Commission (NRC). Re-Evaluation of the Indoor Resuspension Factor for the Screening Analysis of the Building Occupancy Scenario for NRC's License Termination Rule. NUREG-1720. Draft; June 2002.

ORAU 1977
Oak Ridge Associated Universities. The MCW 10-01-49 Dust Exposure Evaluation: Facts and Recommendations about a Prime Record. Report, no author or data listed. Circa 1977. [SRDB Ref ID: 12394]

ORAU 1980a
Oak Ridge Associated Universities. MCW: Entry of the Film Badge Data onto Computer from Hard Copy Documents. No author listed. 5 August 1980. [SRDB Ref ID: 12366]

ORAU 1980b
Oak Ridge Associated Universities. Radiation Exposure Data, Mallinckrodt Uranium Division Operations, January 1947 through June 1956. Report, no author or data listed. Circa 1980. [SRDB Ref ID: 12401]

ORAU 1983a
Oak Ridge Associated Universities (ORAU). Call from Mont Mason. Memorandum of telephone conversation between Mont G. Mason of Mallinckrodt and an unnamed employee of Oak Ridge Associated Universities(?). 2 December 1983.

ORAU 1983b
Oak Ridge Associated Universities (ORAU). Interview with John Harley from NYOO's HASL Concerning Radiation Monitoring Done at HASL. Memorandum to D. Cragle, D. Robie, and W. Tankersley from E. Dupree. 25 March 1983. [SRDB Ref ID: 3890]

ORAU 1989a
Oak Ridge Associated Universities (ORAU). Mallinckrodt Chemical Works: Radon Dose Assessment. Memorandum to MCW File from J. N. Ingle. 31 October 1989. [SRDB Ref ID: 11666]

ORAU 1989b
Oak Ridge Associated Universities (ORAU). Relationship between Breath Radon Measurements and Skeletal Radium Burdens. Memorandum to P. Groer from B. Dolan. 1 September 1989. [SRDB Ref ID: 11670]

ORAU 1991
Oak Ridge Associated Universities (ORAU). Mallinckrodt Chemical Works: Four-Plant Study Classifications of Radium, Radon, and Thorium Exposure. Memorandum from J. N. Ingle to Files. 16 September 1991. [SRDB Ref ID: 12400]

ORAUT 2004
Oak Ridge Associated Universities Team (ORAUT). Technical Basis Document for the Fernald Environmental Management Project – Occupational External Dose, ORAUT-TKBS-0017-6, Rev 00, April 20, 2004.

ORAU 2005
Oak Ridge Associated Universities (ORAU). Research file of Mallinckrodt urinalysis data. Oak Ridge Institute for Science and Education data accessed 2005

ORAUT 2005a
Oak Ridge Associated Universities Team (ORAUT). Estimation of Radium-226 Activity in the Body from Breath Radon-222 Measurements. ORAUT-OTIB-0025. Rev. 0; 5 April 2005.

ORAUT 2005b
Oak Ridge Associated Universities Team (ORAUT). Weldon Spring Plant – Occupational External Dosimetry, ORAUT-TKBS-0028-6, Rev 00, June 24, 2005.

ORAUT 2005c
Oak Ridge Associated Universities Team (ORAUT). Dose Reconstruction Project for NIOSH. Technical Information Bulletin: Dose Reconstruction from Occupationally Related Diagnostic X-ray Procedures. ORAUT-OTIB-0006. Rev. 03 PC-1; 21 December 2005.

ORAUT 2006
Oak Ridge Associated Universities Team (ORAUT). Dose Reconstruction Project for NIOSH. External Dose Reconstruction. ORAUT-PROC-0006. Rev. 01; 5 June 2006.

ORAUT 2007
Oak Ridge Associated Universities Team (ORAUT). Dose Reconstruction Project for NIOSH. Internal Dose Reconstruction. ORAUT-OTIB-0060. Rev. 00; 6 February 2007.

ORNL 1979
Oak Ridge National Laboratory (ORNL). Radiological Survey of the St. Louis Airport Storage Site, St. Louis, Missouri. DOE/EV-0005/16; September 1979. [SRDB Ref ID: 10302]

ORNL 1981
Oak Ridge National Laboratory (ORNL). Radiological Survey of the Mallinckrodt Chemical Works, St. Louis, Missouri. DOE/EV-0005/27; ORNL-5715; December 1981. [SRDB Ref ID: 9154]

Raabe 2002
Raabe O. Re: Radon Limits. E-mail message to J. Skowranek regarding NBS Handbook H27; 30 October 2002. Available at http://www.vanderbilt.edu/radsafe/0210/msg00481.html. Accessed 4 April 2003. [SRDB Ref ID: 12534]

Rochester 1945
Rochester, University of (Rochester). Gamma Radiation from High-Grade My Ore. Report by W. F. Bale. 11 June 1945. [SRDB Ref ID: 7688]

Rochester 1948a
Rochester, University of (Rochester), School of Medicine and Dentistry. No subject. Letter from R. Hayes of Rochester to B. S. Wolfe of the Atomic Energy Commission. 29 January 1948. [SRDB Ref ID: 10841, p. 79]

Rochester 1948b
University of Rochester, School of Medicine and Dentistry (Rochester). No subject. Letter from R. Hayes of Rochester to Z. Atlas of the Atomic Energy Commission. 18 November 1948. [SRDB Ref ID: 10844]

Rochester 1950
Rochester, University of (Rochester), School of Medicine and Dentistry, Atomic Energy Project. No subject. Letter from R. Hayes of Rochester to J. Cherry of the Atomic Energy Commission, New York Operations Office. 12 January 1950. [SRDB Ref ID: 6585]

Ross 1975
Ross DM, Campbell CM. A Statistical Summary of ERDA Contractors' Internal Exposure Experience, 1957–1974. In: Occupational Health Experience with Uranium. Proceedings of a United States Atomic Energy Commission conference. Arlington, Virginia: ERDA-93; 1975. [SRDB Ref ID: 4613, p. 224]

Salmon and Hermann 1993
Salmon R and Hermann OW. ALPHN: A Computer Program for Calculating (α, n) Neutron Production in Canisters of High-Level Waste. ORNL/TM-12239; October 1993. [SRDB Ref ID: 14588]

Salutsky 1956
Salutsky MI, Shaver K, Elmlinger A, Curtis ML. Separation of Protactinium from Uranium Residues. J Inorg Nucl Chem, 3: 289-295; 1956. [SRDB Ref ID: 1962, p. 295]

Sanders 1975
Sanders M. Analysis of Long-Term Data on Uranium in Air at Y-12. In: Occupational Health Experience with Uranium. Proceedings of a United States Atomic Energy Commission conference. Arlington, Virginia: ERDA-93; 1975: 365-386. [SRDB Ref ID: 4613, p. 373]

Schwendiman 1975
Schwendiman LC, Andersen BV, Selby JM, Waite DA. Considerations in Developing a Work Place Standard for Sampling Airborne Uranium. In: Occupational Health Experience with Uranium. Proceedings of a United States Atomic Energy Commission conference. Arlington, Virginia: ERDA-93; 1975: 420-435 [SRDB Ref ID: 4613, p. 428].

Shleien 1992
Shleien B. The Health Physics and Radiological Health Handbook. Revised Edition. Silver Spring, Maryland: Scinta, Inc.; 1992.

Srivastava 1986
Srivastava GK, Raghavayya M, Kotrappa P, and Somasundaram S. Radium-226 Body Burden in U Miners by Measurement of Rn in Exhaled Breath. Health Physics, 50(2): 217-22; 1986.

Utnage 1958a
Utnage WL. Is There Significant Correlation between Alpha Surface Contamination and Air Concentration of Radioactive Particles in a Uranium Feed Materials Plant. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 147-161. [SRDB Ref ID: 7886, p. 155]

Utnage 1958b
Utnage WL. Laundry Operations in a Uranium Feed Materials Plant. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 168-171. [SRDB Ref ID: 7886, p. 155], p. 176

Turcic 2005
Turcic, P. M. letter to L. J. Elliot (Director, Office of Compensation Analysis and Support). Return of All Mallinckrodt Cases for New SEC Class 1942–1948. Office of Workers' Compensation Programs. Division of Energy Employees Occupational Illness Compensation. Department of Labor. June 17, 2005. (http://www.cdc.gov/niosh/ocas/pdfs/sec/malink/dl061705.pdf)

Watson 1994
Watson JE, Wood JL, Tankersley WG, West CM. Estimation of Radiation Doses for Workers Without Monitoring Data for Retrospective Epidemiologic Studies. Health Physics, 67(4): 402-405; 1994. [SRDB Ref ID: 8601]

Weinstein 1958
Weinstein MS. Environmental Contamination. In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: United States Atomic Energy Commission; HASL-58; 1958: 180-184. [SRDB Ref ID: 7886]

Wilde 1975
Wilde RM. "Occupational Health Experience with Uranium in Ore Processing Mills," Occupational Health Experience with Uranium. Proceedings of a United States Atomic Energy Commission conference. Arlington, Virginia: ERDA-93; 1975:142-146. [SRDB Ref ID: 4613, p. 151]

Wilson 1958
Wilson, RH. The Hanford Uranium Bio-Assay Program In: Symposium on Occupational Health Experience and Practices in the Uranium Industry. Proceedings of a United States Atomic Energy Commission conference. New York City: U. S. Atomic Energy Commission; HASL-58; 1958. [SRDB Ref ID: 7886, p 89]

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Table A-1. Plants and buildings used at the St. Louis Downtown Site for MED/AEC uranium processing work.

Plant	Building	Process, function, or area	Notes
1	25	Lab quality control, R&D	Project offices
1	Alley south of 25	Pitchblende R&D extraction	
1	K1E	Temporary pitchblende ore pilot plant	For MED/AEC work, used only from 1944–1946
1	A	General plant maintenance (for all of Mallinckrodt)	
1	P	Engineering Department (for all of Mallinckrodt)	
1	X	Locker room	
1	Z	Company headquarters; administrative offices	Administrative headquarters for MED work until Plant 6 began operating in 1946
2	38B	Personnel change house	FUSRAP(2003a) says 38B, but ORAU (Mason 1977) says 38A
2	40	Temporary storage of residues	Temporary storage of residues
2	45, 45A	Warehouse	Raw, in-process, and finished materials
2	47	Warehouse	Raw, in-process, and finished materials
2	50	Feed material and product storage, UF_4 experiments, mechanical repairs, tank storage, other	Ore concentrates, UO_3 product; tanks of stored process liquids; UF_4 experiments performed in the “sulfur burner room”
2	51	U_3O_8 feed preparation (nitric acid dissolution), recovery, other	
2	51A	Denitration of UNH to UO_3, reduction of UO_3 to UO_2	
2	51X	Temporary canopy enclosure outside for extraction of pitchblende liquor	
2	52	Ether extraction to produce uranyl nitrate hexahydrate (UNH)	
2	52A	Miscellaneous(?) re-extraction	Pilot plant for countercurrent ether extraction
2	52X	Canopy, temporary structure	
2	55	Shotgun lab -- temporary structure	This was a special restricted area because of the 100-mg RaBe source used in the neutron absorption testing
4	400	Production of UF_4, U metal; slag handling, production control laboratory, changehouse; metals pilot plant	UF_4 product, U recast
4	400, 401	1^{st} floor: casting pilot plant, slag pilot plant, dingot works	In casting pilot plant: lead man office and saw room; in slag pilot plant, roll mill, chip burning area, and Hoffman cleanup area; in dingot works, blender, saw area, bomb air cooler, bomb cooling room, breakout grate, furnace tank pit, and furnace residue pit

Plant	Building	Process, function, or area	Notes
4	400	2nd floor: bomb step area; casting area, laboratory area, ceramic pilot plant	In bomb step area: blending and bomb areas, KB-2 area, bomb tramrail
4	401, 401A	Maintenance, metal storage, and UF_4 pilot plant	
4	402	Warehouse center	
4	403	Machine shop	
4	404	Storage room	
4	405	Part of the lathe and forging area in 408?	
4	406 (A&B)	Magnesium storage	
4	407?	?	
4	408	1st floor: lathe & forging areas; storage of slag, dolomite, KOH, NH3, HF, etc.	Pilot Lab; furnace; forge press; manipulator; lathe area; slag crushing area; salt bath and quench tanks; slag storage
4	400 Yards	Machine shop (403) yard; guard house and guard tower; incinerator	There were also various production dust collectors in these yards outside 406B and 407
6	100	Electrical substation	Shed attached to the west end of the building was used for storage of uranium materials.
6	101	Research laboratory, decontamination(?) room, receiving offices	Also production offices, shipping & receiving, and decontamination (DX) facilities. Lab had hoods, the DX facility a hood.
6	102	Analytical Laboratory (main chemical lab), Control Lab, Metal Lab, Sample Prep Lab; possibly an additional R&D lab; lab offices	The Control Lab had a hood. There was a dust collector on the roof.
6	103	Refrigeration (air conditioning), spectrographic laboratory	
6	104	Main refinery building: ore to UO_3 to UO_2	Entire building housed wet processes. Barium sulfate cake, raffinate cake were residue products
6	104	Ore Room digest area, feed makeup area, M-20 area, C-3 area	Found to be the most contaminated areas in 1958 due to use when pitchblende was main feed; beta, gamma especially high in Ore Room and M-20 areas (latter up to 12 mr/hr)
6	104	Raffinate area, wet pilot plant, ether pilot plant, pot room, pot room addition, QM-2 packaging, NA recovery area, MGX area	Housed the continuous process equipment
6	104A, AA	Main refinery: ore handling and milling	Pitchblende ore (104A)
6	104B	Main refinery: pilot plant area	Pitchblende
6	105	Main refinery: the " Ether House"	Extraction
6	106	Nitric acid recovery	

Plant	Building	Process, function, or area	Notes
6	106A	Nitric acid recovery	
6	107	Nitric acid recovery, tank farm pump house	
6	108	Shotgun sample preparation lab	Superseded by lab in Building 102? ["Old shotgun lab"]
6	109	Acid unloading station	Includes 109, 109A, 109B
6	110	Main warehouse for bagged goods, storage of pitchblende ore and ore concentrates, UO_3 product	Pitchblende ore, ore concentrate, UO_3 and UO_2 product. Was the receiving warehouse for pitchblende ore arriving by rail. Found to be moderately and uniformly contaminated (including gamma) in 1958 due to trackage, especially on loading platforms.
6	110A	Main warehouse, part used as Ledoux Lab	
6	110B	Automotive repair	
6	111	Sample preparation and LeDoux Lab, north end; maintenance shops in the south end	The Ledoux Lab included the main lab room, the oven room, the weighing room, and the dry box room; in these areas were a muffle furnace and dry boxes. It was found to be contaminated in 1958; the main(?) room had a walk-in hood behind which the floor was heavily contaminated.
6	112	Administration (MCW and AEC offices), Health Laboratory, dispensary; maintenance shop, instrument shop, maintenance stores	This building was 50% offices, uncontaminated, and 50% storeroom and shops, both handling some contaminated materials.
6	113	Paint shed	
6	114	Scale house, temporary storage of residues	For temporary storage of residues, including radium-bearing cake (K-65) in drums. Had interior sampling bays and an exterior conveyor. Found to be heavily contaminated in 1958, including some gamma.
6	115	Boiler house and steam plant	
6	119	Steam plant, maintenance storage shed	
6	120 & 121	U metal dissolver (120) with digest and recovery area (pitchblende); pickling building (121)	120 had a sump; 121 had a derby conveyor and pickler. Found to be heavily contaminated in 1958.
6	122	Slag recovery pilot plant	Found to have loose contamination
6	123	Ammonia & dissociator	Ammonia cracking?
6	101 Yard	Loading docks	Used by Shipping & Receiving.
6	104 Yard		Found to be contaminated in 1958. Gamma background from M-20 cell block.
6	105 Yard	Outdoor tanks	Concrete, asphalt, gravel all found to be contaminated in 1958. Tanks, sump in the M-70 pit. Hole by 105 door due to cave-in caused by sump leakage.

Plant	Building	Process, function, or area	Notes
6	106 Yard		Found to be contaminated in 1958.
6	NW Yard	Storage yard	Found to be contaminated in 1958, including some high gamma spots.
6	108 Yard	Laboratory site	A laboratory on this site was demolished in 1955, except for the concrete floor. Materials handled contained radium.
6	110 Yard	Boxcar cleaning site	Boxcars that contained pitchblende ore containers were cleaned on the gravel-soil part of this yard; there was a 1.5 mR/hr hot spot between the rails and a 5 mR/hr hot spot under the shipping dock in 1958. A sewer ran under or over the yard.
6	111 Yard		Found to be contaminated in 1958. A sewer ran through the yard.
6	112 Yard	Concrete between 112 and 117	The main gate opened into this yard, as did the dispensary doors and a change room. Some contamination due to trackage
6	115 Yard	Concrete adjacent to the boiler house	Dust collector and incinerator created heavy contamination in yard. An ash silo and the Hoffman drumming station were located here.
6	116 Yard	Storage area	Storage of feed materials. Some contamination, including gamma.
6E	116 (including 116-1 and 116-2)	UF_4-to-metal facility (116-1?) with various operating areas and a maintenance shop, residue recovery area, warehouses (116-1 and 116-2), graphite machining, foremen's office (116-2), smoking area	Used for manufacturing UF_4 to metal: reduction furnace area (~ 18 furnaces); casting furnace area (with multiple furnaces, 4 hacksaws, Kinney pumps, a crushing station, toilet area); breakout area (with sump, slag conveyor, chipping station, furnace rebuilding station, shop); jolter area (with jolter platform); filling area; center aisle area (with ingot mold station?), generator room, and ingot storage area (with both boxed and finished ingot storage, "pickled derby" shipping enclosure, ingot room with ingot table). Maintenance shop. "F" machine area (2 machines). UF_4 slag residues handled in residue recovery area, which included sump, filter, and recovery pit. Warehouse (blender hopper room, mold outgassing room(?), mold furnace room, loading platforms).
6E	116B	Electrical substation	
6E	116C	Slag (recycle) building	(Magnesium fluoride) Slag handling, grinding, and packaging. Had conveyor in (to?) packaging room; ball mill; rolling mill; elevator to C-3, hopper. Light dust contamination found in 1958.
6E	117 (including 117-1 and 117-2)	Service building: clean locker room (117-1), regulated locker room (117-2), laundry (117-2), security office (117-1), cafeteria (117-2), other offices and support services	The laundry and the regulated locker room were the only areas found in 1958 to be contaminated. In laundry: lobby, laundry storage room, and small and large sewers in the laundry pit. Locker rooms: turnstiles. Clean locker room: clean clothes room.

Plant	Building	Process, function, or area	Notes
7	700	Warehouse, safety office, electrical and carpenter shops, temporary slug machining (fabrication) plant	The slug machining area had lathes and an inspection area. 700 was found in 1958 to be lightly contaminated except for the moderately contaminated slug machining area.
7	701	Slag recovery plant (aka Slag Separation Plant or Slag Processing Plant)	Found in 1958 to be heavily contaminated with loose material, especially with high beta, due to substantial amounts of "aged uranium." It had "Wilfey" tables, pumps, tanks, a ball mill, drum washer w/elevator and sump, and a filter.
7	703	Hydrofluoric acid vaults, HF tank farm	
7	704	HF feed and recovery, HF offgas treatment	704 had sumps, tanks, and a scrubber. 704-707 were all attached and were all found in 1958 to be moderately contaminated.
7	705	Main processing area for manufacturing UO_2, UF_4: packaging station area, maintenance shop, reactor area	Reactor area had UF_4 product hoppers, hydraulic pumps, and access platforms. There were a UO_3 feed station, a Hapman UO_3 conveyor, blenders, a UO_2($_3$?) packaging station(s), and a screw storage area. Localized contamination was found in 1958 around operating stations; green salt was caked on the roof. See also 704.
7	706	Warehouse for U materials (UO_2, UO_3, UF_4)	Had shipping platform. See also 704.
7	707	Ammonia cracking building (manufacturing H_2 and N_2 from NH_3)	See also 704.
7	708	Magnesium storage and packaging building	
7	709	HF refrigeration equipment and pump house	Contained refrigeration equipment for the GS(?) pit
7	710	NH_3 tank farm and pump house, ammonia storage	
7	711	Storage shed	
7 (7E)	712	Minor elements production facility	This had a change room, a "cold" (nonradioactive) lab, a "hot" lab (with hoods and a sump), and a production room (with pumper-decanters, mixer-settlers, settling tank, packaging station, sumps). It was used to process residues to obtain an ionium (Th-230) concentrate. Found in 1958 to have high levels of contamination.
7	SW Yard	Storage of drums, feed materials, and contaminated equipment	Moderate contamination was found in 1958, but it was highest where spills had occurred or equipment was stored.
7	700-701 Yard	Secondary gates in 700 yard; conveyor in 701 yard	Found in 1958 to have visible fixed contamination, higher near 701.
7	703(?), 704-707, and 711 Yards	Storage of contaminated equipment in all yards; Th-230 liquor drainage area and boxcar cleaning area in 711 yard	Screws and tubes were stored in the 704-707 yards. Yards were primarily concrete around Plant 7, except gravel around 703. Highest contamination (both alpha and gamma) found in these yards in 1958 was around 711: in 711 yard, Th-230 liquor was drained to the area by the RR tracks.

Plant	Building	Process, function, or area	Notes
7	706 Yard		UF_4, scrap (??)
7	712 Yard	Mostly open storage, probably of contaminated scrap	Had lean-tos and an open storage bin. There was also a tank farm on a concrete pad at the south end of 712. The concrete in this yard was found to be heavily contaminated in 1958 from the activity from boxcars and contaminated scrap.

The information in this table is drawn from MED 1944p; FUSRAP 2003a ; MCW 1958; MCW 1959; Mason (1977); and ORNL 1981. Information regarding contamination levels found in 1958 and 1959 is from MCW 1958 and MCW 1959, which are reports on the results of Mallinckrodt's postoperation survey prior to the start of intensive decontamination.

Illegible areas in the references are indicated by dots (…..).

Buildings that remained after the general demolishment of 1959–1961 are shown in Table A-42.

Plants 1 and 2 were known collectively as "Main Plant"; Buildings 50, 51, 51A, 52, 52A, and 55 were known collectively as Building 51; and all of the Destrehan site was collectively referred to as Plant 6 at times.

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Table A-2. Summary chronology of operations at the Mallinckrodt St. Louis Downtown Site (SLDS) and at the St. Louis Airport Storage Site (SLAPS).

April 1942	Plant 2 was used to develop a batch process using ether to extract uranium as UO_3 from milled ore and then to convert the UO_3 to UO_2. Plant 1 was used for developmental work.
October 1942	Plant 4 was converted for use in the $UO_2 \rightarrow UF_4 \rightarrow U$ metal process. The ore$\rightarrow UO_2$ operations continued in Plant 2, while miscellaneous activities related to R&D work continued in Plant 1.
April 1943	Production of UF_4 from UO_2 began in Plant 4.
1944	Experimental extraction of uranium using pitchblende ores began in Plant 1.
1945	At some point in 1945 or early 1946, uranium operations at Plant 1 ceased. Plant 2 was apparently still used for some metallurgical-type work. Pitchblende ore began to arrive at the site in greater than research-level quantities in about May 1945.
1946	Plant 6 began operation in early 1946, with all ore$\rightarrow UO_2$ production operations shifted there. Uranium operations at Plant 2 ceased in early 1946, the work (including UO_3 milling) apparently shifting to Plant 6. Only Plants 4 and 6 were in operation.
1946–1947	AEC acquires SLAPS in 1946 and Mallinckrodt residues begin to be sent there for storage in about 1947.
1947–1951	Decontamination of Plants 1 and 2, with unrestricted release to Mallinckrodt in 1951.
1948–1949	K-65 residue is brought back from SLAPS for reprocessing. After about 1949, no more K-65 residue is sent to SLAPS, only low-radium residues.
1949–1950	In 1949–1950, major improvements were made in dust control at Plants 4 and 6, with the latter shut down during part of 1949–1950 for this. Ore milling at Plant 6 stopped in 1950.
October 1950	Plant 6E operations began. The $UF_4 \rightarrow U$ metal work shifted there from Plant 4, with the $UO_2 \rightarrow UF_4$ work remaining at Plant 4. Plant 4 was also modified for metallurgical-R&D work and became known as the Pilot Plant; some metal production (derbies, dingots) continued to take place there for experimental purposes.
1951	Plant 7 operations began in the first half of 1951. At that time, some UF_4 production work continued until perhaps 1952 at Plant 4, while the UO_3-to-UO_2 production at Plant 6 seems to have ended completely. Instead, UO_3 was sent to Plant 7 to be converted in a continuous process to UF_4. Some recovery and storage operations also shifted to Plant 7.
1952–1953	At some point, the continuous UO_3-to-UF_4 process began in Plant 7, after which time Plant 6 made only UO_3.
1954	The Ore Room and K-65 sampling operations in Plant 6 appear to have ended by about August 1954, possibly with the shipment of the last of the pitchblende ore (which would have been processed into at least 1955). It is not clear when the various Plant 6 pilot plant(s) began, but a 1954 start appears reasonable. Also, the Plant 6E Slag Separation Plant started in the first half of 1954. Some reversion of UF_4 to UO_2 and UO_3 was done in Plant 7.
1955	In 1955, thorium extraction from AM-7 residue began in Plant 7E and slag processing began in the Slag Separation Plant (Bldg. 701, part of Plant 7). Also, processing of residues to extract thorium began in early 1955 and the processing of a small amount of "enriched uranium" was done at Plant 7 early in 1955. Predigestion ore grinding ceased. Processing of high-grade pitchblende ore ceased and concentrates became the principal feed material.
1955 or 1956	In late 1955 or early 1956, dingots began to be produced in Plant 4, with derby production only intermittent; both were for experimental purposes.
Late 1956	All operations at Plant 4 ceased.
1957–1958	In 1958, all regular site operations ceased, with some Plant 7 activities continuing until July 1958. Postprocessing and shutdown-related activities continued into 1958.
1959–1962	The St. Louis site is decontaminated in 1959–1961, with unrestricted release of the site to Mallinckrodt in about 1962.
1962	AEC issues a license to a private entity, which then took over control of the SLAPS site.
1976 and 1978	Oak Ridge National Laboratory surveys the St. Louis Airport Site (SLAPS) for DOE.
1977	Oak Ridge National Laboratory surveys the St. Louis site (SLDS) for DOE.

1986, 1990	Applied Nuclear Safety does some surveys of the St. Louis site (SLDS) for DOE.
1995	FUSRAP takes over the St. Louis site (SLDS) for remediation.

Table A-3. Principal changes made in sites, processes, and equipment.

Year	Plants	New method or form	Purpose(s)
1942–1943	4	Converted Plant 4	U metal production from UF_4; UF_4 production from UO_2
1946	6	Began operation of Plant 6	Increase production, reduce all types of exposures from processing of pitchblende ores
1946–7	SLAPS	Began operation of SLAPS	Storage of pitchblende residues
1947	SLAPS	Construction of K-65 storage shed	Control external dose, radon exposures
1948	4, 6	Start of formal health program	Track and reduce exposures
1948	6	Began to use ventilated ore railcars	Reduce radon exposures
1948	6	Began reprocessing the K-65 residue	Recover residual uranium; concerns regarding corroding drums
1949	4	Added ventilation to bomb step and recasting furnaces	Reduce deposition of volatiles and thus reduce beta exposures; reduce airborne dust levels
1949	4	Redesigned UO_2 and UF_4 handling methods (e.g., adding hoods to the tray loading, tray dumping, milling, blending, and packing operations)	Reduce airborne dust levels, eliminate hand scooping
1949	6	Added ore room shielding	Reduce gamma exposures
1949	6	Added remote control for filters	Reduce gamma exposures
1949	6	Added K-65 centrifuge shielding	Reduce gamma exposures
1949	6	Added shield tanks	Reduce gamma exposures
1949	6	Added C-3 cell block shielding	Reduce gamma exposures
1949	6	Revised ore house weighing process	Reduce gamma exposures
1949	6	Redesigned ore room dust control (drum weighing and deheading)	Reduce airborne dust levels
1949	6	Revised UO_2 handling (pneumatic unloading and conveying systems)	Reduce airborne dust levels, eliminate hand scooping
1949	6	Revised UO_3 handling (pneumatic unloading and conveying systems)	Reduce airborne dust levels; eliminate hand scooping
1949	6, SLAPS	Instituted limits on time spent handling ore and K-65 in railcars and at SLAPS	Control external and radon exposure to individuals
1950	4	Installed plantwide vacuum cleaning system	Enhance dust control and reduce airbornes
1950	6	Installed equipment decontamination room, respirator decontamination facility	Control contamination
1950	6E	Began operation of Plant 6E	Increase production, reduce all types of exposures
1951?	6, 6E?	Centralized exhaust ventilation	Reduce airborne dust levels
1951	7	Began operation of Plant 7	Increase production, reduce all types of exposures
1952–3	6	New Ledoux sampling labs with better ventilation	Lower airborne dust levels
1952–4	6	Use of pitchblende ore began to be phased out and soluble feeds were used increasingly	Use other available feeds

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Year	Plants	New method or form	Purpose(s)
1953	6	Mechanical conveyor facilities provided in the Ore Room Addition for handling ore drum lids	Decrease airborne dust levels
1953	6	Increase in capacity of pneumatic gulping system in the Pot Room	Lower breathing zone and general area airborne dust levels
1953?	4	Enclosure around upper part of casting furnace	Reduce dust levels and beta radiation levels when furnace lid is removed
1953	4	Enclosure around blender and charging pit	Reduce dust levels in general area
1955	6E	All-purpose dust hood in the area adjacent to the smoking and maintenance areas	Reduce dust levels in breaking out ruptured derby furnace shells, rebuilding recast furnaces, dumping waste into drums, and dumping out drum to sort

Table A-4. Types and quantities of material produced in association with Mallinckrodt uranium refining and related operations.

Material	Process or operation	Content and form notes	Amount
ORES AND OTHER FEEDS			
All ores	Eldorado processed all the Canadian and part of the Congo pitchblende; Vitro, all the vanadium tailings and some Congo ore (Eisenbud 1975). Some milled ore also came from Linde. Mallinckrodt would have received most of the Congo ore only during and just after the war; Canadian pitchblende and domestic ores were used after that. Pitchblende ores were apparently used exclusively until early 1955.		Mallinckrodt processed up to 50,000 tons of ore from 1942–1957 (DOE 1996). Typical amounts in 1945: Eldorado black oxide, 60,000–160,000 lbs/month, average 80,000 lbs/month; Vitro black oxide, 30,000 lbs weekly; Vitro soda salt, 20,000 lbs per 10 days (MED 1945a)
Belgian Congo ore (Q-11, AQ-4) and leach products (tailings concentrates)	Most of the pitchblende processed by Mallinckrodt was obtained as a concentrate from the Belgian Congo in 1944 (AEC 1967), processed at Middlesex (AEC 1951b), and shipped to St. Louis in 55-gal drums (AEC 1967).	Pitchblende ore, up to 65% (DOE 1997, MED 1949) or 70% (Dupree-Ellis et al. 2000) U_3O_8 by weight; up to 100 mg Ra/ton (Dupree-Ellis et al. 2000); averaged 135 mg Ra/ton (AEC 1949b); 0.185 ppm equilibrium Ra for Q-11 (60%) ores (AEC 1949b); 0.1 Ci/ton (total?), up to 70% U, average U concentration >25%, about 100 mg/ton ore for 25% U (Eisenbud 1975). Tailings: 30–50% U_3O_8 (AEC 1951b)	3,400 tons U produced during wartime (through 1944?) (Eisenbud 1975); AEC (1951b) implies that Mallinckrodt was using only Congo ore, Congo ore tailings concentrates, and soda salt around 1951
Canadian pitchblende ores (Great Bear Lake, Port Hope)		Ores at perhaps 10% U (Eisenbud 1975); at 25–30% in 1951 (AEC 1951b) ores and U_3O_8 concentrate	850 tons U produced from Canadian ore in wartime (through 1944) (Eisenbud 1975);
Domestic ore and tailings: Uravan, Durango, Grand Junction, Naturita (Col); Monticello (Utah)		During wartime (through 1946?) vanadium tailings were used, not fresh ore (Eisenbud 1975); <1% U (Eisenbud 1975); shipped as a 20% ore sludge (Eisenbud 1975). The US stimulated domestic production from 1948 on; ores and lower-grade concentrate (DOE 1997). Colorado ores were carnotite type (Eisenbud 1975); N. American ore contained less than 1% U_3O_8 (AEC 1967)	850 tons U produced from the vanadium tailings (through 1944) (Eisenbud 1975). It is not clear how much if any of this was used by Mallinckrodt, except such as came as soda salt, etc.

Material	Process or operation	Content and form notes	Amount
ORES AND OTHER FEEDS			
U_3O_8 (milled ore or black oxide)	Ore usually arrived at Mallinckrodt in milled or concentrated form, as black oxide. However, DOE (1997) stated that Mallinckrodt produced black oxide, presumably at Plant 6.	Originally, (wooden?) beer barrels were used to transport the Congo ore from Eldorado, with wooden bracing in the railcars. This was unsatisfactory so metal containers (barrels) were used. The metal containers weighed about 100 lbs each when full. (MED 1945a)	Normal in-process inventory circa 1945 was about one month's production (MED 1946a).
Ore concentrates (MGX, etc.)	Special types of ore concentrates, e.g., the MGX, a magnesium uranate prepared in Africa from low-grade ore tailings (AEC 1955a)		
Sodium diuranate (soda salt)	$Na_2U_2O_7$. Packed in fiber containers (MED 1945a)	Vitro converted U ores to sodium diuranate (AEC 1951b; DOE 1997); some apparently also came from Anaconda, Durango, and Fernald (AEC 1956b). Fiber containers weighed about 75 lbs each when full (MED 1945a).	
REFINING PRODUCTS			
UNH (uranium nitrate hexahydrate)	An intermediate product in the digestion-extraction process: $UO_2(NO_3)\cdot 6\ H_2O$		Small quantities produced for research purposes as needed (AEC 1951b)
UO_3 (orange oxide)	Feed digested in nitric acid; precipitation of Ra-Pb w/ sulfuric acid (pitchblende ores); filtration to remove acid-insolubles; sulfate removal w/ Ba salt; centrifuging of solution; boiling of "liquor"; double extraction of U with diethyl ether; water wash to remove uranyl nitrate from ether; dewatering in Sperry press; boiling of molten salt to "hex liquor"; decomposition in pots to form UO_3; UO_3 "gulped" out of pot using vacuum system, packed in fiber containers for shipment.	Digestion took 4–8 hours (MED 1946a). Various solid and liquid wastes were produced, including most of the residues listed below. 2.5-gal fiber containers weighed about 75 lbs each when full (MED 1945a).	Sent to Clinton Engineer Works: 30,000+ lbs monthly prior to 15 DOE 1944 but 15,000 lbs weekly after that (MED 1945a). Plant 6 produced a monthly average of 21 tons in 1950 for R&D work on the continuous UO_3-to-UF_4 production process (apart from what went into the normal UO_3-UO_2 production process) and 146 tons in 1Q 1951 as the principal product for the new UO_3-to-UF_4 process (AEC 1951b).

Material	Process or operation	Content and form notes	Amount
UO_2 (brown oxide)	UO_3 was transferred from fiber containers into stainless steel drums, then weighed out on monel trays; reduced with cracked ammonia in batch electric (muffle) furnace to form UO_2 (MED 1949a); scooped from trays into fiber containers for transfer elsewhere (MED 1945a). Packed in fiber containers for transfer elsewhere.	This step took about 7 hours (MED 1946a). 2.5-gal fiber containers weighed about 75 lbs each when full (MED 1945a). There was 349 lbs on a 4-tray charge (MED 1944o).	By DOE 1942 Mallinckrodt was producing a ton a day (DOE 1996). Mallinckrodt used 32,000 lbs weekly (MED 1944o). Mallinckrodt produced 2/3 of the US total; 64% of what it made stayed at Mallinckrodt, 20% went to Harshaw, and 16% went to Linde (MED 1949a). In 1944–45, 20,000 lbs monthly went to Linde; 10,000 lbs/week went to Harshaw from Sept–Oct 1944, 28,000 lbs in Nov–Dec 1944, and 13,000 lbs/week after that (MED 1946a). The design capacity of Plant 6 was 200 tons/month, using ore @ 65% U_3O_8 (AEC 1951b). The monthly averages from Plant 6 were 94 tons in 1947, 246 tons in 1948, 204 tons in 1949, 207 tons in 1950 and 133 tons in 1Q 1951; large-scale production of UO_2 (as a separate product) ended in March 1951 (AEC 1951b). Plant 7's design capacity was 154 tons/month (i.e., could be produced if desired as a tapoff from the continuous UO_3-to-UF_4 process) (AEC 1951b).

Material	Process or operation	Content and form notes	Amount
UF_4 (green salt)	UO_2 placed on graphite or nickel trays in graphite or nickel boxes in the hydrofluorination reactor (furnace); HF gas passed over it to form UF_4; UF_4 removed from furnace and put through pulverizer; UF_4 packed into fiber containers (MED 1945a) or 5-gal containers for transfer to Plant 4 or 6E or another site (AEC 1949b).	Fiber containers weighed about 75 lbs each when full (MED 1945a). In 1944, one control sample was taken per charge; there were 107 runs per week; 535 lbs per week was sent to a recovery tank; and there were 135 lbs per drum and 3,375 lbs per lot (MED 1944o).	Mallinckrodt was the major producer of UF_4; up to 1949, some UF_4 came from ElectroMet (DOE 1997). Normal in-process inventory circa 1945 was 2 days' production (MED 1946a). In 1944, 37,000 lbs weekly was produced, of which 11,000 lbs was used at Mallinckrodt to make metal (MED 1944o). In 1945, 8,000 lbs/week was being sent to Harshaw and 20,000 lbs/week to Iowa State (MED 1945a). Average monthly production in Plant 4 was 76 tons through Dec 1946, 131 tons in 1947, 147 tons in 1948, 151 tons in 1949, 169 tons in 1950, and 189 tons in 1Q 1951 (AEC 1951b). Plant 7's design capacity was 225 tons/month originally, 375 after expansion (AEC 1951b) (unclear if expansion took place).
U metal in derby form	Reduction with magnesium in furnace to U metal (slag + derby); slag chipped off to leave derby	In 1944–1949, there was 135–140 lbs of UF_4 per bomb, along with 55 lbs of liner (MED 1944o, AEC 1949g). A biscuit weighed 92 lbs and was associated with about 122 lb of slag, of which 10 lb was metal; about 80 lbs of sawdust a week was produced; 15 and 2 lbs of samples were sent (weekly?) to plant and outside labs respectively (MED 1944o).	In 1944, 7,500 lbs of biscuit was produced weekly (MED 1944o). Normal in-process inventory circa 1945 was one week's production (MED 1946a).

Material	Process or operation	Content and form notes	Amount
U metal in billet form	Derby was vacuum recast to form the billet		Normal in-process inventory circa 1945 was one week's production (MED 1946a). In 1945, billets were shipped out every two weeks to Hanford in a carload lot of about 30,000 lbs, from a weekly production of 13,000–15,000 lbs (MED 1945a). Average monthly production in Plant 4 was 33 tons through December 1946, 84 tons in 1947, 102 tons in 1948, 100 tons in 1949, 169 tons in 1950, 189 in 1Q 1951; average monthly production in Plant 6E was 83 tons in 4Q 1950 and 162 tons in 3Q 1951; the latter was said to be AEC's entire requirement for metal at the time (AEC 1951b). Plant 6E's design capacity was 150 tons/month originally, 265 tons/month after the expansion of 3Q 1951 (AEC 1951b).
U metal in dingot form	A dingot was a single massive ingot needing no recasting. The dingot-making operation was most similar to the regular derby-making operation. After the chipping step, the dingot was pressed into a slab. (AEC 1956a)	In late 1955 or early 1956, this replaced the derby-billet operation, except for occasional experimental derby production in Plant 4, per AEC (1956a). But AEC (1956c) reported that in mid-1956 (all?) billet recasting was being done in 6E, using new graphite molds. A dingot weighed about 3,300 lbs (AEC 1956a).	
Radioactive metal samples	"Small" samples were sent to Clinton Engineer Works (Y-12) packed in glass tubes and packed into cardboard boxes. "Eggs" were sent to the Chicago Area Engineer (MED 1944o) packed 8 to a box in wooden cardboard boxes. (MED 1945a)		A "small sample" was sent daily to Y-12; eggs were sent in 2–3 lots daily, 63 lbs to a lot. (MED 1945a)

Material	Process or operation	Content and form notes	Amount
"Tubealloy"	Early synonym for uranium (Fleishman-Hilliard 1967), presumably as the metal. Manufactured by Mallinckrodt and shipped to the Chicago Area Engineer (of MED).		150 lbs shipped daily to Chicago (MED 1945a)
RECYCLED AND RECOVERED MATERIALS			
Organic solution of $Th(NO_3)_4$	AM-7 residue was processed via a nitric acid strip to concentrate Th-230 in Plant 7E; solution was sent to Mound, residue (AM-9) returned to storage.	Concentrate had about 1 kg of Th-230, 0.7% alphas from Th-227 & daughters, <0.03% from Th-228.	350 tons of AM-7 processed for Th- 230 (FUSRAP undated a, AEC 1959); 3,600 gal (13,630 l) of Th-230 solution sent to Mound (DOE 2002).
U slag (derby)	Derby slag was scalped or cut off derby and separated into a MgF_2 part and a C-liner part; the MgF_2 part was sent to Vitro for recovery; the C-liner part was stored as waste. Eventually both parts were processed at Mallinckrodt.	Some of the C-liner slag was apparently reprocessed to recover U from about 1953 on (AEC 1954f). In 1955, an interim pilot plant at Plant 7 was built to scalp off most of the U-bearing segment of the MgF_2 part.	
U slag (recast)	Recast slag was recovered as residue from the recast furnace.	As the uranium melted, the slag floated to the top of the crucible and beta-emitting Th-234 and Pa-234 (UX1 and UX2) sublimed and condensed on the underside of the furnace lid; recast furnace slag was thus highly concentrated in UX1-UX2 (AEC 1949, Eisenbud 1975)	
U slag (dingot)	Dingot slag was broken off and swept down through a floor grill, collected on a conveyor, put through a grinding series, drummed, and sent to the Slag Building (701) for reprocessing. (MCW 1949h)		

Material	Process or operation	Content and form notes	Amount
U scrap	Miscellaneous material, including some residues, ash from incinerating the UO_3 fiber containers, and metal; some oxide and nitrate scrap was sent from the Chicago Area Engineer (MED); some scrap was sent to Du Pont. C-2 scrap was packed in 50-gal whiskey barrels; C-1, C-3, C-4, C-5, and D-2 scrap was packed into 5-gal containers with a steel clamp top. (MED 1945a)		Scrap from Chicago Area Engineer, 1945: 1,500 lbs oxide type per 2 months, 1,500 lbs nitrate type per 4–5 months. Scrap shipped to Du Pont as follows. C-1, C-3, C-5, D-2: 80,000–90,000 lbs total per 4–6 weeks; C-2: 80,000–90,000 lbs per 5–6 weeks; C-4: 100,000–120,000 lbs per 4 months. (MED 1945a)
K-65	One source suggests that this residue was "reworked to recover additional uranium values" (i.e., reprocessed?) before transfer to Lake Ontario.	Radium-bearing residue	
Sawdust and fiber containers	Fiber containers were incinerated and processed to recover uranium; sawdust was apparently processed similarly.		
RESIDUES AND OTHER WASTES			
Pitchblende raffinate (AM-7)	"Airport cake"; produced as part of the pitchblende digestion process (extraction raffinate); see also Sperry cake	0.2% U (AEC 1949b); 0.15% U (AEC 1959); 29 ppm Th-232, 3.8 ppm Th-230 (11.6 isot %) (Figgins and Kirby 1962). Pitchblende residues:Th-232/Th-230 ~ 8. In AEC (1960), sampling in June 1953 showed highest sample at .0038% Th and 0.14% U	33,000 lbs/day (AEC 1949b); 74K tons total, 113 tons U stored through at least 1965 (AEC 1960; AEC 1964; ORNL 1979)
De-thoriated pitch-blende raffinate (AM-9)	Residue after processing AM-7 for ionium (Th-230)	0.12%U (AEC 1959). Carnotite residues: Th-232/Th-230 ~ 15–20 (AEC 1949b)	
Domestic ore raffinate (AM-10)	"Airport cake"; produced as part of the non-pitchblende digestion process	Carnotite residues: Th-232/Th-230 ~ 15–20	32.5K tons total, 48 tons U stored through at least 1965 (AEC 1959, AEC 1960; ORNL 1979)

Material	Process or operation	Content and form notes	Amount
Pb-Ra precipitate (K-65, gangue lead cake)	"Lead cake"; a Ra-bearing residue produced as part of the pitchblende digestion process (resulting from addition of sulfuric acid); sent to Lake Ontario or the airport for storage	750–900 mg Ra/ton (AEC 1949b); 750 mg/ton Ra and 0.2% U (AEC 1949b); up to 300 Ra mg/ton (Eisenbud 1975)	8,000–12,000 lbs/day (AEC 1949b)
Ba sulfate cake (AJ-4)	Produced as part of the digestion process (resulting from addition of barium carbonate)	0.28% U (AEC 1959); 1 mg Ra/ton, 0.1% U (AEC 1949b); .1% U, 1E-9 g Ra per g U (AEC 1949m)	6,800 lbs/day total AJ-4 (AEC 1949b); stored: 1.5K tons total unleached (wit 22 tons U), 8.7K tons total leached (with 7 tons U) (FUSRAP undated a, AEC 1960), i.e., 10.2K tons total (with 29 tons U (AEC 1959; ORNL 1979)
Sperry cake	Produced in Sperry press from aqueous tails from the ether extraction step; some later sent to Mound for processing to extract Pa; apparently a subset of AM-7	Good source of Pa-231 (2 g/20 tons); per Salutsky (1956), this was a cake @ 50% solids, 1.6 g/cm^3 density, 0.1–0.3 ppm Pa-231	20 tons (AEC 1959)
Vitro residues (C-6)	Sent from Vitro (?) for storage at the airport	0.33% U (AEC 1959). C-6 and V-10 were stored in a total of 2,400 drums (FUSRAP undated)	290 tons total, 1.9 tons U (AEC 1959)
Bomb furnace residue (C-Special)	This was from the Mallinckrodt and ElectroMet bomb furnaces and appears to be the same as the "C-liner slag" below. (AEC 1949b)		
U-containing sands, precipitates (V-10)	Captured from the Japanese	C-6 and V-10 were stored in a total of 2,400 drums (FUSRAP undated)	60 tons total, 0.2 tons U (AEC 1959)
Dolomite liner (C-liner or C-liner slag)	Slag material, mainly dolomite, remaining after the derby slag was separated from the derby and the top (MgF_2) part of the slag was detached	<2% U (AEC 1959); 1.6% U (AEC 1959). This remainder slag was produced until early 1953, when dolomite was replaced by recycle magnesium fluoride. Some was reprocessed to recover U from about 1953 on (AEC 1954e).	7,800 tons, 122 tons U (AEC 1959); 4,000 tons, 49 tons U I 1964 (ORNL 1979)

Material	Process or operation	Content and form notes	Amount
Interim residue plant tailings (C-701, D-701)	Resulted from scalping the U content from the Mg fluoride slag from 1955 on; 701 apparently refers to Bldg 701 (AEC 1956d)	2.1% U (AEC 1959)	7K tons total, 144 tons U (AEC 1959)
30- and 55-gallon drums	Empty drums, stored as contaminated waste		55,000 (AEC 1959)
Metal and alloy scrap	Stored as contaminated waste		3,500 tons (AEC 1959)
Aqueous tails	From ether extraction step; filtered and treated with lime; precipitate become airport/Sperry cake, filtrate disposed of as liquid effluent		

See the text for process details. See the keywords table (Table A-5) for other code numbers and terms.

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Table A-5. Functional and process keywords and codes.

Plant	Keyword or code	Note
	2	MED hazard index number for soluble uranium material
	4	MED hazard index number for insoluble uranium material
	6	MED hazard index number for nitrous fumes
	14	MED code for Building 51
	16	MED hazard index number for hydrogen fluoride
	32	MED hazard index number for handling of metal
	38	MED code for the laboratory area in Plant 2
	51	See “Building 51” below
	52	MED code for Plant 4
	128	MED hazard index number for hydrogen fluoride gas
	162, 172, 182	Black oxide (U_3O_8); could appear as “Chemical 162,” etc.
	256	MED hazard index number for radium
	264, 272	Orange oxide (UO_3); could appear as “Chemical 264,” etc.
	306	Brown oxide, i.e., UO_2; could appear as “Chemical 306”
	512	MED hazard index number for radon
	1024	MED hazard index number for solvents
	2048	MED hazard index number for radiation
	4-bagger	Type of dust collector
	A	In film badge records, denotes “absent”; elsewhere, denotes non-specification grade black oxide (U_3O_8)
6	Acid	Acid addition: in ore digestion (nitric) or Pb-Ra precipitation (sulfuric)
7	Adams	A type of polishing filter used in Plant 7
6	AEC	Atomic Energy Commission
	Airport	SLAPS, the former airport site later used for waste storage by the AEC
6	AJ-4	Barium sulfate cake produced from pitchblende ore (ore-to-UO_3)
	AJ-7	Another barium cake
6	AM-7	Raffinate cake produced by treating pitchblende ore
6	AM8	Unclear what this indicates
4,6,6E,7	Area M	Area mechanic
6	Assist LO	Assisting the lead operator
6	AQ-4	Pitchblende ore
4	Ballard	Vertical turret lathe (manufactured by Ballard) used to scalp the dingot
6	Barium	Barium salt addition
	Beets(?)	See Egg
4, 6E	Billet	Final form of uranium metal, produced by recasting from derbies
6	Bird centrifuge	Solid-bowl centrifuge (manufactured by Bird) used to separate liquids and solids
	Black oxide	U_3O_8
4, 6	Blender	Apparently ore in Plant 6; UF_4 + Mg in Plants 4, 6E; slag in Plant 6E
4, 6E	BM	Bottom man
6	Boildown	A step between digestion and ether extraction
4	Bomb	Container for Mg-UF_4 in the metal reduction process
4, 6E	Bomb step	The UF_4-to-derby process
4, 6E	Bottom	Lower (furnace or F machine)
4, 6E	Bottom man	Bottom man in the YM-5 production process -- would physically enter the bottom part of the furnace in Plant 4
4	Box	Crucible holder (external assembly)

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Plant	Keyword or code	Note
6E	Breakout	Removal of the derbies from the bombs
	Brown	Brown oxide, i.e., UO_2
	Brown monster	Apparently the Rockwell furnace(s) (UO_3-to-UO_2)
	Building 51	The 50 series of buildings at Plant 2 (i.e., 50, 51, 51A, 52, 52A, and 55)
	Building K	Apparently Building K1E in Plant 1
6E	Burnout, burn	Crucible burnout (heating)
	C	On film badge records, denotes no badge issued (“clean”?)
6	C-	When followed by a number, denotes material collected by a given dust collector or filter press or a type of scrap
6	C-3 (C-3A, etc.)	C-3 cell block operations (e.g., centrifuging, packing) related to use of the carbonate leaching process to recover uranium from Feinc filter cake (K-65); also dust collection related to this
	C-27	Derby chippings (residue)
	C-55	As “Chemical K-35,” etc., denotes black oxide (U_3O_8) (may be scrap)
4, 6E	Cage	Scrap holding area
4, 6E	Cage man	Handled billet and other metal scrap, degreased billets
6E	Cap	Valved top put on the Mg-UF_4 drum for jolting
	Cats	High-grade ore
	CB	On film badge records, denotes contaminated badge and film
6	CEN, Cent, Cntr	Centrifuge. Also abbreviated CNF?
	Chemical	Start of some code names; was followed by letters or numbers
4	Chipping	Removal of the slag from the derbies using a manual or power hammer
	Classifier	Equipment used in the Ore Room apparently to sort ore pieces by size
---	Cleanup	Generic for area or item cleanup: see associated keyword (e.g., TA-7)
	C-liner	Dolomite slag left after the bomb is opened and the derby removed
	C-Special	Liner slag left on bomb and possible also derby (had to be chipped off)
6	Cloth	Cloth (actual or metal) used to filter solids from liquid streams
	Cl Up	Cleanup, i.e., cleanup of process area
6	CM	Cloth man?
	Cocoa	Brown oxide, i.e., UO_2
4, 6	Continuous furnace, Cont furn	Furnace for processing UO_3 to UF_4 in a continuous run (in Plant 4, experimental process in Pilot Plant)
	Croppings	Chips or pieces taken off derbies, billets, and dingots
6E	Crucible, Cruc	Crucible or crucible assembly (6 should probably be 6E)
	Crusher	Probably the UO_2 crusher (mill)
	CS	Refinery feed material that was an impure calcium uranate
	C-Special	Magnesium fluoride slag formed on top of the derby
	CX	Calcium uranate leach product from the processing of ore tailings at African mills; sent to Mallinckrodt for laboratory research and pilot-scale recovery of the uranium
	D	Radium (the element)
6	D-	When followed by a number, denotes a given dust collector or filter press OR the material collected there or a type of scrap
7	D-30	Dust collector for the FMFL product (dust is the product)
	D-701	Residues collected in the slag grinding area shipped to slag recovery
6	DA	Dissociated (cracked) ammonia or Digest area
6,6E, 7	Decontamination	Generic
	Deheading	Same as Delidding

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Plant	Keyword or code	Note
	Delidding	Removing the lid of a drum, usually of ore
4, 6E	Derby	Crude uranium metal form produced from UF_4
6	Digest, DIG, Dig	Digestion process (ore dissolution by acid), digestion area, digestors
4	Dingot	"Direct ingot," an extra-large ingot produced instead of derbies and billets
	DR	???
	DX	Probably decontamination work
	E	Designates the Mallinckrodt plants in St. Louis
	Egg	1.9-kg egg-shaped piece of U metal produced for external assays
6	Ether, Ether House, EH	Ether storage, handling for U solvent extraction process
4, 6	Extra, Extra Man	Extra (floating) chemical operator for a process or area (4, 6); possibly also "extraction" (6)
6	Extraction	Extraction of uranium in the ether extraction process
	F	Generic feed material designation for types without a code name
4, 6E	Fce	Furnace (metal-making areas)
	FD	On film badge records, denotes factory-damaged film
6	FE, Fe	Feinc (FE Inc) filter (equipment or area)
6	Feed	Ore or other feed material; also could indicate main stream of process (i.e., not residue)
6	Feinc	String discharge rotary vacuum filter (manufactured by Feinc) used to separate solids from liquids
	FF	On film badge records, denotes film fogged, torn, or open (in badge?)
6	FH	Feed hopper?
6	Filter press	Press type of filter for separating solids from liquids and leaving a dewatered cake
	Fin	Slag or magnesium burr on billet, bomb shell lid, etc. that had to be chipped off
6E	F Machine	UF_4-to-derby bomb filling ("F") machine: the top is used for the UF_4, Mg mixing, the bottom for filling the bomb
7	FMFL	Fluorinated MgF_2 liner, used as a low-hydrogen liner in dingot bombs
4, 6	FR, Furnace, Furn	Furnace Room
	Gangue, gangue lead cake	The Pb-Ra cake also known as K-65
	GL	In film badge records, denotes "gone through the laundry" in context of film condition; denotes work with gangue lead cake in context of worker area
6	GLC	Gangue lead cake, i.e., the Pb-Ra cake also known as K-65
	Green	Green salt (UF_4)
6	Gulping	Vacuum-sucking UO_3 out of the pot it was produced in into drums
	GWT-5	Uranium metal eggs (test samples)
	GY-3	U_3O_8 (black oxide), having a minimum assay of 97% U_3O_8
	H-20	??? (H_2O, i.e., water?)
7	Hapmann, Hapman	Conveyor for loose material; typically discharges into a feed hopper
6	Hex, hex liquor	Uranyl nitrate hexahydrate in an aqueous solution
6E	Hoffman	Dust collector (manufactured by Hoffman)
All	House	Generic for dedicated additive handling and storage building or area
4, 6E	Ingot	Same as billet

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Plant	Keyword or code	Note
6	Instrument, Instru, Instr	Instrument Shop
	Ionium	Thorium-230
	Iron maiden	C-Special, while still attached to derby
4, 6E	Jolter, jolting	The jolter-filling machine in UF_4-to-U metal production, also the operator; the operation
	Juice	Orange oxide, i.e., UO3
	K-35, K-82	As "Chemical K-35," etc., denotes black oxide (U_3O_8)
6	K-65	K-65 (Ra-Pb) residue (gangue lead cake) from the (pitchblende) ore-to-UO3 process
6E	KB-2	Derby form of uranium metal
4	Label	Apparently labeling product containers
6	Laboratory, Lab, LAB	Any of several laboratories (Analytical, Shotgun, Ledoux, etc.)
6	Laundry	For both contaminated and uncontaminated clothing; Mallinckrodt had own laundry from ~ 1948 on
	LB	In film badge records, denotes film that was opened (in badge?)
	Ld	Loading (e.g., TA-7)
	LF-9	Brown oxide (UO_2)
	LFD	In film badge records, denotes film lost in the darkroom (torn open)
	LFP	In film badge records, denotes film lost in plant
	LG	Lead gangue? See GLC
6	Ledoux (LeDoux) Laboratory	The raffinate and uranium assay laboratory in Plant 6
6	Liquor	Extracted liquid concentrate, usually after removal of undesirable materials as solids
	LL	Ledoux Laboratory
	LO	Lead operator
4, 6	Loading, Load, Ld	Generic: see associated process keyword, e.g., TA-7
	Location E	The Mallinckrodt St. Louis site (SLDS)
	M	Powdered magnesium metal, work in the metal-making (derby and billet) areas, or maintenance (depending on context)
6	M(+number), M-(+number)	(1) Designates tank(s) used in processing. (2) Designates a type of development work, e.g., M-1 for slag liner work, M-2 for mold improvement, and M-7 for crucible testing
	M-20	Step or tank during which barium sulfate was added
	ME	Refers to processing of AM-7 raffinate to concentrated liquid Th form (Minor Elements)
	MFG, Mfg	Manufacturing: generic for Plant 6 and Plant 4
6	MGX, MgX, MGX Process	Refinery feed material that was an impure magnesium uranate from the Belgian Congo
4	Mag Room	Magnesium [Storage] Room
1, 2	Main Plant	Plants 1 and 2
6, 6E	Maintenance, M, MNT	Maintenance, presumably process maintenance
	ME	Refers to reprocessing of raffinate to a feed concentrate
7	MFL	MgF_2 liner (for use in dingot bombs); loosely, also the associated slag used (recycled) in the liner

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Plant	Keyword or code	Note
6	Mikro	Dust collector (manufactured by Mikro)
6	Mill	See Rod mill
	Mtns	Maintenance
4	Muffle	Batch electric (muffle) furnace used to reduce UO_3 to UO_2
	Mx (note lower case)	Uranium (generic for the element?)
	MX (note upper case)	See MGX
	My	Radium; also, used to indicate a breath radon measurement (since this measurement was used to infer radium body burden)
	Mz, MZ	Radon-222
6	NA, NAH	Nitric Acid House
6	Neutral	Neutralizing uranium solution (in acidification step?)
6	Niagara, Nia	Pressure leaf filter (manufactured by Niagara) used to separate solids from liquids
6	NOK	In the re-extraction process, the OK liquor contained the uranium and the NOK liquor contained the dross (after filtration, it became raffinate).
6	Ntns	Maintenance (Mtns)?
4	Office, OFF	Generic for office
	OH	Hydroxide (e.g., to neutralize excess HF and recover uranium)
6	OK	In the re-extraction process, the OK liquor was the uranium-containing liquid sent to the boildown tanks
6	Oliver	Filter press (manufactured by Oliver)
	Orange, orange juice	Orange oxide, i.e., UO_3
6	Ore, Ore Room, OR	Ore processing, storage before use; also handling of residues
	OZ	Electrically fused dolomite
4, 6, 7	Pack, packing, packaging	Appears to be generic for packaging
6	Pangborn	Type of dust collector (K-65/Ledoux Sample Lab; ore grinding room; C-3)
6	Peterson	Type of filter, often in a hood; at least some was used to filter NOK liquor to produce the raffinate
	PH	Power House
6E	Pickling	Soaking derbies in acid to remove surface impurities (scale, oxides)
All	Pilot Plant, PP	Plant 4's name (for metallurgical research and developmental UF_4 furnace work), after metal production moved to 6E; Plants 1 & 2, around the time Plant 6 started up; a slag recovery pilot plant in 6E; or an unspecified pilot plant at 6 (must be taken from context)
	Pk	Packing (packaging) of a product form
All	Pl	Plant (e.g., Pl. 7 is Plant 7)
	Plant 10	The later name of the Plant 4 area (after Plant 4 was dismantled)
2	Plant 51	Building 51 operations in Plant 2
6E	PLO	Process Lead Operator?
6	Pot, Pot Room	Denitration pot room (producing UO_3)
6	Press	Filter press

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Plant	Keyword or code	Note
6	Production Engineering, Prod Eng, Prod Off Eng	Generic for production/process engineering work
6	Production Office, PO	The MCW [Main] Production Office
	Project (+ number)	Project 89 was Plants 1 and 2; 90, Plant 4 green salt operations; 91, Plant 4 derby production; 92, Plant 4 recast operations
	Q-11	Pitchblende ore, other high-grade ore
	QM-2	Orange oxide (UO_3)
6	Raffinate, Raff	Residues (mainly the cakes)
6	Railcar	Railroad car used to transport ore, K-65 residue, and sometimes scrap
6	Rapping	Knocking a dust collector (usually the Pangborn) to loosen collected material for removal
4,7	Reactor	Reaction vessel/heater in which UO_3 is converted to UO_2 with cracked ammonia
4	Recast, Recast Furnace	Where derbies were recast into billets
4	Receiving & Shipping	Generic? The main Receiving & Shipping area was in Plant 6, but there may have been plant-specific areas
6	Recovery, REC	Nitric oxide recovery (6); slag recovery (7); may have indicated other types of recovery at other plants
	Regulated	Refers to radiologically controlled areas, e.g., the regulated locker room and the general locker room
	Regulus	Same as Derby
6	Reverter (riverter?)	Unclear. Appears to be a type of pump or processor used in the recycling of dust collector material
7	RMF	Recycle magnesium fluoride (from bomb liner residue)
6E	Rockwell	Rockwell furnace (UF_4-Mg reduction to derby metal)
6	Rod mill	Piece of equipment used to grind ore
	Rolls	Billets
6	Rover	Extra pair of hands or swing man?
	S	As “Chemical S,” denotes sodium salt (sodium diuranate, Na2U2O7)); in urinalysis records, denoted sulfate (work)
4	Salt bath	Bath in which a dingot is put to heat it
	Sample Room	Any of several sample rooms, e.g., the K-65 Sample Room
6	Sampler, Spl	Generic for sampling or work in a sample room
SLAPS	Sand	(1) cake residue or (2) uranium-containing sands captured from the Japanese
6E	Saw	Sawing off a portion of the metal billet as a sample
6	SC-5	Uranyl nitrate hexahydrate (UNH)
6E	Scalping	Mechanically slicing off slag from the external surfaces of a billet
6	Scrap	Usually, scrap left over after cleaning the derbies; miscellaneous scrap
4	Semi-works	Term for a facility within a plant, on the scale of or slightly larger than a pilot plant (specifically, the dingot operation in Plant 4)
6	Skip hoist	Hoist used to raise ore drums, dump them into raw ore bin feeding (ore) rod mill
6E	Slag	Byproduct from the Mg-UF_4 reduction step (mostly MgF_2)
7	Slag Processing Plant	Same as Slag Separation Plant

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Plant	Keyword or code	Note
[4]	Slag Shed	Storage of the chipped-off bits of slag?
	SLAPS, SLAPSS	St. Louis Airport Storage Site
6E	Slye	Dust collector (manufactured by Slye)
6	Shotgun Laboratory	Shotgun sample preparation laboratory
6	Shotgun Samp Prep	Shotgun sample preparation (lab)
6	Soda salt	$Na_2U_2O_7$ (sodium diuranate, a feed material); perhaps other soluble feed material
	SP	In film badge records, denotes film spoiled in the darkroom (development) process
6	Sperry	Filter press (manufactured by Sperry); also, the cake produced (same as or subset of AM-7)
	SR	Storeroom
	SS	Stainless steel presses, i.e., the plate and frame filters
	SSP	Usually refers to stainless steel (filter) presses; may indicate Shotgun Sample Prep Lab
	ST	Uranium metal scrap
6	Storeroom	Generic; the main storeroom was in Plant 6
6	Stripper	Unclear; probably piece of equipment rather than operator name
All	T	Generic code term for uranium, including as metal (T metal), in compounds (e.g., TO_2), and as a daughter indication (e.g., TX1)
6	T-3	Typo for C-3?
4	TA-7	Green salt (UF_4)
	TA-7R	UF_4 produced from UO_2 in the experimental continuous reactor
	Talcum	UF_4
6	Thawhouse	Building where ore was thawed in winter before undrumming
6	Thief	Sampling device that opens at a desired depth into the material
6	THP	THP ether?
6	Thumper	Device to “thump” feed drum to dislodge material during digestor loading
4, 6E	TM	Top man, Top-off man, etc., in the YM-5 production process
4, 6E	Top	Refers to the upper or top recasting furnace or the top F machine
4, 6E	Top man	Top man, Top-off man, etc., in the YM-5 production process
4, 6E, 7	Topping	Refers to the operation of adding material to ensure proper fill
	Tubealloy	Uranium metal (generic term also used roughly to indicate any uranium)
	Tumbler, tumbling area	UO_2 breakup (crushing) area
	U	In film badge records, denotes “unidentifiable” in context of film condition; elsewhere, usually denotes uranium
6, 7	U-CON, U-con	Uranium concentrate slurry produced in the Slag Separation (Processing) Plant (7) from reject MgF_2 material and sent to Plant 6 as a feed material
6	UNH	Uranyl nitrate hexahydrate ($UO_2(NO_3)_2 \cdot 6\ H_2O$)
	Unld	Unloading (e.g., TA-7)
6E	Utility	Utility man or “floater” who filled in as needed
	UX1, UX2	Old names for Th-234 and Pa-234m respectively
	V	In film badge records, denotes “on vacation”
	V-4	A form of soda salt used as feed material
	W	In film badge records, denotes “wet from unknown reason”

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Plant	Keyword or code	Note
All	Warehouse, WH	Generic: various warehouses were used, with the main one in Plant 6 and later in Plant 7
4	Weigh, check weigh	Generic: feed and products were weighed at various points
6E	Wilfey	Shaker table (manufactured by Wilfey) used to separate high-U slurry from low-U material
	X	Generic code term for uranium, including in compounds (e.g., XO_2)
	Yard	Open areas outside buildings and guard stations; used to store drums, unload railcars; even used postoperations for decontamination
	YB-1	UO_2 produced from UO_3 in the experimental continuous reactor
	Yellow cake	The generic form of uranium ore, somewhat preprocessed
4	YM-5	Billet form of uranium metal

Table A-6. Thorium and daughter content of the AM-7 residue ("airport cake").

Material	Concentration, ppm	Mass, grams	Specific activity, Ci/g*	Total curies in ore	Notes
Ore	---	3.18×10^{8}	---	---	350 tons processed (see Table A-4)
Th-230	3.8	1,208	0.0202	24.4	Concentration: Figgins and Kirby 1962
Th-232	29	9,222	1.09×10^{-07}	0.00101	Concentration: Figgins and Kirby 1962
*From Shleien 1992					
Isotope	**Half-life**	**Activity after 15 years, Ci**	**Percentage of original**		**Notes**
Th-230 Chain					
Th-230	77,000 years	2.44×10^{1}	~100		
Ra-226	1,600 years	1.58×10^{-1}	0.65		
Rn-222	3.82 days	1.58×10^{-1}	0.65		
Po-218	3.05 minutes	1.58×10^{-1}	0.65		
Pb-214	26.8 minutes				
Bi-214	19.9 minutes				
Po-214	164 microsecs				
Pb-210	22.3 years				
Bi-210	5.01 days				
Po-210	138 days				
Th-232 Chain					
Th-232	1.41×10^{10} years	1.01×10^{-3}	~100		
Ra-228	5.75 years	8.46×10^{-4}	84		
Ac-228	6.13 hours	8.46×10^{-4}	84		
Th-228	1.91 years				
Ra-224	3.66 days				
Rn-220	55.6 seconds				
Po-216	0.15 seconds				
Pb-212	10.6 hours				
Bi-212	60.1 minutes				

Fifteen years is assumed to be the maximum decay time (1942–1957).

As the second part of the table shows, in 15 years secular equilibrium has not been reached for either the Th-230 chain or the Th-232 chain, although Th-232 is almost there. Thus only the activities of the first few members are shown.

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Table A-7. Airborne uranium particle size in process areas.

Area	Location or source type	Method[a]	Average concentration, mg U/m^3	Mass median particle size, microns	GSD
Mallinckrodt UO_2 Production Area (Rochester 1948b)					
UO_3-to-UO_2 conversion	<1 foot of the blow pipe	F	2.14	1.2	2.34
Tumbling	Vicinity of furnace, tumbler tray rack	F C	.11–.46 .64–.93	1.4–1.45	2.5–3.2
	Further from furnace, tumbler rack	F C	.069–095 .41–.53		
	Near skip hoist	F C	2.8–4.2 .59–.69	1.5–1.9	2.45–2.6
	4 feet from skip hoist	F C	0.75 3.5		
	Back of the skip hoist	F		2.6	2.65
Fiberpack packaging		F, C	.060–2.2	.72–3.48	2.96–3.03
Warehouse	Closed containers of UO_2	F	.017–.033	1.1	2.3
General (Non-Mallinckrodt) Foundry (Sanders 1975, Table 2)					
Foundry	Depleted U Enriched U Enriched U	--- --- ---	--- --- ---	2.8 ± 2.7[b] 3.3 ± 2.2[b] 2.1 ± 2.0[b]	--- --- ---
Machining	Depleted U, milling dry	---	---	3.0 ± 2.3	---
Extruding	Depleted U	---	---	3.2 ± 2.7	---

a. This refers to the sampling method. F: filter paper (with air sampling pump). C: cascade impactor
b. 88% of these particles were from particles less than 7 µm.

Table A-8. Uranium dust concentrations, Plants 4 and 6, in alpha dpm/m^3 (Mason 1958a, Tables 1, 2).

	Plant 4 production				Plant 6								
							UO_3 production				UO_2 production		Misc
Year	UO_2	UF_4	KB-2	YM-5	Warehousing	Ore grinding	Feed digest	Milling	Pot room	Packaging	Load	Unload	Packaging
1943	2,100	2,380	1,190	2,520	---	---	---	---	---	---	---	---	---
1944	2,100	2,380	1,190	2,520	---	---	---	---	---	---	---	---	---
1945	2,100	2,380	1,190	2,520	---	---	---	---	---	---	---	---	---
1946	2,100	2,380	1,190	2,520	210	13,300	420	12,600	7,770	1,400	5,320	3,150	11,270
1947	2,100	2,380	1,190	2,520	210	13,650	420	12,600	7,770	1,400	5,320	3,150	11,270
1948	2,100	2,380	1,190	2,520	210	13,650	420	12,600	7,770	1,400	5,320	3,150	11,270
1949	420	280	280	770	210	13,650	420	12,600	7,770	1,400	5,320	3,150	11,270
	---	---	---	---	70	350	70	0	4,200	700	1,400	700	350
1950	280	140	210	770	70	350	70	[a]	770	700	1,400	700	350
	---	---	---	---	28	350	70	---	350	700	700	350	350
1951	280	210	---	---	35	350	140	---	140	70	420	210	350
1952	280	210	---	---	35	210	350	---	210	140	420	210	350
1953	---	---	---	---	63	140	49	---	210	140	420	210	350
1954	---	---	---	---	21	140	42	---	140	140	[b]	[b]	[b]
1955	---	---	---	---	21	[a]	56	---	140	140	---	---	---
1956	---	---	---	---	21	---	28	---	210	280	---	---	---
1957	---	---	---	---	21	---	56	---	210	70	---	---	---

The first two Plant 4 processes were supposedly transferred to Plant 7 in 1952–3, the last two to Plant 6E in 1950–1. Compare to information for Plants 6E and Plant 7 (Table A-9). Prior to 1946, the Plant 6 operations were done in Building 51 of Plant 2; all work was transferred to Weldon Spring in March 1957. Note that the figures above reflect chronologically the significant improvements in ventilation and dust control made in 1949.

a. Discontinued
b. Transferred to Plant 7 in October 1952

Table A-9. Uranium dust concentrations, Plants 6E and 7, in alpha dpm/m^3 (Mason 1958a, Tables 3, 4).

	Plant 6E						Plant 7		
	KB-2 production			YM-5 production			All operations		
Year	Average	High	Source of high reading	Average	High	Source of high reading	Average	High	Source of high reading
1950	7	21	Charging	70	126	Crucible assembly	---	---	
1951	21	56	Residue	77	126	Top furnace	---	---	
1952	28	70	Residue	84	161	Burnout	35	112	UO_2 dumping
1953	21	84	Charging	35	49	Top furnace	28	119	Furnace operation, TA-7 packaging
1954	35	210	Residue	63	119	Bottom furnace	35	490	Sampling, cleanup
1955	112	280	Residue	42	105	Bottom furnace	21	77	UO_2 dumping
1956	28	112	Capping	35	42	Bottom furnace	28	56	UO_2 dumping
1957	28	105	Burnout	49	84	Bottom furnace	21	56	UO_2 dumping
1958	56	147	Breakout	84	147	Bottom furnace	35	98	TA-7 packaging

Plant 6: KB-2 is the derby form and YM-5 the billet form of uranium metal.
Plant 7: Operations were moved to Weldon Spring in 1958.

Table A-10. Early air sample data, short-term sample readings in alpha dpm/m^3.

	1943		1944			1945			1946		
Location and operation	Value	No. of Samples	Value	GSD	No. of Samples	Value	GSD	No. of Samples	Value	GSD	No. of Samples
Plant 1											
Bldg K, Feinc filtration						60		2			
Bldg 25, Laboratory						7		2			
Plant 2 (Bldgs 51/51A)											
Oxide being added to Tank 1A	153	1									
Pot Room, general area	301	1	742		2	511		1			
Pot Room, aisle between pots						700		1			
Pot Room, (un)loading UO_3	2,000	1				2,380		1			
Pot Room, chipping, scooping cake	11,300	1									
Milling UO_3			2,800	3.03	3	3,220		1			
Sifting room general area	304	2									
Sifting room, sifting	2,250	1									
UO_2 being weighed	70	1									
UO_2 unloading			15,540		2						
UO_2 packaging			65,800		1						

Location and operation	1943		1944			1945			1946		
	Value	No. of Samples	Value	GSD	No. of Samples	Value	GSD	No. of Samples	Value	GSD	No. of Samples
Plant 2 (Shotgun Lab, Bldg 55)											
Shotgun residue evaporation			62		2						
Shotgun residue grinding			97	1.54	4						
Plant 4											
UF_4 general area						49		3			
Unloading UF_4			6,160		2	91		1	563	2.36	4
Milling UF_4			6,062		2	74		2	630		2
Mixing/blending/jolting UF_4, Mg			1,960		1				84		2
Bomb area general			5,320	1.22	3						
Bomb loading			2,100		1						
Bomb unloading			1,154	2.79	4				324		2
Biscuit chipping			4,484	1.27	3				42		1
Biscuit sealing			1,540		1						
Slag barreling			210	1.10	4						
Crucible burnout			2,100		1						
Recast furnace general area			976		2						
Recast furnace unloading			700		1						
Recast furnace brushing			980		1						
Ore milling						720	2.70	4			
Ore handling						1,230		2			
Plant 6											
Ore storage area									246	4.08	9
Boxcar									504	4.10	3

The sampling data used to produce the table above are from MED (1943d; 1944b; 1944c; 1944d; 1944e; 1944g; 1944h; 1945d; 1946d; 1946e; MED 1945o) and MCW (1946b; 1946c; 1946d; 1946e; 1946f). The figure given in the Value column is the median, if there were three or more samples; the mean if there were two samples; and the sole value if there was one sample.

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Table A-11. Airborne uranium dust concentrations in Plant 4 Areas, 1948: AEC versus Mallinckrodt measured data (AEC 1949b, Table 3).

Activity	Multiple of "Preferred Level"		ug/m^3		Adjusted to dpm/m^3	
	AEC	Mallinckrodt	AEC	Mallinckrodt	AEC	Mallinckrodt
LF-9 loading						
Operator A	47.7	29.7	2.39E+03	1.49E+03	3.34E+03	2.08E+03
Operator B	47.7	30.7	2.39E+03	1.54E+03	3.34E+03	2.15E+03
Furnace tending						
Operator A	7.5	5.7	3.75E+02	2.85E+02	5.46E+02	3.99E+02
Operator B	9.1	6.1	4.55E+02	3.05E+02	6.37E+02	4.27E+02
TA-7 unloading						
Operator A						
– Manual	186	66.8	9.30E+03	3.34E+03	1.30E+04	4.68E+03
– Semi-mechanized		16.4		8.20E+02		1.29E+03
Operator B						
– Manual	186	57.2	9.30E+03	2.86E+03	1.30E+04	4.00E+03
– Semi-mechanized		20.7		1.04E+03		1.45E+03
TA-7 mixing & packing						
Operator A	63	13.1	3.15E+03	6.55E+02	4.41E+03	9.17E+02
Operator B	57	24.6	2.85E+03	1.23E+03	3.99E+03	1.72E+03
Bomb charging	51	42.4	2.55E+03	2.12E+03	3.57E+03	2.97E+03
Topping	10.4	32.4	5.20E+02	1.62E+03	7.28E+02	2.27E+03
Jolting	51	7.5	2.55E+03	3.75E+02	3.57E+03	5.25E+02
Charge firing	13.3	13.8	6.65E+02	6.90E+02	9.31E+02	9.66E+02
Derby unloading						
Operator A	5	9.1	2.50E+02	4.55E+02	3.50E+02	6.37E+02
Operator B	5	18.7	2.50E+02	9.35E+02	3.50E+02	1.31E+03
Chipping	26.3	11.5	1.32E+03	5.75E+02	1.84E+03	8.05E+02
Slag handling	1.6	2.2	8.00E+01	1.10E+02	1.12E+02	1.54E+02
Top furnace tending						
Operator A	61	36.5	3.05E+03	1.83E+03	4.27E+03	2.56E+03
Operator B	61	23.2	3.05E+03	1.16E+03	4.27E+03	1.62E+03
Bottom furnace tending	73	59	3.65E+03	2.95E+03	5.11E+03	4.13E+03
Sawing	15.8	5.4	7.90E+02	2.70E+02	1.11E+03	3.78E+02
Cage handling	2.7	52	1.35E+02	2.60E+03	1.89E+02	3.64E+03
Office	0.6	4.1	3.00E+01	2.05E+02	4.20E+01	2.87E+02
Shipping & receiving	1.6	6.8	8.00E+01	3.40E+02	1.26E+02	4.76E+02
Mechanics	5	10.7	2.50E+02	5.35E+02	3.50E+02	7.49E+02
Carpenter	2	4.6	1.00E+02	2.30E+02	1.40E+02	3.22E+02
Porters	0.8	2.9	4.00E+01	1.45E+02	5.60E+01	2.03E+02
Guards	0.4	1.4	2.00E+01	7.00E+01	2.80E+01	9.80E+01

At the time of this report, AEC's "preferred level" for U dust in air, 50 µg/m^3, was based on an assumption of exposure 8 hrs/day, 6 days/week (AEC 1949b). Columns 2 and 3 are based on this.

Columns 4 and 5 represent the values in Columns 2 and 3 respectively multiplied by 50 µg/m^3.

Columns 6 and 7 represent the values obtain by multiplying Columns 4 and 5 respectively by 70 dpm/m^3 (assuming 70 dpm/m^3 is equivalent to 50 ug/m^3).

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Table A-12. Plant 4 measured daily weighted average exposure concentrations.

Occupation	Weighted average concentration, alpha dpm/m^3								
	5/ 1956	11/ 1953	3/ 1953	6/ 1950	10/ 1949	9/ 1948	5/ 1948	AEC 1949b	AEC 1951a
Magnesium operator				35	70				
Lime blender				35	70				
Slag man				70	105	210	140		
Cage man (handler)				190		3,640	189	2940	
Derby unloader				175	245	1,260	280		
Bomb topper				210	280	2,310	840		
Charge firing				140	350	980	910		
Derby chipper				140	350	910	1,890		
Jolter				70	140	490	3,500		
Bomb charger				210	490	3,010	3,640		
Green lead man				70	140				
Cleanup man				140	140				
Furnace tender				70	70	350	560		
Furnace box puller				35	140	560	630		
TA-7 Pilot Plant				980	175				
Brown loader				280	350	2,240	3,360		
Green packer				245	210	1,750	3,990		7,210
Green miller and mixer				70	140	980	4,690		
Green unloader				210	490	1,540	13,020		
Plant superintendent	7.3								
Technical supervisor	6.6								
Engineers	7.3	9.8	14						
Chief chemist	5.9								
Vacuum fusion chemist	39								
Vacuum fusion technician	59								
Microscopist	18.4								
Chemist	10								
Chemical technician	10	4.6	7						
Foreman	22.5	6.7	12	35	70	175			
Shift foremen	12.4			56	98	175			
Lead operator	25	8.2	19	119	63	---			
Dingot/bomb, slag grinding oper	85	33	64	X	X	X		X	
Furnace and saw man	17.5			X	X	X		X	
Casting furnace operator	10.8	110	480					5,110	
Furnace operator (UF_4-derby?)				91	70	570			
HF operator				91	70	570			
UO_3 & Brown packer				217	322	2,730		4,200	2,730
Green packing operator				196	315	7,210		4,000; 13,000	
Asst green packing operator				112	133	2,800			
Residue	27.4								
Ceramic	14.8								
Vertical lathe	28.5								
Forge press lead operator	22								
Forge press salt bath man	21.5								

Occupation	Weighted average concentration, alpha dpm/m^3								
	5/ 1956	11/ 1953	3/ 1953	6/ 1950	10/ 1949	9/ 1948	5/ 1948	AEC 1949b	AEC 1951a
Forge press manipulator (oper)	22.6								
Forge press operator	21.9								
Clerk	5							42	
Guard	7.1							28	
Porter	40	2.7	5.8					56	
Area mechanic	---	22	15	84	112	350		350	

Data from the surveys of 6/50, 10/49, 9/48, and 5/48 is from AEC 1950c; data from the surveys of 3/53 and 11/53 is from AEC1954b; and data from the survey of 5/56 is from AEC 1956a. Other data are from the references given in the column headings.

Table A-13. Plant 6 measured daily weighted average exposure concentrations.

Occupation	Weighted average concentration, alpha dpm/m^3								
	May 1956	May 1954	Oct 1953	Jan 1953	Jan 1952	Aug 1950	1949	Oct–Nov 1948	May 1948
Digest area lead operator	6	60	36	62	140	84		686	280
Digest operator	7.3	37	41	52	370	77		399	490
U-Con man #1	7.3								
U-Con man #2	14								
Feinc operator	6.2	96	38	110	175	154		980	840
Barium operator			38	130	144	126			280
Feed operator	40.8	23	100	150	110	126		910	476
C-3 wash filter operator		79	32	48	120	116		497	476
C-3 adjustments operator			22	420	120			497	476
C-3 centrifuge operator		42	630	52		140		567	476
Ore Room operator			140	170	370	392	350	13,720	4,970
Extraction area lead operator	34	5.4	4						
Ether House operator	11					40		46	
Ether House lead operator						66		154	
Sump recovery operator			8.5	100	76	126		273	364
Raffinate operator	216	11	8	170	68	154		273	364
QM-2 (orange) packager	268	1,961	120	130	130				
Furnace operator	12	33	55	96	150	1,400		5,320	24,500
Furnace room sampler								3,150	
Reduction area (furn room) lead oper'r	22	25	28	69	54	147		686	
LF-9 (brown) packager						364		11,270	39,200
Nitric acid recovery operator	20	9.6	19	44	35	99		46	364
Pot Room operator	234	113	45	190	100	336	770	7,770	32,200
Metal dissolver #1	204								
Metal dissolver #2	21								
MGX operator		29	68	52	94				
Utility operator	88	129	94	97					
Miller (Mill Room)						X	X	12,600	46,200
Pilot Plant group leader	7.5	6.9	3.1			105		91	245

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Occupation	Weighted average concentration, alpha dpm/m^3								
	May 1956	**May 1954**	**Oct 1953**	**Jan 1953**	**Jan 1952**	**Aug 1950**	**1949**	**Oct–Nov 1948**	**May 1948**
Pilot Plant lead operator	7.7	8.8	6.1	77	116	105		91	245
Pilot Plant technician	1,940	9.2	6	77	116	105		91	245
Production superintendent	7.7	8.8	56	25					
Experimental continuous furnace						8,540	X	X	X
Asst. production superintendent	18	21	26						
General/Asst foreman	14	18	30	50					
Foreman	17	21	29	58				161	
Technical supervisor	18	21	25	33		52		161	
Production Office clerk	9.1	12	18	17		27		161	
Production Office secretary	3.4	3.4				27			
Shift foreman	19	25	27	81	96			161	
Cloth & Training Grp lead operator			23	25				2,520	
Cloth operator		18	19	92		245		665	
Trainers						231		2,520	
Decontamination man	17	22	19	60	99				
Decontamination man	3.5	2.7	2.8	29					
Receiving clerk	5.2	19	4.5	10	99	28			
Cleanup man	22								
Production Research Lab personnel	3.7	2	5	13	30	12		30	245
Ledoux Lab asst technician (raffinate)	15.2	8.1	39						
Ledoux Lab technician (raffinate)	12.9	8.1	39	140	420	91		189	
Ledoux Lab technician (K-65)	21	7.5	27	440	1,900	1,400		2,100	
Ledoux Lab technician (MgF_2)	21	7.5	27						
Shotgun Lab analyst	24.1	10	27	23	25	239		24 (239)	
Laboratory personnel	42	2.9	30	23	21				
MCW Laboratory west section						21		30	245
MCW Laboratory east section						13		30	245
Powder sample technician	56.5					217?		448	
Metal room sampler	420								
Outside sampling man	22.5								
Sample Room supervisor	41					245		448	
Laboratory Office personnel	42	2	5.6						
Truck operator	16	19	20	63	75				

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Occupation	Weighted average concentration, alpha dpm/m^3								
	May 1956	**May 1954**	**Oct 1953**	**Jan 1953**	**Jan 1952**	**Aug 1950**	**1949**	**Oct–Nov 1948**	**May 1948**
Truck operator	20	19	20	63	75				
Warehouse foreman & Asst Foreman	4.2	2.9	6.2	17		70		161	
Warehouse man -- K-65 sampler			350	270	230	84		189	196
Warehouse man	5.8	10	20	38	46	84		189	196
Boiler House operator	9.3	7.3	7.5	8.9	2	36		44	
Laundry operator	6.2	19	11	19	4.5	13			
Porter	3.9	17	14			39			
General cleanup						39			
Change room						48			
Lunch room						5.6			
Clothes issue man	18	19	9.4	92					
Chief guard	1.7	14	16	14	1.8				
Security Office						6.3			
Guard	10	13	15	22	1.8	32			
Health Office–personnel (office)	1.6	6.7	15	14	0	11			
Health Office–personnel	8.1	11	15	14	0			7.0	14
Health Office personnel (plant monitor/health surveyor)	10	15	15	14	0	46			
Health Office person'l (plant monitor)	15	16	15	14	0				
Medic	1.3	3.5	6.3						
Nurse		3.5	6.3	42	99				
Dispensary & Safety						56		56	175
Instrument Shop technician	12	33	17	40	60	51			252
Instrument Shop machinist	5.5	44	17	27	60	51			252
Maintenance/mechanical supervisor	140	13	10	42	38	50			
Maintenance Office clerk	6.5	12	7.7	39					
Area mechanic	24	29	28						
Ore & Furnace Room AM						189			
Digest & feed AM						133			
Raffinate and C-3 AM						161			
Ether & NA House AM						77			
Welders, pipefitters, etc.						98		128	
Carpenters						66			
Stock Room (storeroom) foreman	3.7	14	22	13	33	21			
Stock Room clerk	2.6	9	34	15	33	21			
AEC Office personnel		2.2	1.8	6.7	0	Non-det		7.7	33
AEC Engineer		19	9.9	31	7				
MCW Office personnel	1.5	2	2.9	0.7	0			7.0	50

Occupation	Weighted average concentration, alpha dpm/m^3								
	May 1956	**May 1954**	**Oct 1953**	**Jan 1953**	**Jan 1952**	**Aug 1950**	**1949**	**Oct–Nov 1948**	**May 1948**
MCW engineer	4.2	4.5	5.4	10	7	15			
MCW Office messenger	15	14	15	40					
MCW Office maintenance	7.5	12	20	10					
MCW Office construction expeditor			9.6	29					
Overall average weighted exposure	41	24	25	56	63				

The first set of 1948 data (Oct–Nov 1948) is from MCW (MCW 1949d (repeated in AEC 1949b and MCW 1950s), the second set (May 1948). The 1949 and 1950 data are from MCW (MCW 1950q) and AEC(AEC 1953); the May 1952, January 1953, and the October 1953 sets of survey data are from AEC (AEC 1954c); the May 1954 survey data are from AEC (AEC 1954d); and the May 1956 survey data are from AEC (AEC 1956b). For some occupations (mostly office types), the May 1948 concentration was the average in the work area, not a DWE, so that the level shown would be higher than what the worker actually experienced.

Table A-14. Plant 6E measured daily weighted average exposure concentrations.

Occupation	Weighted average concentration, alpha dpm/m^3					
	7/1956	**3/1955**	**6/1954**	**11/1953**	**4/1953**	**10/1952**
Lime blender/Slag blender	5.7	11	13	8.9	19	8.9
Jolter	15	79	18	8.9	17	25
Utility operator	50	38	33	32	56	37
Top/Upper “F” machine operator	23	100	46	12	85	25
Bottom/Lower “F” machine operator	29	52	24	13	17	23
Top(ping)-off man	24	113	17	13	17	28
Reduction furnace operator	7.2	20	7.4	6.8	17	14
Breakout operator/man	23	42	28	23	42	25
Residue man	24	300	115	210	80	66
Reduction (KB-2) lead operator	21	36	26	24	36	45
Furnace loaders				23	16	15
Crucible loader	60	19	49	43	130	28
Burnout man	39	31	23	26	26	160
Crucible assembler	42	32	31	58	43	81
Upper/Top furnace operator/man	26	28	30	23	16	21
Bottom furnace operator/man	41	107	118	34	28	68
Saw operator/man	13	425	34	49	17	30
4th or cage saw man		38	21	66	94	17
Cage/cage grinding man	349	35	20	55	166	55
Billet grinder	668	425	34			
Brushing man		47				
Brushing man/chipper	19	2,110				
Recast furnace (YM-5) lead operator	71	30	47	21	19	49
Production machinist	7	11	7.5	10	17	380
Mechanic	73	36	23			
Millwright	14	36	23			
Maintenance man	27	36	23	53	26	45
Porter	15	23	12	19	8.8	42
Production clerk	9.5	14	7.8	18	13	13

Occupation	Weighted average concentration, alpha dpm/m^3					
	7/1956	3/1955	6/1954	11/1953	4/1953	10/1952
Technical superintendent	4.4	24	15			
Technical/Chemical engineer	5.7	24	15	11	16	27
Shift foreman	12	31	23	17	17	44
Foreman/General foreman	6.1	27	19	12	13	20
Lift truck driver	8	22	17	14	15	30
Electrician		35	14	43	34	
Decontamination man	15	34	24	21	21	
Slag building operator	18	224	110			
Average of all personnel	44	113	30	33	43	55

The 10/52, 4/53, and 2/54 sets of data are from AEC (AEC 1954d); the 6/54 survey data are from AEC (AEC 1954e); the 3/55 survey data are from AEC (1955e); and the 7/56 survey data are from AEC (AEC 1956c).

Table A-15. Plant 7 measured daily weighted average exposure concentrations.

Occupation	Weighted average concentration, alpha dpm/m^3						
	7/1956	3/1955	6/1954	11/1953	4–5/1953	10/1952	9/1951
Utility operator/man	17	18	23	77	14	28	9
Area mechanic	12	12	6	11	63	14	37
Welder	14	13	7	10	14	14	
Porter	32	25	13	6	14	14	
Lift truck operator/driver	41	26	14	6	14	14	
HF operator	5.3	5	5	4	14	14	8
TA-7 hoisting operator	17	11	13	11	14	14	
Furnace operator	14	16	10	120	14	21	25
Sampler and cleanup man	9.1	8	8	530	42	28	
36’ Level operator	19	6	5	20	14	14	
Panel board operator	16	30	16	7	21	21	
TA-7 packager	24	49	68	150	56	28	242
QM-2 dumper/hoister	56	74	48	42	63	112	107
Magnesium Room operator	4.5						
Foreman	15	16	7	6	14	21	28
Assistant foreman					8	21	22
Asst plant superintendent	32	70	7				
Technical supervisor	18	15	6				
Engineer		70	7	13	7	14	
Lead operator	30	17	9	12	14	21	38
Clerk/Record clerk	20	32	8	6	14	21	
Decontamination/-ator	18	17	9	10	14	21	
Safety inspector		9	12	16	28		
Fire marshal		9	12	16			
Safety clerk		14	9	17			
Average for all personnel	19	19	13	57	22	21	

The 9/51 survey data are from AEC (AEC 1951a); the 10/52 survey data are from AEC (AEC 1952a); the 4–5/53 and 11/53 survey data are from AEC (AEC 1954f); the 6/54 survey data are from AEC (AEC 1954g); the 3/55 survey data are from AEC (AEC 1955d); and the 7/56 survey data are from AEC (AEC 1956d).

The 5/53 data includes the screw-pulling operation, which was nonroutine.

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Table A-16. Plant 7E measured daily weighted average exposure concentrations.

Occupation	Weighted average concentration, alpha dpm/m^3, 3/1955
Ionium plant operator	0.06
Ionium plant lead operator	0.1
Overall average	0.07

Survey data are from AEC (1955e). The ionium plant was the thorium processing plant, in operation from mid-1955 through March 1957. Some bench-scale processing was done in the spring of 1955 also.

Table A-17. Average and highest airborne dust concentrations in the laundry (alpha dpm/m^3) (Utnage 1958b, Table 2).

	Concentration	
	Average	Worst
Operation		
Load washer with coveralls	560	820
Load dryer with coveralls	50	140
Unload dryer with coveralls	20	70
Press white coveralls	40	55
Repair white coveralls	60	90
Sorting to wash	20	870
Weighted average by job		
Washer operator	50	
Presser	40	
Repairman	40	
Sorting and handling	30	140
Average general air in laundry	20	110

"Worst" measurements for sorting and handling were taken with no ventilation; "Worst" measurements for the general air case were taken with ventilation turned off for 4 hours.

"Average" measurements were taken with ventilation on. The worst "average" air in the general area case was found in the vicinity of handling and loading into the washer.

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Table A-18. Job titles and classifications, with geometry factors.

Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
7	36' Level operator	Subclassification of 7 Furnace operator (rotating jobs): mainly the UO_2-to-UF_4 reactor area	---	---	---
6E	4th saw man	Mostly same as Saw man	90	10	
6	AEC engineer	Spent time in Plants 4, 6, 6E, and 7 but office was in 6	10	90	
6	AEC Office personnel	Spent time only in AEC office in Plant 6		100	
All	Area mechanic	May have worked in all buildings, but appears that he was usually dedicated to one building or process step	50	50	
6E	Asst foreman	See Shift foreman	50	50	
7	Asst plant superintendent	May have been in charge of only Plant 7 or of the whole site	10	90	
6	Asst production superintendent	Assumed to have spent time in Plants 6, 6E, and 7 production areas as well as Plant 6 offices, as the production superintendent did	50	50	
6	Asst warehouse foreman	Worked in the U products warehouse, apparently	25	75	
6	Bag inspector	Checked dust collector bags	75	25	
6	Barium operator	Worked in the barium salt addition phase of digestion	50	25	25
6E	Billet grinder	Cleaned and finished billets after recasting and before shipping	90	10	
4, 6E	Blender	See Lime blender	50	50	
6	Boiler House operator	Presumably worked to provide steam for the boildown processes		100	
4	Bomb charger	Blended UF_4, Mg; charged bomb; dumped out dust collectors	75	25	
4	Bomb makeup operator	Blended UF_4, Mg; charged bomb; dumped out dust collectors	75	25	
4	Bomb makeup/deslagging (slag grinding) operator	Performed combined functions of Bomb makeup operator and Slag grinding operator	75	25	
6E	Bottom "F" machine operator	Charged bomb (using F machine): UF_4-Mg mixture, Mg	75		25
4, 6E	Bottom furnace operator/man	Removed assembly from recast furnace, removed mold, put in new assembly	75	25	
6E	Breakout operator/man	Removed (broke out) derby from bomb	75	25	
6	Brown furnace operator/ unloader/ packager	See UO_2 operator/unloader/packager	75	25	
6E	Brushing man	Same as Chipper	75	25	
6E	Burnout man	Removed broken crucible, knocking lid off	80	20	
6	C-3 adjustments operator	Cleaned wash precipitate filter press; other duties	50	25	25
6	C-3 centrifuge operator	Operated and "plowed off" Bird(?) centrifuge (digestion process)	50	25	25
6	C-3 wash filter operator	Operated and cleaned the wash precipitate filter press	50	25	25
6E	Cage grinding man	Mostly same as Saw man	90	10	
4, 6E	Cage operator/man	Cleaned and finished billets after recasting; handled scrap in cage	90	10	
6E	Cage saw man	Mostly same as Saw man	90	10	

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Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
6E	Capping man	Put the valved top on the Mg-UF4 drum for jolting?	75	25	
4	Carpenter	May have worked in all buildings, not dedicated to one	25	50	25
4	Casting operator/man	Operated the billet casting furnace	75	25	
6	C. Eng	See Chemical engineer	25	75	
4	Ceramic (technician?)	Split time: ceramic lab (Ceramic Pilot Plant), Production Research Lab	50	50	
4	Charger	Same as Bomb charger	75	25	
4	Charge firing (man)	Furnace operator for bomb furnace	75	25	
6E	Chemical engineer	Worked in production aspects; had production area access	25	75	
4	Chemical technician	Did chemical analyses in Analytical Lab; possibly some assays	90	10	
4	Chemist	Did chemical analyses in Analytical Lab; possibly some assays	90	10	
4	Chief chemist	Did chemical analyses in Analytical Lab; possibly some assays	90	10	
6	Chief guard	Spent time in Plants 4, 6, 6E, and 7 but base was in Plant 6		100	
4, 6E	Chipper	Deslagged and cleaned derbies (and dingots?)	75	25	
4, 6	Cleanup man	Miscellaneous cleanup activities	50	50	
4, 6E, 7	Clerk	Plant 7 clerk worked in Plant 6E as well as inventorying in the Plant 7 production area; Plant 4 clerk may have been same person(s)		100	
6	Cloth operator/man	Cut and replaced filter cloth for Feinc and similar filters	50	25	25
6	Cloth & Training Group lead operator	Apparently dual position: coordinated cloth ops, headed Training Grp	10	90	
6	Clothes issue man	Issued work and protective clothing in the locker rooms		100	
6E	Crucible assembler	Assembled crucible and mold assembly in billet production process	75		25
6E	Crucible loader	Loaded the crucible assembly into the recast furnace	75		25
6,6E,7	Decontamination man	Did decontamination in all plants, on boxcars, in Plant 6 Decon Room	50	25	25
7	Decontaminator	Same as Decontamination man	50	25	25
6E	Derby chipper	Same as Chipper	75	25	
4	Derby unloader	Unloaded bomb from furnace	75	25	
6	Digest area lead operator	Worked on the digestion process (up to extraction)	50	25	25
4	Dingot operator/forging	Prepared, loaded, removed dingot bomb; probably operated furnace	50	25	25
6	Dispensary (personnel)	Medical-pharmaceutical personnel; no prod area access assumed		100	
6E	Electrician	May have worked in all buildings, not dedicated to one	25	50	25
4, 6E, 7	Engineer	Assumed to be the process engineer assigned to individual plant; may have worked in all; had production area access	25	75	
6	Ether House operator	Worked in the Ether House (operating tanks, valves, etc.)	50	50	
6	Experimental Continuous Furnace	Pilot Plant project for eventual plant-scale use in Plant 7	25	50	25
6	Extraction area lead operator	Worked on the extraction process (up through UO3 production?)	50	25	25

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Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
6E	Extra man	Presumably a "floating" worker (cf. Utility man)	50	50	
6E	F (machine) charger	Loaded Mg, UF_4 into bomb and sealed it; may have blended them	75		25
6E	F machine operator	Charged bomb (using F machine): UF_4-Mg mixture, Mg	75		25
6	Feed operator	Loaded black oxide and other feeds for digestion; washed out feed Niagara; may have handled other aspects of the ore-to-UO_3 process	50	25	25
6	Feed sampling	Sampling of feed (soda sat, MGX, etc.)	50	25	25
6	Feinc operator	Operated Feinc filter; cleaned out cake; washed out feed Niagara	50	25	25
7	Filter operator	Operated solids-removal(?) filters in Slag Separation Plant (Bldg 701)	50	50	
7	Fire Marshall	Did inspections in Plants 4, 6, 6E, and 7, but base was in Plant 6		90	10
All	Foreman	Apparently dedicated to individual plant, but may have worked in more	50	50	
4	Forge press lead operator	Operated the forge press in dingot finishing	75		25
4	Forge press manipulator	Same as Forge press operator	75		25
4	Forge press operator	Operated the forge press in dingot finishing	75		25
4	Forge press salt bath man	Operated the salt bath segment of dingot finishing	75	25	
All	Fork truck operator/driver	Same as lift truck driver; some did work at SLAPS and with railcars	25	75	
4	Furnace and saw man	Divided duties: see Furnace operator and Saw man	75	25	
4, 6E	Furnace loader	Loaded bomb or crucible assembly into furnace, depending on plant	75		25
4, 6E	Furnace operator	Operated recasting (billet) furnace	75		25
6	Furnace operator	Operated the UO3-to-UO2 (Rockwell) furnace	75	25	
7	Furnace operator	Job (Plant 7) rotated 36' Level, Panel Board, and Sampler & Cleanup tasks: see individual job titles	75	10	15
4	Furnace puller	Unloaded UO_2-to-UF_4 furnace?	75	10	15
4	Furnace tender	Tended UO_2-to-UF_4 furnace	75		25
6E	Furnace unloader	Unloaded bombs from furnace, cleaned out residue(?)	75		25
6, 6E, 7	General foreman	UF_4 production (for Plant 6E); or may have spent time in all plants	50	50	
6E	Graphite shop personnel	Assumed to be doing only clean work manufacturing graphite molds		100	
7	Green packager	Packaged UF_4 (green salt)	75	25	
4	Grinding and lead operator	Apparently work in the dingot area	50	25	25
All	Guard	Spent time in Plants 4, 6, 6E, and 7 and SLAPS but base was in 6		75	25
6	Health Office–office personnel	Assumed to spend all time in Health Office		100	

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Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
6	Health Office–other personnel	Spent time in Plants 4, 6, 6E, and 7 but base in 6; assume no production area access		100	
6	Health Office–plant monitor	Spent time in Plants 4, 6, 6E, 7 but base in 6; production area access	50	50	
6	Health Office–health surveyor	Spent time in Plants 4, 6, 6E, 7 but base in 6; production area access	50	50	
4, 7	HF operator	Spent some time at Bird centrifuge (7), in recovery areas (7), as well as in providing HF for the hydrofluorination process (UO_2-to-UF_4)(4,7)	10	90	
7	Hoisting (slag) operator	Worked in the Slag Separation Plant (Bldg 701)	50		50
6	Instrument Shop machinist	Worked only in Instrument Shop; some equipment contaminated	10	90	
6	Instrument Shop technician	Spent time in Plants 4, 6, 6E and 7 but base in 6 (Instrument Shop); production area access	25	75	
7E	Ionium plant lead operator	Th-230 processing (mostly operating chemical tanks and filters)	75	25	
7E	Ionium plant operator	Th-230 processing (mostly operating chemical tanks and filters)	75	25	
4, 6E	Jolter	"Jolted" (air hammer?) bomb liner, other material to compress, remove	75	25	
6	K-65 sampler	See Warehouse man: K-65 sampler	90	10	
4, 6E	KB-2 lead operator	Handled all aspects of derby (KB-2 production)	75	15	10
6	Laboratory Office personnel	Worked in the Analytical Lab (Building 102)		100	
6	Laboratory personnel	Worked in the Analytical Lab (Building 102)	90	10	
6	Laundry lead operator	Handled operations at the laundry (incl contaminated items)	10	90	
6	Laundry operator	Laundered work and protective clothing (incl contaminated items)	10	90	
4, 6, 6E, 7	Lead Operator	Generic: see specific titles; otherwise, (default) geometry factors at right may be used	75	25	
6	Ledoux Lab asst tech (raff)	Worked in the Ledoux Lab pulverizing, prepping, assaying raffinate	90	10	
6	Ledoux Lab technician (raff)	Worked in the Ledoux Lab pulverizing, prepping, assaying raffinate	90	10	
6	Ledoux Lab technician (K-65)	Worked in the Ledoux Lab assaying K-65 residue	90	10	
6	Ledoux Lab technician (MgF_2)	Worked in the Ledoux Lab assaying MgF_2, incl recycle MgF_2	90	10	
4	LF-9 (furnace) loader	See Furnace loader, Furnace operator for Plant 4 (UO_2-to-UF_4)	75	25	
6	LF-9 unloader/packager	See UO_2 operator/unloader/packager	75	25	
6E, 7	Lift truck driver (operator)	Drove lift truck, handling miscellaneous materials, possibly at all plants, including SLAPS	25	75	
4, 6E	Lime blender	Charge blender for derby production	50	50	
4	Magnesium operator	Handled magnesium storage and disbursal; limited exposure potential?	75	25	

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Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
7	Magnesium Room operator	Handled magnesium storage and disbursal; limited exposure potential?		100	
6E	Maintenance man	May have worked in all buildings; assume production area access	50	50	
6	Maintenance Office clerk	Worked only in Maintenance Office		100	
6	Maintenance supervisor	Spent time in Plants 4, 6, 6E and 7 but base was in 6 (same person?)	25	75	
	Manufacturing	Generic term for process/storage area work	75	25	
4, 7W	Metal fab	Metal fabrication, i.e., the derby and recast or dingot areas	50	50	
6	MCW engineer	Spent time in Plants 4, 6, 6E and 7 but base was in 6	10	90	
6	MCW Lab (personnel)	This lab was not the Ledoux, Shotgun, or Research Labs, which were listed separately in the records; perhaps the Analytical Lab	25	75	
6	MCW Office construction expeditor	Spent time in Plants 4, 6, 6E, and 7, but probably only in office and construction areas		100	
6	MCW Office maintenance	Spent time in Plants 4, 6, 6E, and 7, but apparently only in office areas		100	
6	MCW Office messenger	Spent time in Plants 4, 6, 6E, and 7, but probably only in office areas		100	
6	MCW Office personnel	Spent time only in MCW offices in Plant 6 (Bldg 112?)		100	
All	Mechanic	See Area mechanic	50	50	
6	Mechanic supervisor	See Maintenance supervisor	50	50	
6	Medic	Worked in dispensary presumably, but may have gone into production areas on occasion		100	
6	Metal dissolver (#1, #2)	Dissolved scrap U metal in acid for recycling as feed? Also spent up to half time in Pot Room	75	25	
6	Metal room sampler	Sampled scrap and other metal for U or content?	75	25	
6	MgX operator	Processed the MgX feed material	25	50	25
4	Microscopist	Worked full-time in the Microscopy Room, probably on U specimens		100	
4, 6	Miller	Performed the UF4 pulverizing (4)? Milled UO_3 (orange oxide)(6)	50	50	
6E	Millwright	May have worked in all buildings, not dedicated to one	25	50	25
6	Nitric acid recovery operator	Worked in the nitric acid recovery area (several buildings)	50	25	25
6	Nurse	Worked in dispensary presumably, but may have gone into production areas on occasion		100	
4, 6E	Office employees	Assume they are Plants 4 and 6E production(?) office-only personnel		100	
6	Ore Room operator	Handled ore, residue: storage, lidding, delidding, cleaning drums	70	20	10
6	Outside sampling man	Sampled dust collectors; sampled drums (incl. opening and sealing)	50	50	

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Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
7	Panel board operator	Subclassification of 7 Furnace operator (rotating jobs): vacuuming C-3 into reverter, sampling D-30 material, replacing D-30 drums, work at panel board area including reverter operation	---	---	---
6	Pickler	Worker in area where derbies were “pickled,” i.e., put into acid bath	75	25	
6	Pilot Plant engineer	Participated in experimental extraction processes and like activities	25	75	
6	Pilot Plant group leader	Participated in experimental extraction processes and like activities	75	25	
6	Pilot Plant lead operator	Participated in experimental extraction processes and like activities	75	25	
6	Pilot Plant technician	Unclear what activities this Pilot Plant was carrying on	75	25	
6	Pipefitter	May have worked in all buildings, not dedicated to one	50		50
4	Plant superintendent	May have been in charge of only Plant 4 or of the whole site	10	90	
4, 6, 6E, 7	Porter	Some porters may have worked in a janitorial capacity, entering only office areas, while others apparently served production areas; may have worked in several plants or in only one		100	
6	Pot Room operator	Worked in the denitration (UO_2-to-UF_4) pot room	50	25	25
6	Powder sample technician	Assume mainly did sampling and worked with small samples	75	25	
6E	Production clerk	Kept records, did inventories; assumed to spend some time in production area		100	
6E	Production machinist	Spent all time in graphite shop machining molds and the like		100	
6	Production Office clerk	Kept records, did inventories; assumed to spend some time in production area		100	
6	Production Office secretary	Assumed spent all time in office		100	
6	Prod Research Lab personnel	Worked in the Production Research Lab	90	10	
6	Production superintendent	Spent time in Plants 6, 6E, and 7 production areas and Plant 6 offices	50	50	
7	QM-2 dumper	Loaded UO_3 into trays for the UO_3-to-UF_4 conversion	75	15	10
7	QM-2 hoister	Same as QM-2 dumper	75	15	10
6	QM-2 loader	See UO_3 loader	75	25	
6	QM-2 (orange) packager	“Gulped” (vacuum-extracted) UO_3 out of the pot and into drums; weighing and making up (weight) in drums, emptying dust collectors	75	15	10
6	Raffinate operator	Handled the various residues from the filters (drummed, sampled); spent up to half time in Pot Room	75	25	
6E	Recast furnace lead operator	Operated the billet casting furnace	50		50

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Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
6	Receiving clerk	Recorded and inventoried incoming shipments of ore and U products	50	50	
7	Record clerk (A, B)	Kept records of receipts, production, and shipments; some entry into production areas and outside areas for inventory and like purposes		100	
6	Reduction (area) lead operator	Operated UO_2 (Rockwell) furnace; assumed to load UO_3, unload UO_2	75	25	
6E	Reduction (area) lead operator	Operated the bomb (UF_4-to-U metal) furnace	50	25	25
6E	Reduction furnace operator	Operated the bomb (UF_4-to-U metal) furnace	50	25	25
4,6E	Residue man	Changed derby chip drums and Hoffman and Mikro dust collectors; cleaned residue from the plate and frame press; picked out KB-2	75		25
7	Safety clerk	Worked full-time in the Safety Office		100	
7	Safety inspector	Did inspections in Plants 4, 6, 6E, and 7 (production area access)	10	80	10
4	Salt bath man	Same as Forge press salt bath man	75	25	
7	Sampler and cleanup man	Subclassification of 7 Furnace operator (rotating jobs): sampling UF_4, cleanup of furnace platforms	---	---	---
6	Sample Room supervisor	Supervisor operations in the Sample Room (probably in Bldg 111)	75	25	
4,6E	Saw operator/man	Removed billet from quench tank; ground, sawed, and weighed it	90	10	
6	Security office (personnel)	Assumed to be other than guards (e.g., clerical)		100	
6,6E	Shift foreman	Assumed to be generic, although may have covered several plants; default geometry factors at right may be used	50	50	
4	Shipping & Receiving (personnel)	Handled the receipt and shipment of U products	50	50	
6	Shotgun Lab analyst	Worked in Shotgun (sample assay) Lab, first in Bldg 55 in Plant 2, then Bldg 108 in Plant 6, then Bldg 102(?) of Plant 6	90	10	
6E	Slag blender	Blended C-liner and other slag from Plants 4 and 6 for use in bombs	75	25	
6E	Slag building operator	Ground C-liner and other slag, sorted it via shaker tables, drummed it	75	25	
4	Slag man, slag grinding operator	Mostly the same as Chipper	75	25	
6	Soluble feed operator	Loaded soda salt (“diuranate”) at appropriate point in digestion process; see also Feed operator	75		25
6	Stockroom clerk	Stockroom possibly in Bldg 112. Spent time in Receiving (Bldg 101)		100	
6	Stockroom foreman	Stockroom possibly in Bldg 112. Spent time in Receiving (Bldg 101)		100	
6	Sump recovery operator	Worked on U recovery from sump fluids	25	50	25

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Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
6E	Supervisor	Probably same as Technical supervisor	50	50	
7	TA-7 hoisting operator (hoister)	Hoisted and loaded UO2 into reactor for conversion to UF_4 (TA-7)	25	50	25
4,7	TA-7 packager	Packaged UF_4 (green salt)	75	25	
4	TA-7 Pilot Plant (personnel)	Assumed to be technicians and operators producing UF_4 (green salt)	50	50	
4	TA-7 unloader (operator)	Unloaded UF_4 (green salt) from hydrofluorination reactor	50	50	
7	Tables operator	Worked in the Slag Separation Plant (701) operating shaker tables	25	75	
6E	Technical engineer	Same as Chemical engineer or (Process) Engineer	25	75	
6E	Technical superintendent	May have spent time in all the plants	25	75	
All?	Technical supervisor	Unclear what duties were; probable frequent production area access	50	50	
	Tinner	Type of metal worker	25	50	25
4	Top cleaner	Cleaned top furnace in billet (YM-5) production; not Top seat man	75	25	
6E	Top "F" machine operator	Charged bomb (using F machine): UF_4-Mg mixture, Mg	75		25
6E	Top furnace operator/man	Operated recasting (billet) furnace, removed crucible parts	50		50
6E	Top-off operator/man	"Topped off" bomb with slag, bolted on lid	75	25	
4	Topper	Same as Top-off operator?	75	25	
4	Top seat man	Involved in billet production, furnace area; same as Top-off operator?	75	25	
6	Trainer	Duties not clear. Assumed to train operators, especially in filter work	10	90	
6	Trainman	Associated with packing/unloading of railcars; perhaps was railcar dispatcher/coordinator/inspector; associated with the warehouse	25	50	10
6	Truck operator/driver	Spent time in Plants 6, 6E, and 7 areas; radiation most likely from the back in hauling, the front in loading: * 50 AP, 25 PA, 25 ROT	*		
6	UO_2 (furnace) operator	Operated the UO_3-to-UO_2 (Rockwell) furnace	75	25	
6	UO_2 unloader/packager	Unloaded UO_2 from the Rockwell furnace, packaged it	75	25	
4	UO_3 & brown packer	Loaded UO_2 into Rockwell furnace; unclear regarding UO_2	75	25	
6	UO_3 loader	Loader UO_3 onto trays and into the Rockwell furnace (may have been collateral duty of the UO_2 furnace operator)	75	25	
6E	Upper furnace man	Same as top furnace man	50		50
6	U-con man (#1, #2)	Handled U-containing slurry from Slag Sep Plant that went to Plant 6	50	25	25
7	Utility operator/man	Worked on various production jobs	50	25	25
6,6E	Utility operator	Average of all production jobs for the respective plant	75	25	
4	Vacuum fusion chemist	Worked in office and vacuum fusion area; did some hands-on U work	90	10	
4	Vacuum fusion technician	Worked in office and vacuum fusion area; did some hands-on U work	90	10	
4	Vertical lathe (operator)	Scalped dingot after casting and before forge-pressing	75		25

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Plant	Job title or classification	Notes	Geometry classification, %		
			AP	ROT	ISO
6	Warehouse foreman	Handled storage of ore and U products	25	75	
6	Warehouse man: K-65 sampler	New job, 1953: sampled K-65 residue, plus typical warehouse duties	90	10	
6	Warehouse man (other)	Handled storage of ore and U products	25	75	
6	Weighmaster	Duties not clear. Assumed to perform or approve ore, K-65 weighings	25	75	
6,7	Welder	May have worked in all buildings, not dedicated to one	10	90	
6E	YM-5 lead operator	Worked on billet (YM-5) casting	80	20	

Since these classifications are mostly based on later records (after the UO_3-to-UF_4 direct process was established at Plant 7), UO_2 (brown oxide, LF-9) unloading and packaging classifications and UO_3 (orange oxide, QM-2) milling and loading classifications have been added for Plant 6.

Table A-19. Uranium dust daily weighted average exposure levels, Plant 4.

Job title	Airborne dust exposures, alpha dpm/m^3								
	Oct 1942–1946	1947	1948–1949	1950	1951	1952–1953	1954–1955	1956–1958	1957–1958
Mechanic/area mechanic	350	350	350	84	15	15	22	22	X
Blender/bomb charger/ charger/ bomb makeup/ dingot operator/ slag grinding operator	3,010	3,010	3,010	210	64	64	33	85	X
Cage operator/man	3,640	3,640	3,640	190	X	X	X	X	X
Carpenter/other craft	140	140	140	84	15	15	22	22	X
Casting operator/furnace operator/top seat man	5,100	910	980	140	480	480	110	11	X
Lab: ceramics/microscopy	X?	X?	X?	X?	18	18	18	18	X
Charge firing (man)	931	910	980	140	X	X	X	X	X
Chemist/chief chemist/chemical technician	40	40	40	40	7	7	10	10	X
Chipper/cleanup man/Saw operator/man	1,890	1,890	910	140	140	140	140	140	140
Derby unloader	350	280	1,260	175	X	X	X	X	X
Foreman/shift foreman/engineer/technical supervisor	175	175	175	56	12	12	10	23	X
Forge press operator/lead operator/manipulator[a]	X	X	X	X	X	23	23	23	X
Furnace and saw man	X	X	X	X	18	18	18	18	X
Furnace loader (UF_4-derby)	3,360	3,360	2,240	280	X	X	X	X	X
Furnace tender	560	560	350	70	X	X	X	X	X
Guard/Chief guard	28	28	28	28	28	5.8	2.7	7.1	X
HF (fluorination) operator	570	570	570	70	X	X	X	X	X
Jolter	3,500	3,500	490	70	X	X	X	X	X
KB-2/YM-5/dingot lead operator/Furnace puller	931	630	560	35	19	19	8.2	19	X
UO_2/LF-9 loader/packer	4,200	3,360	2,240	280	X	X	X	X	X

Job title	Airborne dust exposures, alpha dpm/m^3								
	Oct 1942–1946	**1947**	**1948–1949**	**1950**	**1951**	**1952–1953**	**1954–1955**	**1956–1958**	**1957–1958**
Lime blender/magnesium operator	70	70	70	35	X	X	X	X	X
Miller-mixer (UF4/TA-7)/top cleaner	4,690	4,690	980	70	X	X	X	X	X
Office: plant superintendent/ clerk/other	42	42	42	42	42	5.8	2.7	7.3	X
Porter	112	112	112	56	56	5.8	2.7	40	X
Residue man/salt bath man/Vertical lathe operator	X	X	X	X	X	X	28	28	X
Shipping & receiving	126	126	126	126	15	15	22	22	X
Slag man/slag grinding operator	140	140	210	70	X	X	X	X	X
TA-7 packager	7,210	7,210	7,210	245	X	X	X	X	X
TA-7 unloader (operator)	13,000	13,000	1,540	210	X	X	X	X	X
Topper	840	840	2,310	210	X	X	X	X	X
Vacuum fusion[a]: chemist/technician	X?	X?	X?	X?	X?	59	59	59	X

This table is derived from the data given in Table A-12 and from supplementary information in the references.

An "X" indicates that the job title did not exist during the indicated period. An "X?" indicates that it is uncertain if the job title existed, i.e., it is not certain when that job began.

a. Work started in 1953.

Table A-20. Uranium dust daily weighted average exposure levels, Plant 6.

Job title	Airborne dust exposures, alpha dpm/m3							
	1946–1948	**1949**	**1950**	**1951**	**1952**	**1953**	**1954**	**1955–1958**
AEC engineer	X?	X?	X?	7	31	9.9	19	19
Barium operator	1.8	1.8	126	144	130	38	X	X
C-3 centrifuge/wash filter/adjustments operator	567	567	140	140	420	630	79	79
Cleanup man/utility operator	X	X	X?	97	97	94	129	88
Cloth operator	665	665	245	245	92	19	18	18
Cloth & training group lead operator/trainer	2,520	2,520	231	231	23	25	18	18
Clothes issue man	92	92	92	92	92	9.4	19	18
Crafts: carpenter/ pipefitter/welder	126	126	98	28	28	28	29	24
Decontamination man/ U-Con man[a]	99	99	99	99	60	19	22	17
Cloth/digest/reduction operator, outside sampling[a]	686	686	245	370	92	41	60	22

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Job title	Airborne dust exposures, alpha dpm/m3							
	1946–1948	**1949**	**1950**	**1951**	**1952**	**1953**	**1954**	**1955–1958**
Dispensary: nurse/medic/other (personnel)	175	175	56	99	42	6.3	3.5	1.3
Boiler/Ether House/ extraction /nitric acid recovery operator	46	46	99	50	44	19	11	34
"Experimental Continuous Furnace": Pilot Plant project[b]	X?	8,540	8,540	X?	X	X	X	X
Feinc/feed/soluble feed operator	980	980	154	175	150	100	96	41
Foreman/general foreman/shift foreman/technical supervisor	161	161	161	96	81	30	25	19
Furnace operator	24,780	24,780	1,400	150	96	55	33	12
Guard/chief guard	32	32	32	1.8	22	16	14	10
Health/security office personnel; engineer (MCW, chemical)	15	15	15	7	14	15	11	8.1
Health office: health surveyor/plant monitor	46	46	46	42	14	15	16	15
Instrument shop machinist/technician	252	252	51	60	40	17	44	12
Laboratory office personnel	100	100	10	5.6	5.6	5.6	2	42
Laboratory personnel–generic/MCW/shotgun	245	245	24	25	23	30	10	42
Laundry operator/lead operator	X?	X?	X?	4.5	19	11	19	6.2
Ledoux Lab technician/assistant technician–raffinate, MgF_2	189	189	91	420	140	39	8.1	27
Ledoux Lab technician (K-65)	2,100	2,100	1,400	1,900	440	27	7.5	21
LF-9/brown/UO_2 packager/unloader	38,990	38,990	364	350	350	X	X	X
Maintenance supervisor	50	50	50	38	42	10	13	140
Mechanic/Area mechanic: ore & furnace room, digest & feed, raffinate & C-3, Ether House, Nitric Acid House	189	189	2.7	28	28	28	29	24
Metal dissolver (#1, #2)	X?	X?	X?	204	204	204	204	204

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Job title	Airborne dust exposures, alpha dpm/m3							
	1946–1948	**1949**	**1950**	**1951**	**1952**	**1953**	**1954**	**1955–1958**
Metal room sampler	X?	X?	X?	420	420	420	420	420
MgX operator	94	94	94	94	52	68	29	29
Miller (UO_3/QM-2)[c]	12,600	12,600	X	X	X	X	X	X
Office: MCW–clerk/maintenance/messenger/porter/expeditor	50	50	50	48	48	20	17	15
Office: MCW–other, AEC–all AEC except engineer	50	50	50	0	6.7	2.9	2.2	2.2
Office: production–clerk/secretary, receiving–clerk	161	161	52	99	17	18	19	9.1
Ore Room operator[C]	13,720	350	392	370	170	140	140	X
Pilot Plant engineer	123	123	53	58	39	3.1	6.9	7.5
Pilot Plant lead operator/group leader	245	245	105	116	77	6.1	8.8	7.7
Pilot Plant technician	245	245	105	116	77	6	9.2	1,940
Pot Room operator	7,770	770	336	100	190	45	113	234
Powder sample technician	3,150	3,150	217	217	57	57	57	57
Prod Research Lab personnel	84	84	12	30	13	5	2	3.7
Production superintendent/asst production superintendent	25	25	25	25	26	56	21	18
QM-2 (orange) loader	5,320	5,320	1,400	420	420	420	X	X
QM-2 (orange) packager	1,400	1,400	1,400	420	130	130	120	[e]
Raffinate/Sump recovery operator	273	273	154	76	170	8.5	11	216
Sample Room supervisor	448	448	245	245	245	41	41	41
Stockroom foreman/clerk	21	21	21	33	15	34	14	3.7
Truck/forktruck operator/driver	75	75	75	75	63	20	19	20
Warehouse foreman/assistant foreman/warehouseman	196	196	84	70	38	20	10	5.8
Warehouse K-65 sampler/weighmaster[d]	196	196	84	230	270	350	350	X?

This table is derived from the data given in Table A-13 and from supplementary information in the references.

An "X" indicates that the job title did not exist during the indicated period. An "X?" indicates that it is uncertain if the job title existed, i.e., it is not certain when that job began.

a. Outside sampling and U-Con positions began in 1955
b. Pilot Plant work began in 1948.
c. Milling work ended by June 1949.
d. These jobs apparently ended in 1954 or were subsumed in other job titles
e. 1961 dpm/m3 in 1955, 268 in 1956–58

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Table A-21. Uranium dust daily weighted average exposure levels, Plant 6E.

Job title	Airborne dust exposures, alpha dpm/m^3				
	Oct 1950–Dec 1952	1953	1954	1955	1956–1958
Area mechanic	23	23	23	36	73
Billet grinder	34	34	34	425	668
Blender; lime/slag blender	8.9	14	13	11	5.7
Bottom/Lower “F” machine operator	23	15	24	52	29
Breakout operator/man	25	33	28	42	23
Brushing man	X	X	X	47	47
Burnout man	160	26	23	31	39
Cage grinding/cage operator/man	55	111	20	35	349
Cage/4th saw man	17	80	21	38	38
Capping man/crucible assembler	81	51	31	32	42
Chipper/derby chipper	2,110	2,110	2,110	2,110	19
Crafts: maintenance/electrician/mechanic/millwright; graphite shop	45	40	23	36	73
Crucible loader	28	87	49	19	60
Engineer/chemical engineer/technical engineer; superintendent/supervisor	27	14	15	24	5.7
F (machine) charger/extra man/utility operator	37	44	33	38	50
Foreman/assistant foreman/general foreman	20	13	19	27	6.1
Furnace loader; reduction furnace operator	15	20	23	23	23
Furnace operator/unloader; bottom furnace operator; generic lead operator	68	31	118	107	41
KB-2/reduction lead operator; shift foreman; porter	45	40	26	36	27
Lift truck driver (operator)	30	15	17	22	8
Office employees/Clerk; production clerk	13	16	7.8	14	9.5
Production machinist	380	14	7.5	11	7
Recast furnaceYM-5 lead operator	49	20	47	30	71
Residue man	66	145	115	300	24
Saw operator/man	30	33	34	425	13
Slag building operator	110	110	110	224	18
Top/upper/generic “F” machine operator; top(-ping) operator; jolter	28	49	46	113	24
Top/upper furnace operator; decontamination man	21	21	30	34	26

This table is derived from the data given in Table A-14 and from supplementary information in the references.

An “X” indicates that the job title did not exist during the indicated period. An “X?” indicates that it is uncertain if the job title existed, i.e., it is not certain when that job began.

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Table A-22. Radioactive dust daily weighted average exposure levels, Plant 7 (including the Slag Separation Plant) and Plant 7E.

Job title	Airborne dust exposures, alpha dpm/m^3					
	1951	**1952**	**1953**	**1954**	**1955**	**1956–1958**
Plant 7						
Area mechanic; welder	37	14	37	7	13	14
Asst foreman/plant superintendent/engineer	22	21	10	7	70	32
Clerk/record clerk; porter	22	21	10	13	32	32
Decontamination man/decontaminator	161	21	12	9	17	18
Filter/tables operator[a]	X	X	X	X	9	9
Foreman/technical supervisor; safety inspector/fire marshal	28	28	22	12	16	18
Furnace operator/utility operator	25	28	67	23	18	17
HF/Magnesium Room operator	8	14	9	5	5	5.3
Hoisting (slag) operator[a]	x	X	X	X	15	15
Lead (UO3-to-UF4, TA-7) operator; 36' level/panel board operatorb	38	21	17	9	30	30
Lift truck driver (operator)	14	14	10	14	26	41
QM-2 dumper/hoister	107	56	61	42	63	112
Safety clerk	17	17	17	9	14	14
Sampler and cleanup man	X	28	286	8	8	9.1
TA-7 hoisting operator (hoister)	121	14	13	13	11	17
TA-7 (green/UF_4) packager	242	28	103	68	49	24
Plant 7E (thorium/ionium) process)						
Ionium plant operator/lead operator[c]	X	X	X	X	0.1	0.3

This table is derived from the data given in Table A-15 and from supplementary information in the references.

An "X" indicates that the job title did not exist during the indicated period. An "X?" indicates that it is uncertain if the job title existed, i.e., it is not certain when that job began.

UO_3 processing operations continued until July 1958 (Mallinckrodt 1994), but most other operations stopped in 1957. Plant 7E was said to be in its startup phase when the only known measurements were taken in March 1955 (AEC 1955e); these may have been taken as part of bench-scale processing (AEC 1955c). Thus as AEC (1955e) noted, the full processing figures would likely be higher. Thus figures for 1956 and 1957 have been tripled to allow for full processing. Processing ceased at some point in late 1956 or very early 1957, so an end date of March 1957 should be taken.

a. These positions began after July 1955. Clearly, this was in the pilot plant (as implied by the information in AEC 1955c).
b. The 36' Level operator position began in 1953, the panel board operator position in 1952.
c. The ionium pilot plant work began after July 1955 and continued until March 1957 (AEC 1955c).

Table A-23. Early radon data, 1945.

	% Tolerance	Ventilation condition	Reference
Bldg 40 storeroom, 1,000 lbs ore and active residues	724	F[a]	MED 1945f
Bldg 40, center of storeroom between stacks of residue drums	<15	F	MED 1945j
Bldg 40, residue storage: BZ, residue work -- floor covered with residue	<24		MED 1945g
Bldg K, center of storeroom with ore and residues	90	F	MED 1945j
Bldg K storeroom, center, 2–3 drums fresh residue and open drums of ore	25	F	MED 1945f
(Bldg K) Pilot Plant storeroom with 2,000–3,000 lbs of ore	50	F	MED 1945m
(Bldg K) Pilot Plant, over digestion tank during addition of ore	147	N	MED 1945m
(Bldg K) Pilot Plant, center of Pilot Plant during digestion	132	N	MED 1945m
(Bldg K) Pilot Plant, over digestion tank 15 minutes after digestion	18	N	MED 1945m
(Bldg K) Pilot Plant, N end, away from operation	216	N	MED 1945m
Bldg K, N end of room, away from operation	<15	N	MED 1945h
Bldg K, center of room	<22	N	MED 1945h
Bldg K, center of room, no operation	26	N	MED 1945j
(Bldg K) Pilot Plant, discharge end of Feinc filter during filtration	<15	N	MED 1945m
Bldg K, S end near Feinc filter, not operating	29	N	MED 1945j
Bldg K, S end of plant near Feinc filter, not operating	<15	N	MED 1945h
Bldg K, vicinity of Feinc filter, no operation	<12	W	MED 1945f
Bldg K, work desks at NE corner	12	W	MED 1945f
Bldg K, work desks, center of room	12	W	MED 1945f
Bldg K, alley outside at exhaust	<11		MED 1945f
Bldg K alley, directly under stack emitting brown fumes	<15	N	MED 1945j
Storeroom on RR siding, between 2 tiers of residue drums, 10' from each	32		MED 1945g
Plant 4, ore storage: center of room with 1,800 lbs ore	211	F	MED 1945h
Plant 4(?), W end of ore room during full operation	65	F, N	MED 1945i
Plant 4, W end or ore milling area near sifter, full operation	58	F, N	MED 1945i
Plant 4, center of ore milling room near mill	113	F, N	MED 1945i
Plant 4, operator's hand when unloading ball mill, 300 lbs of ore, fan on	407	F	MED 1945f
Plant 4, near mill, 10 min after unloading, fan on	<15	FW	MED 1945f
Plant 4, opening at top of empty mill	<25		MED 1945f
Plant 4, ore milling area: no operation for 3 days	30	N	MED 1945h
Plant 4, residue storage: directly above drums of residue	763		MED 1945g
Plant 4, laboratory: center of cage	<26	N	MED 1945h
Plant 6 ore storage warehouse, SE corner	55	N	MED 1945k
Plant 6 ore storage warehouse, center of empty aisle	21	N	MED 1945k
Inside [unspecified] lab, no activity	<11		MED 1945f

a. Fan on (F), windows open (W), natural ventilation (N)

The data above was taken at various times in 1945. The tolerance level was 1.0×10^{-10} Ci/L of radon.

"Bldg K" was apparently Building K1E, also known as a pilot plant.

Table A-24. Measured radon concentrations, 1947–1949, in units of 1×10^{-10} Ci/L.

	1947				1948					1949			
	No.	Min	Med/ Mean	Max	No.	Min	Med/ Mean	Max	GSD	No.	Min	Med/ Mean	Max
INDOOR AREAS													
Ore Milling					11	0.03	0.39	0.81					
Ore Rm: open drums[a]											0.58	8.50	260
Ore Storage					27		0.46		3.28				
Ore Storage					58	0.03	0.30	2.86					
Thawing oven, K-65													
Heat off, fan off										28		3.84	
Heat off, fan on										36		0.60	
Heat on, fan on										18		4.06	
Outside, heat on										12		1.09	
Outside, heat off										24		0.07	
Thawing oven, K-65[b]										4	540	622	805
Scalehouse			0.10		21	0.00	4.05	33		44	0.03	0.45	4.4
Scalehouse	2		.60		193	0.03	2.02	32.8		158	0.03	1.03	
Scalehouse	5	.09	.27	.84									
Scalehouse/Ore Storage/Warehouse	4	.55	.69	.92								5.00	
Scalehouse Sample Rm	46	0.0	2.40	13	6	0.22	4.10	19					
Scalehouse Sample Rm	3	.06	.09	.12	68	0.03	2.84	25					
Digest/Feed	4	.05	.23	.52	57	0	0.39	7.8					
Extraction Cells					14	0	1.08	4.1					
Centrifuge Area	2		.38		74		1.00			74	0.00	0.76	3.86
Centrifuge Area					141	0	1.13	12		48	0	1.55	12
Feinc/Filter/C-3/Raffinate/Cloth Storage/Niagara	4	.08	.12	.2	9		0.18		1.98				
Feinc/Filter/C-3/Raffinate/Cloth Storage/Niagara					56	0.00	0.05	9.74					
Feinc/Filter/C-3/Raffinate/Cloth Storage					186	0	12.3	894		172	0	0.75	468
Ledoux Lab					30	0	0.08	0.4					

	1947				1948					1949			
	No.	**Min**	**Med/ Mean**	**Max**	**No.**	**Min**	**Med/ Mean**	**Max**	**GSD**	**No.**	**Min**	**Med/ Mean**	**Max**
Recovery area (aisle betw Recovery and feed makeup)	4	.05	.16	.31									
Sump by M-19, skid of recovery cake beside sump			.26										
Maintenance Shop (aisle between shop and Feincs)	4	.04	0.11	.18									
Dispensary	3	.04	.07	.11									
YARDS AND OTHER OUTDOOR AREAS													
General Plant 6					35	0	0.19	2.1					
Bldg 104/Scalehouse	3	.07	0.17	.36	9		0.07		1.47				
Bldg 104 (Pilot Plant)					7	0	0.15	0.6					
Warehouse					17		0.10		2.05				
Warehouse exhaust					33	0.1	0.91	3.3					
Near warehouse, K-65 drum welding					8		0.11		2.84				
Labs, guard office					8		0.06		1.38				
Parking lot area					9		0.13		1.56				
Scalehouse intake/exhaust					3		0.12		2.06				
Scalehouse exhaust					18		0.13		3.08				
Scalehouse exhaust					1		0.93						
Scalehouse exhaust					24	0	2.2	49					
Ore storage intake/exhaust					6		0.68		2.44				
Ore storage exhaust					2		0.31		1.77				
Railcar, ore, fans on[a]					2	0.5	<1.00	7					
Drums outside Scalehouse					4	0.0	0.39	0.90					
K-65 drums in sun[b]										2	637	654	670
SLAPS													
In K-65 storage shed					5		4.2		3.2				
At K-65 storage shed												19	
15 ft from K-65 shed					2	0.04	0.99	24	93				

	1947				1948					1949			
	No.	Min	Med/ Mean	Max	No.	Min	Med/ Mean	Max	GSD	No.	Min	Med/ Mean	Max
25–30 ft, K-65 shed					2		7.8		1.6			6.6	
50 ft from K-65 shed					3		3.8		2.1			4.4	
50–120 ft, K-65 shed					13		2.1		5.0				
100 ft from K-65 shed												2.4	
150 ft from K-65 shed, at guard shack					3	0.00	0.21	1.1	14			1.4	
180–250 ft, K-65 shed					5		1.1		5.8				
200 ft from K-65 shed												0.94	

Values in this and the next table are taken from AEC (AEC 1948b; AEC 1949; AEC 1948j; AEC 1949j) and MCW (various, MCW 1950b; MCW 1948l; MCW 1948e; MCW 1948j; MCW 1948e; MCW 1951c; MCW 1949f).

Where there was only a single measurement for the time period, the value is given above in the Median/Mean column. Where there were only a minimum, average, and maximum reported, the three values are given above in the Min, Median/Mean, and Max columns. Where there were two or more measurements and the data were given in full, a lognormal distribution was used for the analysis and the geometric mean and geometric standard deviation (GSD) are given above in the Median/Mean and GSD columns. In each case where the number of measurements was given in the reference, the number is given above in the No. column.

Control readings were taken in the Dispensary. Measurements were taken at face level whenever possible.

a. These items are an exception to the note above. For the Ore Room case, the value in the Min column is the point at which the concentration drops below 1×10^{-10} Ci/L (25 minutes), the value in the Mean column is the average concentration over the elapsed time (i.e., the 25 minutes), and the value in the Max column is the value at time zero. For the railcar case, the value in the Min column is the average of readings at about 3.5 hours (stable concentration), the value in the Mean column is the point at which the concentration drops below 1×10^{-10} Ci/L (about 20 minutes), and the value in the Max column is the average value at time zero. More information can be found in MCW (MCW 1949m) and MCW (MCW 1948h) respectively.

b. These items correspond to samples taken of the standard 30-gallon K-65 drums sitting inside sealed 55-gallon drums (to facilitate sampling) after heating in the thawing oven or being allowed to heat in the sun (MCW 1949r); these thus represent the maximum radon evolved over 2–4 hours of heating, concentrated in the larger drum head space but not actually in the breathing zone.

Table A-25. Measured radon concentrations, 1950–1957, in units of 1×10^{-10} Ci/L.

	1950			1951			1952			1953			1954					1955			1956			1957		
	No.	Med/ Mean	GSD	No.	Med/ Mean	GSD	No.	Med/ Mean	GSD	No.	Med/ Mean	GSD	No.	Min	Med/ Mean	Max	GSD	Min	Med/ Mean	Max	No.	Med/ Mean	GSD	No.	Med/ Mean	GSD
INDOOR AREAS																										
Scalehouse				35	0.09	5.9	95	0.09	6.0	66	0.01	5.0														
Scalehouse		1.02																								
Scalehouse/ore storage/warehouse													74		0.01		5.4	5	0.01	1.00						
Scalehouse sample room																		0.09	0.24	0.50						
Digest/feed				2	0.05	11				17	0.12	5.2	57		0.03		3.8				18	0.01	5.1	3	0.03	5.5
Extraction cells				33	0.36	5.9	92	0.37	5.3	59	0.28	3.8	101		0.26		5.8				33	0.01	7.0	3	0.01	8.7
Centrifuge area	8	0.11	2.3	35	0.06	4.8	95	0.12	5.0	55	0.05	5.6	51		0.07		6.5				7	0.01	5.2	3	0.01	1.0
Feinc/filter/C-3/ raffinate/cloth storage/ niagara		34		34	0.18	3.7	94	0.14	4.1	60	0.10	4.8	114		0.14		6.2	<.01	0.50	1.7	41	0.07	5.8	5	0.01	6.8
Orange packing													1	0.12	0.12	0.12										
Pot room													2		0.02		2.2									
Ledoux lab										6	0.10	1.3	10		0.02		3.4									
Shotgun lab													2		0.04		5.8									
Other lab (research/control/X-ray/MY)													3		0.01		1.0							2	0.04	8.0
6E breakout													3		0.01		1.0									
6E recast													4		0.01		1.0									
Recovery area													1	0.11	0.11	0.11										
Decontamination room													1	0.01	0.01	0.01										
Metal dissolver bldg													4		0.01		2.6									
NA house													3		0.01		16									
Ether house													2		0.02		2.7									
Refrigeration room													1	0.01	0.01	0.01										
Receiving													1	0.01	0.01	0.01										
Welding shop													1	0.01	0.01	0.01										
Millwright shop													1	0.01	0.01	0.01										
Electric shop													3		0.01		1.0									
Maintenance shop													3		0.04		6.9									
Smoking room													1	0.01	0.01	0.01										
Production office													1	0.01	0.01	0.01										
Dispensary													2		0.04		6.1									
YARDS AND OTHER OUTDOOR AREAS																										
Ether house/ Bldg 109													1	0.01	0.01	0										
Drum storage outside Bldg 115													3		0.30		8.6									

Values in this and the next table are taken from AEC (AEC 1948b; AEC 1949; AEC 1948j; AEC 1949j) and MCW (MCW various, MCW 1950b; MCW 1948l; MCW 1948e; MCW 1948j; MCW 1948e; MCW 1951c; MCW 1949f).

Where there was only a single measurement for the time period, the value is given above in the Median/Mean column. Where there were only a minimum, average, and maximum reported, the three values are given above in the Min, Median/Mean, and Max columns. Where there were two or more measurements and the data were given in full, a lognormal distribution was used for the analysis and the geometric mean and geometric standard deviation (GSD) are given above in the Median/Mean and GSD columns. In each case where the number of measurements was given in the reference, the number is given above in the No. column.

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Table A-26. RESERVED

Table A-27. Contamination levels and associated dose rates from work clothing.

Surface contamination measurements for various types of work clothing					
	Spot		**Whole garment or group**		
Item	**Max**	**Average**	**Max**	**Average**	**Contamination notes**
Regulated coveralls	80% had ≥ 1–2 in^2 spot >3,000 cpm	Most coveralls had more than 1 spot >1 mr/hr	60% had ≥ 1 mrep/hr over whole garment	1.5 mrep/hr; range, 0.2 to 12; 100% had avg >100 cpm per 2 in^2	Apparent U spots on 70%; area was from 10 cm^2 to 30% of total area
Nonregulated coveralls	30% have more than 1 spot >1,000 cpm		100% <3 mrep/hr	80% <1 mrep/hr; 0% with avg <100 cpm	5% visibly contaminated
Handkerchiefs	>1,000 cpm			<300 cpm	10% visibly contaminated
Socks			800 cpm	200 cpm	
Underwear			800 cpm	200 cpm	
Caps				300 cpm	Low to moderate
Blue smocks	>1,000 cpm			200 cpm	Low to moderate
White smocks	>1,000 cpm				More than blue smocks (more spots)
Lab smocks	>1,000 cpm			<300 cpm	Low (few spots)
Gloves				~5,000 cpm per 2 in^2	All: heavy
Shoe covers				>90% have >1,000 cpm	"Destrehan": "high"
Gloves, contaminated on the inside			47 mrep/hr	Range 23–47 mrep/hr	Beta dose rate, on contact with the inside
Shielding of beta radiation by various materials					
Item	**Distance**	**Reduction factor**	**Std deviation**		
Coveralls, 9-oz denim	5 inches–3 ft	.78	7.5%		
Gloves, neoprene-covered cotton		.50			3 gloves were measured

Measurements of surface contamination on clothing are from Utnage (1958b); measurements of beta shielding and exposure rates inside gloves are from AEC (AEC 1950j). Measurements were taken after wearing but before washing; gloves contaminated on the inside were taken at random from workers actually using the gloves and were not discarded gloves.

The beta reduction factor is the ratio of shielded dose rate to unshielded dose rate. The source was a sheet of uranium metal, 18" x 24," in equilibrium with UX1 and UX2.

The "smocks" appear to be cover clothing.

Table A-28. RESERVED.
Table A-29A. RESERVED.
Table A-29B. RESERVED.
Table A-29C. RESERVED.
Table A-29D. RESERVED.
Table A-29E. RESERVED.
Table A-29F. RESERVED.

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Table A-30. RESERVED.
Table A-31A. RESERVED.
Table A-31B. RESERVED.
Table A-31C. RESERVED.
Table A-31D. RESERVED.
Table A-31E. RESERVED.
Table A-31F. RESERVED.

Table A-32. Exposure rates from K-65 residue and Q-11 ore, in mR/hr (AEC 1949b, Figure 21).

Source	Position	Distance, feet	Dose rate	Dose rate A	Dose rate B	Dose rate C
96 drums of K-65, along the full width of a railcar and ~46 ft along its length (57 ft)	Drum group centerline perpendicular to long side of railcar, 4 ft from ground	1	85			
		3	72.5			
		5	50			
		8	37.5			
		12	27			
		18	19			
		24	12.5			
		30	9.4			
	Top of railcar	Contact	104			
87 drums of Q-11, distributed in two groups at ends of railcar	One drum group centerline perpendicular to long side of railcar (A); at center door (B); at end (C)	2		37	7.75	24
		4		24	8.75	
		6		18	9	9.5
		8		16	9.5	
		10		14	9.7	6.6
		12		12	9.7	
		14		10.5	9.5	5.5
		16		9	8.5	
	Top of railcar, over one group (A); over empty center (B)	Contact		21	11	
5 railcars in a row containing unspecified amount of K-65	Along a line perpendicular to the axis of the line of railcars, even with the center of the middle car	10	50			
		25	22			
		43	13			
		50	10.2			

The total length of a railcar was given as 57 feet.

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Table A-33. Measured dose rates in various work areas.

	Exposure, % tolerance	Exposure, mrep/hr or mR/hr[a]	Year	Reference
PLANTS 1 and 2				
Soda salt, near-contact: gamma; beta	20; 20	2.5; 13	1943	MED 1944f
Soda salt, 6": gamma; beta	10; 20	1.2; 13	1943	MED 1944f
Vanadium sludge, over 1 month old, 10 cm from 216 jar: gamma; beta	1.5; 20	.19; 13	1943	MED 1944f
High-grade pitchblende ore, 55-gal drum, 1,000 lbs ore: 60"		3.8	1945	Rochester 1945
High-grade pitchblende ore, 55-gal drum, 1,000 lbs ore: 45"		6.1	1945	Rochester 1945
High-grade pitchblende ore, 55-gal drum, 1,000 lbs ore: 30"		12	1945	Rochester 1945
High-grade pitchblende ore, 55-gal drum, 1,000 lbs ore: 15"		29	1945	Rochester 1945
High-grade pitchblende ore, 55-gal drum, 1,000 lbs ore: 6"		66	1945	Rochester 1945
High-grade pitchblende ore, 55-gal drum, 1,000 lbs ore: contact		100	1945	Rochester 1945
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: 60"		2.4	1945	Rochester 1945
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: 45"		3.6	1945	Rochester 1945
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: 30"		7.1	1945	Rochester 1945
High-grade pitchblende ore, 15-gal drum, 443 lbs ore: contact		90	1945	Rochester 1945
Ether extraction tanks	25	3.1	1943	MED 1944f
Residue drier (beta only)	120	75	1943	MED 1944f
"SM sub 2": gamma; beta	42; 40	5.2; 25	1943	MED 1944f
"SN sub 4": gamma only	30	3.8	1943	MED 1944f
"SB sub 3": gamma; beta	35; 40	4.4; 25	1943	MED 1944f
Tank 1A cake from SN sub 2: gamma; beta	10; 120	1.2; 13	1943	MED 1944f
Tank 7 press cake, 10 days old, 10 cm from the edge: gamma; beta	20; 400	2.5; 250	1943	MED 1944f
308 [material] from Tank 7 press cake residue, 10 days old: beta only	400	250	1943	MED 1944f
Residue Chem. 4217, 2 months old, 10 cm from 2-lb bottle: gamma; beta	5; 30	.62; 10	1943	MED 1944f
Over top of Shed #1 recovery cake: gamma, beta	12; 30	1.5; 19	1943	MED 1944f
Acid press cake from tank treatment, 10" above: gamma; beta	---	6.3; 300	1944	MED 1945b
Barrel of residue after storage for 6 months, top: gamma; beta	---	6.2;50	1944	MED 1945b
Barrel of residue after storage for 6 months, 6' from side: gamma, beta	---	6.2; 75	1944	MED 1945b

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	Exposure, % tolerance	Exposure, mrep/hr or mR/hr[a]	Year	Reference
Caustic precipitate before it enters the drier, 5–6": gamma; beta	---	6.2, 450	1944	MED 1945b
Plate of residue being dried in oven, 3," beta only	---	250	1944	MED 1945b
Trays in drier, pile, in which NG & SNG residues are dried: 2 " above: gamma; beta	---	5; 50	1944	MED 1945b
Trays in the drier, along the axis about 1': gamma, beta	---	6.2, 250	1944	MED 1945b
Flat dish of residue on top of above crucible covering, 3": gamma; beta	---	0; 1000	1944	MED 1945b
Concrete crucible covering, residue cooling for 4 hours, 3" above: beta	---	400	1944	MED 1945b
Flat dish of slag dust, 3," beta only	---	0	1944	MED 1945b
Floor of Hood #6, 4," where most 4th extractions spilled: gamma; beta	50; 30	6.2; 19	1944	MED 1944m
Most contaminated part of hood floor where shotgun samples dried: gamma; beta	70; 40	8.8; 25	1944	MED 1944m
Shotgun prep lab table top with daily change of brown paper, 4": gamma; beta	---	<13; <25	1944	MED 1945b
Lip of evaporating dish with 3rd-extraction liquor, .5": gamma; beta	50; 30	6.2; 19	1944	MED 1944m
Lip of evapor'g dish w/ 4th-extraction liquor, .5" away, 2" above liquor: gamma; beta	100; 600	13; 375	1944	MED 1944m
Lip of evaporating dish with shotgun sample, .5": gamma; beta	60; 100	7.5; 62	1944	MED 1944m
Lip of evaporating dish containing shotgun sample, 7": gamma; beta	30; 20	3.8; 13	1944	MED 1944m
Lip of evaporating dish containing 5.17-g shotgun sample, 10": beta only	20	13	1944	MED 1944m
Lip of evaporating dish, cleaned, that had held shotgun sample, .5": gamma; beta	30; 20	2.5; 25	1944	MED 1944m
3.36 g shotgun sample, 3" above: gamma; beta	200; 1600	25; 1000	1944	MED 1944m
5.15 g shotgun sample in bottom of evaporating dish, 4": gamma; beta	130; ---	16; >375	1944	MED 1944m
4.31 g shotgun sample, 7": gamma; beta	100; 400	13; 250	1944	MED 1944m
5.15 g shotgun sample in bottom of evaporating dish, 7": beta only	700	440	1944	MED 1944m
5.15 g shotgun sample in bottom of evaporating dish, 11": beta only	340	215	1944	MED 1944m
5.15 g shotgun sample in dish, 11," through rubber glove: beta only	170	106	1944	MED 1944m
Surface of rubber glove above: beta only	20	13	1944	MED 1944m
Outside bottom of evaporating dish with 3.36 g sample, .5": gamma; beta	50; 140	6.2; 88	1944	MED 1944m

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	Exposure, % tolerance	Exposure, mrep/hr or mR/hr[a]	Year	Reference
Bottom of cleaned evaporating dish (had held shotgun sample), 2": gamma; beta	20; 40	2.5; 25	1944	MED 1944m
Glass shipping bottle with 3.08-g shotgun sample, 1": gamma; beta	60; 100	7.5; 62	1944	MED 1944m
Shotgun package containing three bottles: gamma; beta	---	2.5; 0	1944	MED 1945b
Bottom of package with 5 shotgun samples to be shipped, 2": gamma; beta	100; 0	13; 0	1944	MED 1944m
PLANT 4				
Sublining material, 6" from pail: gamma; beta	42; >400	5.2; >250	1943	MED 1944f
Insulating brick from recast furnace: beta only	>400	>250	1943	MED 1944f
Freshly cast metal: beta only	10	6.2	1943	MED 1944f
Green salt, form normally handled, 1": beta only	---	100	1944	MED 1945b
Green salt, contact with tray of green salt: beta only	---	108	1948	MCW 1948a
Green salt, exposure to any large surface (tray, open can, etc), 1': beta only	---	64	1948	MCW 1948a
Above bench on which green salt is packed, 4": gamma, beta	---	<13; <25	1944	MED 1945b
Bomb step, exposure to large surfaces of green salt, 1': beta only	---	50	1948	MCW 1948b
Bomb step, loading bomb, full bomb, 1': beta only	---	53	1948	MCW 1948b
Bomb step, unloading bomb, knockout grate, 1': beta only	---	3.6	1948	MCW 1948a
Bomb step, at edge of unloader jolter, 1': beta only	---	3	1948	MCW 1948a
Top of table where ingot is pushed out of bomb, beta only	---	100	1944	MED 1945b
Bomb step, derby transport table, 1': beta only	---	5.3	1948	MCW 1948a
Bomb step, contact with unchipped derby: beta only	---	116		MCW 1948a
Bomb step, chipping, 1' (chipper location): beta only	---	42	1948	MCW 1948a
Top of chipper's table, beta only	---	125	1944	MED 1945b
Contact with the chipper's table: beta only	---	465	1948	MCW 1948a
Ingot storage room, 4' from pile of ripe metal, beta only	---	25	1944	MED 1945b
Ingot storage and packing room, 3' from ore scrap pile in crib, beta only	---	25	1944	MED 1945b
Recasting step, cleaning crucible lids and stoppers, 1' above tray: beta only	---	3000	1948	MCW 1948B

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	Exposure, % tolerance	Exposure, mrep/hr or mR/hr[a]	Year	Reference
Recasting step, cleaning crucible lids and stoppers, chest high: beta only	---	280	1948	MCW 1948a
Recasting furnace platform, 6” above, beta only	---	168	1944	MED 1945b
Recasting step, above top of furnace immediately after opening, 1’: beta only	---	1450	1948	MCW 1948a
Recasting step, above top of furnace, baffle & crucible lid removed, 1’: beta only	---	650	1948	MCW 1948a
Recasting step, contact with cleaned crucible lid: beta only	---	155	1948	MCW 1948a
Recasting step, chest high while cleaning top of furnace: beta only	---	135	1948	MCW 1948a
Recasting step, cleaning furnace top, edge of top cleaning hood: beta only	---	220	1948	MCW 1948a
Recasting step, inside bottom of furnace before removing rolls, 1’: beta only	---	12	1948	MCW 1948a
Recasting step, inside bottom of furnace after cleaning, 1’: beta only	---	16	1948	MCW 1948a
Recasting step, average for general area of bottom furnace work: beta only	---	16	1948	MCW 1948a
Recasting step, above drum of D-7, 1’: beta only	---	140	1948	MCW 1948a
Recasting step, above D-7 table, 1’: beta only	---	270	1948	MCW 1948a
Billets stored by desk and scale, gamma+beta		90–270	1953	MCW 1953e
Saw with no uranium billet in it, gamma+beta		100–150	1953	MCW 1953e
Empty furnace, lid off, top center//edge//1 foot, gamma+beta		300–400//100//70	1953	MCW 1953e
Furnace lid and brush, center//edge, gamma+beta		1200//100	1953	MCW 1953e
Furnace bottom plate (operator foot position), gamma+beta		800	1953	MCW 1953e
Empty furnace, bottom opening, edge//1 foot, gamma+beta		300//100–250	1953	MCW 1953e
Used crucible before loading		380	1953	MCW 1953e
Sample storage room (Plant 4), beta only	---	25	1944	MED 1945b
Storage and packaging, average for general area: beta only	---	3	1948	MCW 1948a
Storage and packaging, facing table of derbies, 1’ above table edge: beta only	---	21	1948	MCW 1948a
Storage and packaging, surface of cleaned derby: beta only	---	85	1948	MCW 1948a
Storage and packaging, box of rolls, 1’ above: beta only	---	5	1948	MCW 1948a

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	Exposure, % tolerance	Exposure, mrep/hr or mR/hr[a]	Year	Reference
Slag from reaction bomb, 4," beta only	---	250	1944	MED 1945b
Bomb step, edge of the slag barrel: beta only	---	66	1948	MCW 1948a
Pile of slag in sample aging room, 2": gamma; beta	---	<25, 200	1944	MED 1945b
Piece of slag (~30 in3), 1.5": gamma; beta	---	2.5; 100	1944	MED 1945b
PLANT 6				
Ore barrels, direct contact with a group	---	200	1947	AEC 1947a
Ore drum, 4" away through 2" of steel(?) shielding	---	9.5	1948	AEC 1948a
Removing lids from ore drums, hands	---	25–38	1948	AEC 1948d
Ore milling feeder tube, 3" away, gamma	---	53	1948	AEC 1948a
Ore milling hopper general vicinity, first platform	---	15	1948	AEC 1948a
Ore milling hopper, 8" away through 1/8" steel plate shielding	---	40	1948	AEC 1948a
Ore milling hopper, 3" away, first platform	---	20	1948	AEC 1948a
Ore milling hopper, 35" from revolving ore drum at first platform guardrail	---	7	1948	AEC 1948a
Ore milling gas blower, 15" from revolving ore drum	---	9.5	1948	AEC 1948a
By Tank M-2 on platform, 5 hrs after addition of 6,000 lbs ore: 1 foot	100		1946	MCW 1946a
By Tank M-2, on platform (catwalk): 6"; 18"; 36" from tank	230; 120; 90		1947	AEC 1949f
By Tank M-3 on platform while adding ore (2,000 lbs in tank): 1 foot	70		1946	MCW 1946a
By Tank M-3, on platform (catwalk): 6"; 18"; 36" from tank	220; 120; 90		1947	AEC 1949f
Under Tank M-3, containing GLC: 1 foot	120		1946	MCW 1946a
By Tank M-4, on platform (catwalk): 6"; 18"; 36" from tank	80–200; 50–60; 40		1947	AEC 1949f
By Tank M-72, containing wash water: 1 foot	50		1946	MCW 1946a
By Tank M-1, on platform: about 250 gal GLC (3 days old), 1 foot	90		1946	MCW 1946a
By Tank M-1, on platform (catwalk): 6"; 18"; 36" from tank	220; 180; 90		1947	AEC 1949f
By Tank M-83: three-quarters full of GLC (2 days old), 1 foot	220		1946	MCW 1946a
By Tank M-83: 6" from tank	500		1947	AEC 1949f
At operator position between skid and Tank M-14, on platform: 1 foot	120		1946	MCW 1946a
Above skid of GLC on M-14: 1 foot	280		1946	MCW 1946a
Between Tanks M-14 and M-20, midway, on platform (catwalk)	350		1947	AEC 1949f

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	Exposure, % tolerance	Exposure, mrep/hr or mR/hr[a]	Year	Reference
By Tank M-14, on platform (catwalk): 6"; 18"; 36" from tank	450; 400; 250		1947	AEC 1949f
By Tank M-19, on platform:reslurrying skid cake batch: 1 foot	120		1946	MCW 1946a
By Tank M-19, on platform: 18" from tank	300		1947	AEC 1949f
By Tank M-19, on top of tank: 1 foot	250		1946	MCW 1946a
In front of Feinc filter while filtering reslurry batch: 1 foot	210 (2)		1946	MCW 1946a
At Feinc filter GI-4/GI-9: front (walkway); side; back; top (all at 6")	400; 350; 500; 900		1947	AEC 1949f
Near Feinc filter, on platform: gamma min//avg//max		5//16//50	1948	MCW 1948E
Feinc cloth change, < 3 feet from Feinc: gamma, beta		30; 69	1951	MCW 1951a
Feinc cloth change, general vicinity: gamma, beta		12; Negligible	1951	MCW 1951a
Leach (cell) cloth change, < 3 feet: gamma, beta		16; 158	1951	MCW 1951a
Leach (cell) cloth change, general vicinity: gamma, beta		10; 40	1951	MCW 1951a
Wash (cell) cloth change, < 3 feet:gamma, beta		42; 150	1951	MCW 1951a
Wash (cell) cloth change, general vicinity: gamma, beta		17; 48	1951	MCW 1951a
Old material work in old cloth room: average gamma, beta		5; 20	1951	MCW 1951a
Carrying, laundering Feinc, Leach, & Wash cloths, old cloth room: gamma, beta		3; 25	1951	MCW 1951a
Carrying, repairing Feinc blankets, old cloth room: gamma, beta		6; 30	1951	MCW 1951a
Washing Feinc blanket with brush on floor: carrying//changing -- gamma, beta		28; 105//28; 150	1951	MCW 1951a
Changing strings, Feinc, Leach, and Wash filters in cells: typical gamma, beta		30;75	1951	MCW 1951a
Cloth storage room, gamma		0.3–2.0	1955	MCW 1957
Feinc filter plates (removed for cleaning, with some residue caked on them)		<1–5; <10	1950	MCW 1950b
Floor surface under Feinc platform: 1 foot	30 (8)		1946	MCW 1946a
Floor around Feinc filters: 1 foot	110 (7)		1946	MCW 1946a
Feinc filtrate residue, contact (gamma; beta)		>300; >500	1948	AEC 1948k
Operator position while filling drums of GLC: about 1 foot	110 (2)		1946	MCW 1946a
Skids of acid press cake (2–3 days old): 1 foot	200 (5)		1946	MCW 1946a
55-gal drum: 521 lbs of K-65 less than 24 hours old, side contact (gamma)	275		1949	MCW 1949g

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	Exposure, % tolerance	Exposure, mrep/hr or mR/hr[a]	Year	Reference
GLC (3 days old), centered among 4 barrels; between 2 barrels	150; 120		1946	MCW 1946a
4 drums "aged" K-65, 6 feet	---	28	1947	AEC 1947c
2 drums "aged" K-65, 6 feet	---	23	1947	AEC 1947c
Sump recovery skids, all full (1 foot)	80 (5)		1946	MCW 1946a
Dempster body of Chem 6BC; Chem 6BP (1 foot)	30; 40		1946	MCW 1946a
Scalehouse sample room, sampling K-65: gamma; beta		2.0–4.0; 2.5–5.0	1955	MCW 1955n
Scalehouse sample room, carrying K-65 sample pans: gamma; beta		6.0; 12.5	1955	MCW 1955n
Sample Prep Room, pile of K-65 in hood: 1 foot	60		1946	MCW 1946a
Sample Prep Room, 3-gal bottle of K-65 at equilibrium; 3 2-qt bottles at equil (1 foot)	160; 100		1946	MCW 1946a
Sample Prep Room, operator position at Ro-Tap	50		1946	MCW 1946a
Sample Prep Room, operator position while milling GLC	130		1946	MCW 1946a
Sample Prep Room, near drying oven: 1 foot	20		1946	MCW 1946a
Laboratory sample room: center; vault	0; 80		1946	MCW 1946a
Analytical Lab, Dry Sample Prep Room, making up shotgun samples: gamma, beta	3; 1		1956	MCW 1956l
Shotgun Lab, scooping samples into vats: gamma, beta	3; 8		1956	MCW 1956l
Shotgun Lab, draining residue, 1st ether contact, max (NLO sample): gamma, beta	5; 8		1956	MCW 1956l
Shotgun Lab, draining residue, later ether contacts, max: gamma, beta	6; 50		1956	MCW 1956l
Shotgun Lab, moving residue to hot plate, max: gamma, beta	6; 25		1956	MCW 1956l
Shotgun Lab, removing material from muffle furnace, max: gamma, beta	8; 30		1956	MCW 1956l
Shotgun Lab, removing material from mold, max: gamma, beta	8; 25		1956	MCW 1956l
Shotgun Lab, paint and place in box: gamma, beta	8; 10		1956	MCW 1956l
Shotgun Lab, counting samples: gamma, beta	2; 2		1956	MCW 1956l
Shotgun Lab, lab assay work	1.5; ND		1956	MCW 1956l
Shotgun Lab, general area work	1; ND		1956	MCW 1956l
Fork truck driver position while loading GLC(rail?)car	140		1946	MCW 1946a
UO_2 packing area, cylindrical boxes containing UO_2, cover on, beta	4.5		1948	Rochester 1948b

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	Exposure, % tolerance	Exposure, mrep/hr or mR/hr[a]	Year	Reference
UO_2 packing area, cylindrical boxes containing UO_2, cover off, beta	22.5		1948	Rochester 1948b
UO_2 packing area, inside 55-gal drum half-filled with UO_2, beta	27		1948	Rochester 1948b
Warehouse, on 25 cylindrical boxes containing UO_2, cover on, beta	15		1948	Rochester 1948b
PLANT 6E				
Lid cleaner of the furnace enclosures: gamma, beta		170; 7500	1955	MCW 1955t
Crucible, large unpainted, contact: gamma, beta		5; 3000	1955	MCW 1955s
Crucible, large painted, contact: gamma, beta		4; 1000	1955	MCW 1955s
Crucible, small unpainted, contact: gamma, beta		4; 700	1955	MCW 1955s
Crucible, small painted, contact: gamma, beta		2; 560	1955	MCW 1955s
Painting used crucible: gamma, beta		1; 300	1955	MCW 1955s
Painting used crucible, body or arm: gamma, beta		2; 500	1956	MCW 1956k
Painting used crucible, hand: gamma, beta		4; 1500	1956	MCW 1956k
Assembling used crucible: gamma, beta		1; 70	1955	MCW 1955s
Assembling crucible, body at enclosure armhole: gamma, beta (mR/wk, mrep/wk)		36; 2500	1956	MCW 1956n
Assembling crucible, body: gamma, beta		2; 200	1956	MCW 1956k
Assembling crucible, arm: gamma, beta (in mR/week, mrep/week)		74; 17500	1956	MCW 1956n
Assembling crucible, arm: gamma, beta		6; 1800	1956	MCW 1956k
Assembling crucible, hand: gamma, beta (in mR/week, mrep/week)		78; 25000	1956	MCW 1956n
Assembling crucible, hand: gamma, beta		4; 1500	1956	MCW 1956k
General crucible assembly area: gamma, beta		ND; 30	1955	MCW 1955s
General crucible assembly area work: gamma, beta		0.5; 3	1956	MCW 1956k
Crucible assembly operator, wrist: gamma, beta (mR/day, mrep/day)		50; 740	1956	MCW 1956m
Adjusting crucible jack: gamma, beta		1; 25	1956	MCW 1956k
Assembled used crucible, before loading: gamma, beta		1; 20	1955	MCW 1955s
Loading high-carbon/CST, max, body: gamma, beta		1; 20	1956	MCW 1956k
Loading high-carbon/CST, max, arm: gamma, beta		2; 120	1956	MCW 1956k
Loading high-carbon/CST, max, hand: gamma, beta		6; 300	1956	MCW 1956k
Loading crucible: gamma, beta		1; 20	1955	MCW 1955s

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	Exposure, % tolerance	Exposure, mrep/hr or mR/hr[a]	Year	Reference
Lining up crucible: gamma, beta		1; 48	1955	MCW 1955s
Handling crucible lid: gamma, beta		1; 300	1955	MCW 1955s
Top insulation block: gamma, beta		1; 75	1955	MCW 1955s
Fixing stuck (crucible removal) sleeve: gamma, beta		2; 400	1955	MCW 1955s
General furnace enclosure area: gamma, beta		0.5; 8	1955	MCW 1955s
General furnace enclosure area work: gamma, beta		1; 100	1956	MCW 1956k
Crucible loader (top man), wrist: gamma, beta (mR/day, mrep/day)		0; 90	1956	MCW 1956m
Cleaning furnace enclosure, body at enc armhole: gamma, beta (mR/wk, mrep/wk)		23; 196	1956	MCW 1956n
Cleaning furnace enclosure, body at enclosure armhole: gamma, beta		1; 100	1956	MCW 1956k
Cleaning furnace enclosure, arm: gamma, beta (in mR/week, mrep/week)		23; 488	1956	MCW 1956n
Cleaning furnace enclosure, arm: gamma, beta		1; 300	1956	MCW 1956k
Cleaning furnace enclosure, hand: gamma, beta (in mR/week, mrep/week)		25; 628	1956	MCW 1956n
Cleaning furnace enclosure, hand: gamma, beta		1; 240	1956	MCW 1956k
Vacuum-cleaning burners: gamma, beta		1; 120	1955	MCW 1955s
Setting crucible over to cool: gamma, beta		1; 25	1955	MCW 1955s
Unlidding crucible: gamma, beta		1; 25	1955	MCW 1955s
Removing crucible lid, body: gamma, beta		3; 215	1956	MCW 1956k
Removing crucible lid, arm: gamma, beta (in mR/week, mrep/week)		22; 506	1956	MCW 1956n
Removing crucible lid, arm: gamma, beta		4; 1600	1956	MCW 1956k
Removing crucible lid, hand: gamma, beta (in mR/week, mrep/week)		23; 685	1956	MCW 1956n
Removing crucible lid, hand: gamma, beta		8; 2400	1956	MCW 1956k
Removing crucibles and slugs from enclosure: gamma, beta		2; 400	1955	MCW 1955s
General burnout area: gamma, beta		1; 8	1955	MCW 1955s
General burnout area work: gamma, beta		0.5; 3	1956	MCW 1956k
Gen'l burnout area work, body at enclo armhole: gamma, beta (mR/wk, mrep/wk)		22; 200	1956	MCW 1956n
Burnout operator, wrist: gamma, beta (mR/day, mrep/day)		90; 215	1956	MCW 1956m
SLAPS (all as "beta; gamma" except where indicated)				
At contact with aged raffinate heaps		0.5–3.3;0.3–0.8	1949	MCW 1949g
Fresh raffinate heap, 1 foot		70; 1.6	1949	MCW 1949g
Fresh raffinate heap, chest height		33; 1.3	1949	MCW 1949g

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	Exposure, % tolerance	Exposure, mrep/hr or mR/hr[a]	Year	Reference
Fresh raffinate heap, on bulldozer cab pushed into heap		2.7; 1.0	1949	MCW 1949g
"C" material heap, top of pile at waist height		11.5; 1.6	1949	MCW 1949g
"C" material heap, bulldozer cab pushed into heap (ratioed by raff bulldozer result)		7.7; 0.8	1949	MCW 1949g
Aged BC (barium sulfate cake) heap, top of pile at waist height		10; 3–10	1949	MCW 1949g
Aged BC heap bulldozer cab pushed into heap (ratioed by raff bulldozer result)		8.9; 0.13	1949	MCW 1949g
Fresh BC (barium sulfate cake) heap, top of pile at waist height		35; 2.5	1949	MCW 1949g
Fresh BC heap bulldozer cab pushed into heap (ratioed by raff bulldozer result)		2.5; 0.5	1949	MCW 1949g
K-65 storage shed, 2 feet (gamma only)	1,760	220	1948	MCW 1948m
K-65 storage shed, 3 feet (gamma only)	1,240	160	1948	MCW 1948m
K-65 storage shed, 6 feet (gamma only)	900	110	1948	MCW 1948m
K-65 storage shed, 9 feet (gamma only)	750	94	1948	MCW 1948m
K-65 storage shed, 12 feet (gamma only)	620	78	1948	MCW 1948m
K-65 storage shed, 15 feet (gamma only)	430	54	1948	MCW 1948m
K-65 storage shed, 18 feet (gamma only)	360	45	1948	MCW 1948m
K-65 storage shed, 21 feet (gamma only)	260	33	1948	MCW 1948m
K-65 storage shed, 24 feet (gamma only)	180	23	1948	MCW 1948m
K-65 storage shed, 27 feet (gamma only)	130	16	1948	MCW 1948m
K-65 storage shed, 30 feet (gamma only)	080	10	1948	MCW 1948m
K-65 storage shed, 150 feet (gamma only) -- guard shack location	3.2	0.4	1948	MCW 1948m
PLANT 4, measured beta dose rates analyzed for the design of Plant 6E	**Meter reading, mrep/week**	**Worker film badge avg beta, mrep/wk**	**Year**	**Reference**
Green salt, loading and unloading	816	480	1948	MCW 1948b
Green salt, box pulling	300	415	1948	MCW 1948b
Green salt, milling	432	530	1948	MCW 1948b
Green salt, extra man	300	510	1948	MCW 1948b
Green salt, lead operator	300	360	1948	MCW 1948b
Bomb step, jolting	600	440	1948	MCW 1948b
Bomb step, charging	600	370	1948	MCW 1948b
Bomb step, topping	600	380	1948	MCW 1948b
Bomb step, furnace tender	500	380	1948	MCW 1948b
Bomb step, unloading	600	460	1948	MCW 1948b
Bomb step, chipping	1,900	845	1948	MCW 1948b
Bomb step, lime mixing	---	415	1948	MCW 1948b
Bomb step, magnesium mixing	---	300	1948	MCW 1948b
Recasting, furnace tending	500	665	1948	MCW 1948b
Recasting, top furnace tending	2,125	1220	1948	MCW 1948b
Recasting, bottom furnace tending	1,050	800	1948	MCW 1948b
Recasting, sawing	>500	535	1948	MCW 1948b

	Exposure, % tolerance	Exposure, mrep/hr or mR/hr[a]	Year	Reference
Recasting, weighing and packing	613	580	1948	MCW 1948b
PLANT 6, gamma dose rates at area film badge monitoring locations	**Meter reading, mR/hr**	**Average, mR/hr**	**Year**	**Reference**
Digest area: upper platform	2.5	3.8	1955	MCW 1955c
Digest area: lower platform	3	5	1955	MCW 1955c
Cell: lower C-3 area (M-14, M-203); upper C-3 area (Olivers); leach area (Olivers)	2.5; 10; 3	2.6; 14.2; 3.1	1955	MCW 1955c
C-3: lower platform at M-214; upper platform	2; 2	3.8; 2.4	1955	MCW 1955c
Centrifuge area	2	3.4	1955	MCW 1955c
Feinc area: lower platform; upper platform; east area	2; 2; 4.5	3.1; 2.0; 6.5	1955	MCW 1955c
Cell: Feinc Niagara area	1.5	1.7	1955	MCW 1955c

a. The mrep/hr should be assumed for mixed beta-gamma or for beta alone; the mR/hr should be assumed for gamma only (i.e., either when stated explicitly or when it can be assumed, such as from the side of a tank or bottle). Slashes indicate multiple values. ND means not detectable.

Many figures are given in units of per cent of tolerance, defined in MCW (1949f) as "the amount of exposure that a person can receive 8 hrs/day for an indefinite period of time," presumably corresponding to 100 mR per eight-hour day for gammas and 500 mrep per eight-hour day for betas at the relevant time period. The exposure rates in mR/hr or in mrep/hr were in most cases converted from the original units of R per 8 hours. MED (1945b) gave beta exposure rate figures in "beta units," which as MED (1945c) explained, were the same as "T units," with a T unit being 0.25 "r/hr" of beta radiation. This unit was taken to be 0.25 rep in the table above.

Parentheses indicate the number of measurements, if more than one, used to form the average reported.

Data from AEC 1949f were taken at waist height except where indicated.

Table A-34. Neutron dose rates and doses from the alpha-neutron reaction sources and from a RaBe source.

Alpha-neutron source information and dose rates						
Form	**Source**	**Target element(s)**	**Weight in container**	**Dose rate at 1 foot, rem/hr**	**Dose rate at 3 feet, rem/hr**	**Annual dose, rem**
U_3O_8	U natural mix	O	100 lbs	1.29E-07	1.44E-08	4.31E-05
	U natural mix + daughters	O	100 lbs	1.10E-06	1.22E-07	3.67E-04
UO_3, UO_2	U natural mix	O	75 lbs	9.71E-08	1.08E-08	3.24E-05
	U natural mix + daughters	O	75 lbs	8.27E-07	9.19E-08	2.76E-04
UF_4	U natural mix	F	75 lbs	6.92E-06	7.69E-07	2.31E-03
	U natural mix + daughters	F	75 lbs	5.91E-05	6.57E-06	1.97E-02
$Na_2U_2O_7$ (soda salt)	U natural mix	O, Na	75 lbs	2.61E-07	2.90E-08	8.70E-05
	U natural mix + daughters	O, Na	75 lbs	2.13E-06	2.37E-07	7.11E-04
ThF_4	Th-230/Th232 mix	F	198 g	4.08E-04	4.53E-05	1.36E-01
	Th-230/Th-232 mix + daughters	F	198 g	8.97E-04	9.96E-05	2.99E-01
$Th(NO_3)_4$	Th-230/Th232 mix	O	309 g	4.74E-06	5.26E-07	1.58E-03
	Th-230/Th-232 mix + daughters	O	309 g	1.04E-05	1.16E-06	3.47E-03

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RaBe source information and dose rates						
RaBe	Ra-226	---	100 mg Ra	1.60E-02	1.77E-03	4.44E+00
Annual organ doses (based on ThF_4 for the alpha-neutron case; Ra-226 for the RaBe case)						
Organ					**Alpha-neutron dose, rem**	**RaBe dose, rem**
Bladder					2.09E-01	5.00E+00
Bone marrow					1.16E-01	3.37E+00
Bone surface					1.34E-01	3.15E+00
Breast					3.10E-01	5.08E+00
Colon					1.34E-01	4.17E+00
Esophagus					1.17E-01	4.02E+00
Lung					1.62E-01	4.32E+00
Gonads (ovaries)					1.19E-01	4.15E+00
Gonads (testes)					3.39E-01	5.50E+00
Liver					1.78E-01	4.54E+00
Remainder organs					2.57E-01	4.13E+00
Skin					9.64E-09	4.33E+00
Stomach					2.20E-01	4.96E+00
Thyroid					2.95E-01	5.15E+00

Data used to calculate the alpha-neutron dose rates (except for the assumed amount of U, Th, or Ra material) is from Shleien (1992), Tables 8.4.1, 7.3, and 7.2; Salmon and Hermann (1993), Table 3; DOE (2001a), Table 6-5; Foderaro (1978); and Mlekodaj (2002). Data used to calculate the RaBe dose rates are from Shleien (1992), Tables 7.5 and 8.4.1, and Foderaro (1978). In both cases, the dose conversion factors were taken from NIOSH (2007). The quantities listed correspond to one drum of material for the uranium forms; to one day's processing for the thorium forms (on a 70-day basis); and to the known RaBe source for the Ra form.

In the alpha-neutron case, the neutron energy was taken as 1.5 MeV because it is the approximate maximum energy for Th-232, the other isotopes also emit neutrons in the range 1.0–2.0, and the flux-to-dose conversion factor varies slowly in this range. For the annual dose, it was assumed that 1 hour /day was spent at 1 foot from the container and three hours/day spent at 3 feet, every working day for a year. In the RaBe case, the neutron energy was taken as 4.0 MeV and it was assumed that 1 hour/day was spent at 1 foot from the unshielded source and 1 hour/day spent at 3 feet, every working day for a year. (This is conservative since the source was likely to be at least partially shielded when in use and completely shielded when not in use.)

In both cases, the maximum organ dose was based on the maximum annual whole-body dose taken to be the ambient dose. For the alpha-neutron source case, an exposure geometry of 75% AP/25% ROT was assumed, as per Table A-18 (for "ionium plant operator"); for the RaBe case, 90% AP/10% ROT was assumed, as per Table A-18 (for "Shotgun Lab analyst").

Table A-35. External gamma dose rates from processing AM-7 residue to concentrate thorium.

Radionuclide	**Gamma energy MeV**	**Freq**	**Ci**	**R/h@1 ft**	**Annual dose, R**
Th-230	0.142	0.0007	24.4	2.08E-04	6.93E-02
Th-230	0.143	0.00045	24.4	1.35E-04	4.49E-02
Th-232	0.126	0.0004	0.001	4.32E-09	1.44E-06
Ra-226	0.186	0.0328	0.158	8.26E-05	2.75E-02
Total	---	---	48.959	4.25E-04	1.42E-01
	Ratio, Ra/Th	---	3.24E-03	2.41E-01	2.41E-01
	Ratio, Ra/Total	---	3.23E-03	1.94E-01	1.94E-01

Note: Assumptions for the annual dose are as for Table A-34, i.e., 1 hour per day was spent at one foot from the unshielded source and 3 hours per day at 3 ft for 250 working days.

Table A-36. Reserved.

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Table A-37. Monitoring experience from the decontamination/demolition period, 1960–1961 (MCW 1961b).

General outside air concentration during decontamination and demolition

Date sampled	Airborne activity, in units of 10^{-13} uCi/cc		No. samples
	Uranium	Gross alpha	
Dec 1960	4.0	6.8	16
Jan 1961	7.4	6.5	48
Feb 1961	1.1	1.6	104
Mar 1961	1.4	1.7	141
Apr 1961	2.0	6.9	115
May 1961	2.0	4.0	97
Jun 1961	3.3	5.6	69
Jul 1961	1.6	2.8	48
Aug 1961	1.9	4.1	77
Sep 1961	2.2	2.9	83
Oct 1961	3.8	5.0	77
Nov 1961	12.0	6.7	21
Weighted average	2.6	4.0	---

Operational area air concentrations, as airborne alpha activity in uCi/cc

Operation or Area	Average	High
Cutting and removing iron structures, equipment	8.7 E-11	7.7 E-10
Loading iron, equipment by hand and by lift	8.7 E-11	5.3 E-10
Demolishing wood, concrete, or masonry	2.7 E-11	9.2 E-11
Mechanically loading debris and rubble	1.8 E-11	1.1 E-10
Removing tar and gravel roofs	2.5 E-11	1.5 E-11
Dry-sandblasting the insides of buildings	3.6 E-10	7.4 E-10
General area outside blogs during inside sandblasting	2.7 E-11	9.5 E-11
Dry-sandblasting outside surfaces	4.2 E-11	1.1 E-10
Shoveling residues into small quarters	2.4 E-10	---
Jack hammering Unite from tanks	8.2 E-10	1.8 E-09
Outside hood during removal of Unite inside hood	3.4 E-12	---
Cleaning sand, residues from inside vessel after sandblasting	6.4 E-11	---
Steam cleaning of no salvageable materials	2.0 E-12	---
Source sampling with wire brush inside pipe after solvent soaking	8.8 E-10	---
Stack exhaust area, from dust collector-hood setup	3.3 E-11	---
General air in building during period of inactivity	1.4 E-11	---

Concentrations of uranium in urine, in mg/L

Sample type		Average	Range
Equipment removal phase	Pre-exposure sample	0.007	0.002–0.013
	Monday before work sample	0.010	0.005–0.008
	Friday after work sample	0.025	0.003–0.078
Decontamination and demolition	Pre-exposure sample	0.005	0.001–0.014
	Monday before work sample	0.019	0.003–0.058
	Friday after work sample	0.036	0.006–0.271
	Termination sample	0.017	0.006–0.027
Special operations	Sandblasting	0.031	0.007–0.080
	Torch-cutting stainless steel	0.032	---
	Cutting, wrecking a rod mill	0.098	0.061–0.135
	Dismantling vacuum, dust collector	0.065	---
	Stripping wiring, metal from blogs	0.045	0.007–0.158

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Film badge data					
	Gamma			Beta	
User	Annual average, rem	Highest quarterly reading, rem	Highest monthly reading, rem	Annual average, rem	Highest monthly reading, rem
Contractor	0.04	0.15	0.08	0.3	0.29
AEC	0.1	---	---	0.6	---
MCW	0.2	---	---	0.8	---
AEC/MCW	---	---	0.14	---	0.15
Visitor	---	---	0.05	---	---

Table A-38. Summary of post-decontamination exposure data as measured by two survey groups.

		1981	1986	1990		Overall averages, 1981		
Plant	Bldg remaining	Radon daughters, WL	Radon yearly Avgas, WLM/yr	Radon yearly Avgas, WLM/yr		Source	BG	Average measured levels at St. Louis Site
1	K1E	0.009–0.02	0.05	0.12		Radon in air	<1 phi/L	0.4–37 phi/L, avgas daytime; 69 phi/L max
	25-1	0.001		0.01		Radon daughters in air	<0.01 WL	0.0009–0.07 WL, avgas daytime concentration
	25-2	0.0009		0.01		Gamma from Ra, U daughters	8 or/hr	8–290 or /yr @ 1 m above floor
	38							
	40							
2	50	0.0003						
	51	0.0005	0.02	0.01				
	51A		0.02	0.01				
	52A	0.07						
	52	0.0007–0.001		0.00				
6	100			0.02				
	101		0.10	0.01				
6E	116-1		0.00	0.04				
	116-2			0.00				
	116B			0.01				
	117-1			0.00				
	117-2			0.00				
7	700			0.00				
	704		0.03	0.00				
	705			0.00				
	706			0.00				
	708			0.01				

Measurements are from ORNL (1981) and Applied Nuclear Safety (1986; 1990).

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Table A-39. Measured data used to produce source terms for decontamination and post-decontamination exposure calculations.

			Internal exposure		External exposure			
Plant	**Case**	**Dose potential**	**Surface alpha, dpm/100 cm^2**	**Volume alpha, phi/g**	**Maximum average gamma, mR/hr**	**Typical average gamma, mR/hr**	**Maximum average beta, prep/hr**	**Typical average beta, prep/hr**
4	Decon	Low	4.4E+03	1.0E+04	8.0E-02	2.4E-02	1.3E+01	7.5E+00
		Moderate	8.3E+03	4.2E+04	3.0E-01	9.0E-02	2.4E+01	1.4E+01
		High	1.7E+04	8.1E+04	2.0E+00	6.0E-01	4.7E+01	2.7E+01
6	Decon	Low	1.2E+02	1.0E+01	1.0E-01	1.2E-02	1.0E+00	1.2E-01
		Moderate	3.9E+03	7.7E+02	2.5E-01	2.9E-02	2.0E+00	2.4E-01
		High	6.0E+04	3.0E+03	3.0E+00	1.7E+00	3.9E+01	4.6E+00
6E	Decon	Low	4.0E+02	0.0E00	1.0E-01	5.0E-02	2.0E-01	4.3E-02
		Moderate	2.7E+03	3.8E+02	5.0E-01	1.0E-01	1.3E+00	2.8E-01
		High	3.5E+04	1.6E+03	1.4E+00	5.0E-01	1.2E+01	2.5E+00
7	Decon	Low	8.5E+01	0.0E+00	5.0E-02	2.0E-02	1.0E-01	1.7E-02
		Moderate	2.8E+03	1.9E+02	1.0E-01	4.0E-02	1.7E+00	2.9E-01
		High	1.2E+05	2.6E+02	2.5E-01	1.0E-01	1.8E+01	3.0E+00
1	Post-decon	---	---	---	8.7E-02	2.1E-02	8.9E+00	9.0E-01
2	Post-decon	---	---	---	2.1E-02	1.0E-02	9.7E+00	2.3E-01
6E	Post-decon	Low	1.2E+03	0.0E+00	5.4E-02	1.7E-02	5.0E-01	1.0E-01
		Moderate	3.0E+03	3.8E+02	8.1E-02	4.2E-02	7.5E-01	2.5E-01
		High	4.5E+03	1.6E+03	1.6E-01	8.3E-02	1.5E+00	5.0E-01
7	Post-decon	Low	1.0E+03	0.0E+00	8.1E-03	3.2E-03	2.5E-01	1.0E-01
		Moderate	2.8E+03	1.9E+02	1.6E-02	8.1E-03	5.0E-01	2.5E-01
		High	7.5E+03	2.6E+02	3.2E-02	1.6E-02	1.0E+00	5.0E-01

The data in this table was extracted from MCW (1958), MCW(1959), MCW (1961a), and ORNL (1981).

For the Plants 6E and 7 post-decontamination dose rates, the beta/gamma ratio was assumed to be the same as for the corresponding decontamination maximum case. For both decontamination and post-decontamination cases, the High maximum was taken as the maximum average or representative maximum for the respective plant; the High typical value was the average of the non-zero average levels, hence is conservative. Similarly, the Moderate maximum and the Low maximum were the respective middling and low averages. The Moderate and Low typical values were rationed from the High typical values.

For the Plants 1 and 2 case, the maximum averages were derived from the highest representative measurements in each building and the maximum building in each plant was chosen to be representative of all buildings in that plant. Also for Plants 1 and 2, the measured beta-gamma dose rate was assumed to be all beta, for conservatism and in default of other information; the gamma measurements are based on true gamma-only readings taken with a different instrument than was used to measure the beta-gamma level. The beta-gamma measurements were taken at less than 1 inch (the MCW references) or at 1 cm (ORNL 1981), while the gamma measurements were generally at 3 feet (1 m).

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Table A-40. Annual internal exposures during the decontamination and post-decontamination periods.

Decontamination		Annual average exposure, 1959–1961			
		Plant 4	Plant 6	Plant 6E	Plant 7
Inhalation, phi	Low	8.39E+02	1.98E+01	6.86E+01	1.46E+01
	Moderate	1.77E+03	6.67E+02	4.66E+02	4.82E+02
	High	3.48E+03	1.03E+04	6.02E+03	1.97E+04
Radon, WLM	Low	1.43E-02	3.73E-04	1.30E-03	2.76E-04
	Moderate	2.69E-02	1.25E-02	8.76E-03	9.09E-03
	High	5.36E-02	1.95E-01	1.14E-01	3.73E-01
Ingestion, phi	Low	1.75E+01	4.13E-01	1.43E+00	3.04E-01
	Moderate	3.68E+01	1.39E+01	9.72E+00	1.00E+01
	High	7.25E+01	2.15E+02	1.25E+02	4.11E+02

Post-decontamination	Annual average exposure, 1962–1995 (1959–1995 for Plants 1 and 2)							
	Plant 1				Plant 2			
	1959–1965	1966–1975	1976–1985	1986–1995	1959–1965	1966–1975	1976–1985	1986–1995
Inhalation, phi	3.77E+01	3.78E+01	3.80E+01	3.77E+01	3.77E+01	3.78E+01	3.80E+01	3.77E+01
Radon, WLM	4.25E-01	4.17E-01	4.04E-01	3.92E-01	1.42E+00	1.39E+00	1.35E+00	1.31E+00
Ingestion, pCi	7.84E-01	7.87E-01	7.92E-01	7.85E-01	7.84E-01	7.87E-01	7.92E-01	7.85E-01

Post-decontamination		Plant 6E				Plant 7			
		1959–1965	1966–1975	1976–1985	1986–1995	1959–1965	1966–1975	1976–1985	1986–1995
Inhalation, pCi	Low	9.12E+00	5.72E+00	5.75E+00	5.70E+00	4.75E+00	4.77E+00	4.79E+00	4.75E+00
	Moderate	1.71E+01	1.72E+01	1.73E+01	1.72E+01	1.47E+01	1.48E+01	1.49E+01	1.48E+01
	High	3.35E+01	3.36E+01	3.37E+01	3.36E+01	3.76E+01	3.77E+01	3.79E+01	3.76E+01
Radon, WLM	Low	4.54E-03	4.45E-03	4.31E-03	4.18E-03	3.78E-03	3.71E-03	3.60E-03	3.48E-03
	Moderate	1.13E-02	1.11E-02	1.08E-02	1.04E-02	1.06E-02	1.04E-02	1.01E-02	9.75E-03
	High	1.70E-02	1.67E-02	1.62E-02	1.57E-02	2.84E-02	2.78E-02	2.70E-02	2.61E-02
Ingestion, pCi	Low	1.90E-01	1.19E-01	1.20E-01	1.19E-01	9.90E-02	9.93E-02	9.99E-02	9.90E-02
	Moderate	3.57E-01	3.58E-01	3.60E-01	3.57E-01	3.07E-01	3.08E-01	3.10E-01	3.07E-01
	High	6.97E-01	6.99E-01	7.03E-01	7.00E-01	7.83E-01	7.86E-01	7.90E-01	7.84E-01

Inhalation and radon data in this table was calculated with the RESRAD-BUILD computer code (ANL 2003), using measured data from MCW (1958; 1959; 1961a). Both surface contamination and bulk floor and wall contamination were taken into account in calculating the inhalation and radon contributions. Ingestion data were calculated using the ingestion model of OCAS (2004).

"High" exposure potential represents those working in the most contaminated areas, i.e., the former process areas; "Moderate", those accessing less contaminated areas or infrequently accessing former process areas; and "Low", those accessing uncontaminated areas. Plants 1 and 2 did not have enough data for these classifications to be applied.

The Plants 1 and 2 inhalation and ingestion figures were taken to be the same as the Plant 7 figures since the post-D&D contamination figures as given in ORNL (1981) for them were similar to the data for Plant 7. ORNL (1981) showed that while most radon daughter readings were similar in all of the plants, there was one significantly higher reading in both Plant 1 and Plant 2. Thus the Plants 1 and 2 readings are the Plant 7 readings multiplied by the factor of difference for the respective buildings (15 for Plant 1 and 50 for Plant 2). This should be quite conservative since the measured Plant 1 and 2 readings were maxima.

Intake quantities listed above in Table A-40 (both inhalation and ingestion) represent total alpha activity. Isotopic distribution should be based on either the likely source term or selected to be favorable to claimants based on the tabulation below (total alpha source term factors). For areas in which only uranium ores were present, the intake can be based on the isotopic distribution of uranium in equilibrium with its progeny (shown below). If the work area cannot be determined, or if exposure to uranium raffinates was likely, then the total alpha activity can be distributed as 94.6% Th-230 and 5.4% Ac-227. This distribution is based on the isotopic composition of the total alpha activity of the ionium product which was determined to be 94.6% th-230 and 5.4% th-227 (Ac-227 progeny) (Kuhlman 1955) and results in an internal dose that is bounding of that which would be calculated based on the possible raffinate mixtures potentially present.

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Total Alpha Source Term Factors – uranium ore.

Source	Uranium in equilibrium	
	Ratio to Uranium	Fraction of Total Gross Alpha[a]
Uranium	1	0.4
Th-230	0.49	0.2
Ra-226	0.49	0.2
Pb-210	0.49	0.2
Po-210	0.49	0.2
Pa-231	0.02	0.01
Ac-227	0.02	0.01

a. Total alpha fraction based on ratio of each nuclide activity to the total alpha emitting fraction (Uranium + Th-230 + Ra-226 + Po-210 + Pa-231) and assuming that the Pb-210 activity is equal to that of Po-210 and the Ac-227 activity is equal to that of Pa-231.

Table A-41. Annual external photon organ doses, decontamination, and post-decontamination periods (rem per year).

Decontamination years (1959–1961)													
		Plant 4			Plant 6			Plant 6E			Plant 7		
Organ	Type	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Bladder	Min	5.6E-02	2.1E-01	1.4E+00	4.9E-02	1.2E-01	3.0E+00	9.2E-02	2.9E-01	1.1E+00	4.0E-02	8.1E-02	2.0E-01
	Mode	1.1E-01	4.1E-01	2.7E+00	9.7E-02	2.4E-01	5.8E+00	1.8E-01	5.7E-01	2.1E+00	7.9E-02	1.6E-01	4.0E-01
	Max	2.9E-01	1.1E+00	7.2E+00	2.5E-01	6.4E-01	1.5E+01	4.7E-01	1.5E+00	5.5E+00	2.1E-01	4.2E-01	1.0E+00
Bone (red marrow)	Min	3.8E-02	1.4E-01	9.5E-01	3.4E-02	8.4E-02	2.0E+00	6.2E-02	2.0E-01	7.2E-01	2.7E-02	5.5E-02	1.4E-01
	Mode	7.4E-02	2.8E-01	1.9E+00	6.6E-02	1.6E-01	4.0E+00	1.2E-01	3.9E-01	1.4E+00	5.4E-02	1.1E-01	2.7E-01
	Max	2.0E-01	7.3E-01	4.9E+00	1.7E-01	4.3E-01	1.0E+01	3.2E-01	1.0E+00	3.7E+00	1.4E-01	2.8E-01	7.1E-01
Bone (surface)	Min	6.7E-02	2.5E-01	1.7E+00	6.0E-02	1.5E-01	3.6E+00	1.1E-01	3.5E-01	1.3E+00	4.9E-02	9.7E-02	2.4E-01
	Mode	1.3E-01	4.9E-01	3.3E+00	1.2E-01	2.9E-01	7.0E+00	2.2E-01	6.9E-01	2.5E+00	9.5E-02	1.9E-01	4.8E-01
	Max	3.5E-01	1.3E+00	8.6E+00	3.1E-01	7.7E-01	1.8E+01	5.7E-01	1.8E+00	6.6E+00	2.5E-01	5.0E-01	1.3E+00
Breast (female)	Min	5.9E-02	2.2E-01	1.5E+00	5.2E-02	1.3E-01	3.1E+00	9.7E-02	3.1E-01	1.1E+00	4.3E-02	8.5E-02	2.1E-01
	Mode	1.2E-01	4.3E-01	2.9E+00	1.0E-01	2.6E-01	6.1E+00	1.9E-01	6.1E-01	2.2E+00	8.3E-02	1.7E-01	4.2E-01
	Max	3.0E-01	1.1E+00	7.6E+00	2.7E-01	6.7E-01	1.6E+01	5.0E-01	1.6E+00	5.8E+00	2.2E-01	4.4E-01	1.1E+00
Colon	Min	5.0E-02	1.9E-01	1.3E+00	4.5E-02	1.1E-01	2.7E+00	8.3E-02	2.7E-01	9.6E-01	3.6E-02	7.3E-02	1.8E-01
	Mode	9.9E-02	3.7E-01	2.5E+00	8.7E-02	2.2E-01	5.3E+00	1.6E-01	5.2E-01	1.9E+00	7.1E-02	1.4E-01	3.6E-01
	Max	2.6E-01	9.7E-01	6.5E+00	2.3E-01	5.7E-01	1.4E+01	4.3E-01	1.4E+00	4.9E+00	1.9E-01	3.7E-01	9.4E-01
Esophagus	Min	3.9E-02	1.5E-01	9.8E-01	3.5E-02	8.7E-02	2.1E+00	6.4E-02	2.1E-01	7.5E-01	2.8E-02	5.7E-02	1.4E-01
	Mode	7.7E-02	2.9E-01	1.9E+00	6.8E-02	1.7E-01	4.1E+00	1.3E-01	4.0E-01	1.5E+00	5.5E-02	1.1E-01	2.8E-01
	Max	2.0E-01	7.5E-01	5.0E+00	1.8E-01	4.5E-01	1.1E+01	3.3E-01	1.1E+00	3.8E+00	1.5E-01	2.9E-01	7.3E-01
Eye	Min	6.0E-02	2.3E-01	1.5E+00	5.3E-02	1.3E-01	3.2E+00	9.9E-02	3.2E-01	1.1E+00	4.4E-02	8.7E-02	2.2E-01
	Mode	1.2E-01	4.4E-01	2.9E+00	1.0E-01	2.6E-01	6.3E+00	1.9E-01	6.2E-01	2.3E+00	8.5E-02	1.7E-01	4.3E-01
	Max	3.1E-01	1.2E+00	7.7E+00	2.7E-01	6.9E-01	1.7E+01	5.1E-01	1.6E+00	5.9E+00	2.2E-01	4.5E-01	1.1E+00
Gonads (ovaries)	Min	4.8E-02	1.8E-01	1.2E+00	4.2E-02	1.1E-01	2.5E+00	7.9E-02	2.5E-01	9.1E-01	3.5E-02	6.9E-02	1.7E-01
	Mode	9.4E-02	3.5E-01	2.3E+00	8.3E-02	2.1E-01	5.0E+00	1.5E-01	4.9E-01	1.8E+00	6.8E-02	1.4E-01	3.4E-01
	Max	2.5E-01	9.2E-01	6.1E+00	2.2E-01	5.4E-01	1.3E+01	4.0E-01	1.3E+00	4.7E+00	1.8E-01	3.6E-01	8.9E-01
Gonads (testes)	Min	6.3E-02	2.3E-01	1.6E+00	5.5E-02	1.4E-01	3.3E+00	1.0E-01	3.3E-01	1.2E+00	4.5E-02	9.1E-02	2.3E-01
	Mode	1.2E-01	4.6E-01	3.1E+00	1.1E-01	2.7E-01	6.5E+00	2.0E-01	6.5E-01	2.3E+00	8.9E-02	1.8E-01	4.4E-01
	Max	3.2E-01	1.2E+00	8.0E+00	2.9E-01	7.1E-01	1.7E+01	5.3E-01	1.7E+00	6.1E+00	2.3E-01	4.7E-01	1.2E+00
Liver	Min	5.2E-02	1.9E-01	1.3E+00	4.6E-02	1.1E-01	2.8E+00	8.5E-02	2.7E-01	9.9E-01	3.7E-02	7.5E-02	1.9E-01
	Mode	1.0E-01	3.8E-01	2.5E+00	9.0E-02	2.2E-01	5.4E+00	1.7E-01	5.3E-01	1.9E+00	7.3E-02	1.5E-01	3.7E-01
	Max	2.7E-01	1.0E+00	6.6E+00	2.4E-01	5.9E-01	1.4E+01	4.4E-01	1.4E+00	5.1E+00	1.9E-01	3.8E-01	9.6E-01
Lung	Min	5.1E-02	1.9E-01	1.3E+00	4.5E-02	1.1E-01	2.7E+00	8.4E-02	2.7E-01	9.7E-01	3.7E-02	7.4E-02	1.8E-01
	Mode	1.0E-01	3.8E-01	2.5E+00	8.9E-02	2.2E-01	5.3E+00	1.6E-01	5.3E-01	1.9E+00	7.2E-02	1.4E-01	3.6E-01
	Max	2.6E-01	9.8E-01	6.6E+00	2.3E-01	5.8E-01	1.4E+01	4.3E-01	1.4E+00	5.0E+00	1.9E-01	3.8E-01	9.5E-01
Remainder organs	Min	4.6E-02	1.7E-01	1.1E+00	4.1E-02	1.0E-01	2.4E+00	7.5E-02	2.4E-01	8.7E-01	3.3E-02	6.6E-02	1.7E-01
	Mode	9.0E-02	3.4E-01	2.2E+00	7.9E-02	2.0E-01	4.8E+00	1.5E-01	4.7E-01	1.7E+00	6.5E-02	1.3E-01	3.2E-01
	Max	2.4E-01	8.8E-01	5.9E+00	2.1E-01	5.2E-01	1.3E+01	3.9E-01	1.2E+00	4.5E+00	1.7E-01	3.4E-01	8.5E-01
Skin	Min	4.9E-02	1.8E-01	1.2E+00	4.3E-02	1.1E-01	2.6E+00	8.0E-02	2.6E-01	9.3E-01	3.5E-02	7.1E-02	1.8E-01
	Mode	9.6E-02	3.6E-01	2.4E+00	8.5E-02	2.1E-01	5.1E+00	1.6E-01	5.0E-01	1.8E+00	6.9E-02	1.4E-01	3.5E-01
	Max	2.5E-01	9.4E-01	6.3E+00	2.2E-01	5.6E-01	1.3E+01	4.1E-01	1.3E+00	4.8E+00	1.8E-01	3.6E-01	9.1E-01

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Decontamination years (1959–1961)													
		Plant 4			Plant 6			Plant 6E			Plant 7		
Organ	Type	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Stomach	Min	5.7E-02	2.1E-01	1.4E+00	5.1E-02	1.3E-01	3.0E+00	9.4E-02	3.0E-01	1.1E+00	4.1E-02	8.3E-02	2.1E-01
	Mode	1.1E-01	4.2E-01	2.8E+00	9.9E-02	2.5E-01	6.0E+00	1.8E-01	5.9E-01	2.1E+00	8.1E-02	1.6E-01	4.0E-01
	Max	2.9E-01	1.1E+00	7.3E+00	2.6E-01	6.5E-01	1.6E+01	4.8E-01	1.5E+00	5.6E+00	2.1E-01	4.2E-01	1.1E+00
Thymus	Min	6.2E-02	2.3E-01	1.6E+00	5.5E-02	1.4E-01	3.3E+00	1.0E-01	3.3E-01	1.2E+00	4.5E-02	9.0E-02	2.2E-01
	Mode	1.2E-01	4.6E-01	3.0E+00	1.1E-01	2.7E-01	6.5E+00	2.0E-01	6.4E-01	2.3E+00	8.8E-02	1.8E-01	4.4E-01
	Max	3.2E-01	1.2E+00	8.0E+00	2.8E-01	7.1E-01	1.7E+01	5.2E-01	1.7E+00	6.1E+00	2.3E-01	4.6E-01	1.2E+00
Thyroid	Min	6.9E-02	2.6E-01	1.7E+00	6.1E-02	1.5E-01	3.7E+00	1.1E-01	3.7E-01	1.3E+00	5.0E-02	1.0E-01	2.5E-01
	Mode	1.4E-01	5.1E-01	3.4E+00	1.2E-01	3.0E-01	7.2E+00	2.2E-01	7.2E-01	2.6E+00	9.8E-02	2.0E-01	4.9E-01
	Max	3.6E-01	1.3E+00	8.9E+00	3.2E-01	7.9E-01	1.9E+01	5.9E-01	1.9E+00	6.8E+00	2.6E-01	5.2E-01	1.3E+00
Uterus	Min	4.8E-02	1.8E-01	1.2E+00	4.2E-02	1.1E-01	2.6E+00	7.9E-02	2.5E-01	9.1E-01	3.5E-02	6.9E-02	1.7E-01
	Mode	9.4E-02	3.5E-01	2.3E+00	8.3E-02	2.1E-01	5.0E+00	1.5E-01	4.9E-01	1.8E+00	6.8E-02	1.4E-01	3.4E-01
	Max	2.5E-01	9.2E-01	6.2E+00	2.2E-01	5.5E-01	1.3E+01	4.1E-01	1.3E+00	4.7E+00	1.8E-01	3.6E-01	8.9E-01
Whole-body dose rate	Min	7.6E-02	2.9E-01	1.9E+00	6.7E-02	1.7E-01	4.1E+00	1.3E-01	4.0E-01	1.5E+00	5.5E-02	1.1E-01	2.8E-01
	Mode	1.5E-01	5.6E-01	3.7E+00	1.3E-01	3.3E-01	7.9E+00	2.4E-01	7.8E-01	2.8E+00	1.1E-01	2.2E-01	5.4E-01
	Max	3.9E-01	1.5E+00	9.8E+00	3.5E-01	8.7E-01	2.1E+01	6.4E-01	2.1E+00	7.5E+00	2.8E-01	5.7E-01	1.4E+00
Post-decontamination years (1962–1995)													
		Plant 1			Plant 2			Plant 6E			Plant 7		
Organ	Type	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Bladder	Min	---	---	5.5E-02	---	---	1.9E-02	3.8E-02	7.6E-02	1.5E-01	6.5E-03	1.5E-02	3.0E-02
	Mode	---	---	1.1E-01	---	---	3.7E-02	7.5E-02	1.5E-01	3.0E-01	1.3E-02	2.9E-02	5.8E-02
	Max	---	---	2.8E-01	---	---	9.6E-02	2.0E-01	3.9E-01	7.8E-01	3.3E-02	7.6E-02	1.5E-01
Bone (red marrow)	Min	---	---	3.7E-02	---	---	1.3E-02	2.6E-02	5.1E-02	1.0E-01	4.4E-03	1.0E-02	2.0E-02
	Mode	---	---	7.3E-02	---	---	2.5E-02	5.1E-02	1.0E-01	2.0E-01	8.7E-03	2.0E-02	3.9E-02
	Max	---	---	1.9E-01	---	---	6.5E-02	1.3E-01	2.6E-01	5.3E-01	2.3E-02	5.2E-02	1.0E-01
Bone (surface)	Min	---	---	6.6E-02	---	---	2.3E-02	4.6E-02	9.1E-02	1.8E-01	7.8E-03	1.8E-02	3.6E-02
	Mode	---	---	1.3E-01	---	---	4.4E-02	9.0E-02	1.8E-01	3.6E-01	1.5E-02	3.5E-02	7.0E-02
	Max	---	---	3.4E-01	---	---	1.2E-01	2.4E-01	4.7E-01	9.4E-01	4.0E-02	9.2E-02	1.8E-01
Breast (female)	Min	---	---	5.8E-02	---	---	2.0E-02	4.0E-02	8.0E-02	1.6E-01	6.9E-03	1.6E-02	3.1E-02
	Mode	---	---	1.1E-01	---	---	3.9E-02	7.9E-02	1.6E-01	3.1E-01	1.3E-02	3.1E-02	6.1E-02
	Max	---	---	3.0E-01	---	---	1.0E-01	2.1E-01	4.1E-01	8.2E-01	3.5E-02	8.0E-02	1.6E-01
Colon	Min	---	---	5.0E-02	---	---	1.7E-02	3.4E-02	6.8E-02	1.4E-01	5.9E-03	1.3E-02	2.7E-02
	Mode	---	---	9.7E-02	---	---	3.3E-02	6.7E-02	1.3E-01	2.7E-01	1.2E-02	2.6E-02	5.2E-02
	Max	---	---	2.6E-01	---	---	8.7E-02	1.8E-01	3.5E-01	7.0E-01	3.0E-02	6.9E-02	1.4E-01
Esophagus	Min	---	---	3.9E-02	---	---	1.3E-02	2.7E-02	5.3E-02	1.1E-01	4.6E-03	1.0E-02	2.1E-02
	Mode	---	---	7.6E-02	---	---	2.6E-02	5.2E-02	1.0E-01	2.1E-01	8.9E-03	2.0E-02	4.1E-02
	Max	---	---	2.0E-01	---	---	6.7E-02	1.4E-01	2.7E-01	5.4E-01	2.3E-02	5.3E-02	1.1E-01
Eye	Min	---	---	5.9E-02	---	---	2.0E-02	4.1E-02	8.2E-02	1.6E-01	7.0E-03	1.6E-02	3.2E-02
	Mode	---	---	1.2E-01	---	---	4.0E-02	8.1E-02	1.6E-01	3.2E-01	1.4E-02	3.1E-02	6.3E-02
	Max	---	---	3.1E-01	---	---	1.0E-01	2.1E-01	4.2E-01	8.4E-01	3.6E-02	8.2E-02	1.6E-01
Gonads (ovaries)	Min	---	---	4.7E-02	---	---	1.6E-02	3.3E-02	6.5E-02	1.3E-01	5.6E-03	1.3E-02	2.5E-02
	Mode	---	---	9.2E-02	---	---	3.1E-02	6.4E-02	1.3E-01	2.5E-01	1.1E-02	2.5E-02	5.0E-02
	Max	---	---	2.4E-01	---	---	8.2E-02	1.7E-01	3.3E-01	6.7E-01	2.9E-02	6.5E-02	1.3E-01
Gonads (testes)	Min	---	---	6.2E-02	---	---	2.1E-02	4.3E-02	8.5E-02	1.7E-01	7.3E-03	1.7E-02	3.3E-02
	Mode	---	---	1.2E-01	---	---	4.1E-02	8.4E-02	1.7E-01	3.3E-01	1.4E-02	3.3E-02	6.5E-02
	Max	---	---	3.2E-01	---	---	1.1E-01	2.2E-01	4.4E-01	8.7E-01	3.8E-02	8.5E-02	1.7E-01
Liver	Min	---	---	5.1E-02	---	---	1.7E-02	3.5E-02	7.0E-02	1.4E-01	6.0E-03	1.4E-02	2.7E-02
	Mode	---	---	1.0E-01	---	---	3.4E-02	6.9E-02	1.4E-01	2.7E-01	1.2E-02	2.7E-02	5.4E-02
	Max	---	---	2.6E-01	---	---	8.9E-02	1.8E-01	3.6E-01	7.2E-01	3.1E-02	7.1E-02	1.4E-01
Lung	Min	---	---	5.0E-02	---	---	1.7E-02	3.5E-02	6.9E-02	1.4E-01	6.0E-03	1.4E-02	2.7E-02
	Mode	---	---	9.9E-02	---	---	3.4E-02	6.8E-02	1.4E-01	2.7E-01	1.2E-02	2.7E-02	5.3E-02
	Max	---	---	2.6E-01	---	---	8.8E-02	1.8E-01	3.6E-01	7.1E-01	3.1E-02	7.0E-02	1.4E-01
Remainder organs	Min	---	---	4.5E-02	---	---	1.5E-02	3.1E-02	6.2E-02	1.2E-01	5.3E-03	1.2E-02	2.4E-02
	Mode	---	---	8.8E-02	---	---	3.0E-02	6.1E-02	1.2E-01	2.4E-01	1.0E-02	2.4E-02	4.8E-02
	Max	---	---	2.3E-01	---	---	7.9E-02	1.6E-01	3.2E-01	6.4E-01	2.7E-02	6.2E-02	1.2E-01
Skin	Min	---	---	4.8E-02	---	---	1.6E-02	3.3E-02	6.6E-02	1.3E-01	5.7E-03	1.3E-02	2.6E-02
	Mode	---	---	9.4E-02	---	---	3.2E-02	6.5E-02	1.3E-01	2.6E-01	1.1E-02	2.5E-02	5.1E-02
	Max	---	---	2.5E-01	---	---	8.4E-02	1.7E-01	3.4E-01	6.8E-01	2.9E-02	6.7E-02	1.3E-01
Stomach	Min	---	---	5.6E-02	---	---	1.9E-02	3.9E-02	7.7E-02	1.5E-01	6.7E-03	1.5E-02	3.0E-02
	Mode	---	---	1.1E-01	---	---	3.7E-02	7.6E-02	1.5E-01	3.0E-01	1.3E-02	3.0E-02	5.9E-02
	Max	---	---	2.9E-01	---	---	9.8E-02	2.0E-01	4.0E-01	7.9E-01	3.4E-02	7.8E-02	1.6E-01

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Post-decontamination years (1962–1995)													
		Plant 1			Plant 2			Plant 6E			Plant 7		
Organ	Type	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
Thymus	Min	---	---	6.1E-02	---	---	2.1E-02	4.2E-02	8.4E-02	1.7E-01	7.2E-03	1.6E-02	3.3E-02
	Mode	---	---	1.2E-01	---	---	4.1E-02	8.3E-02	1.6E-01	3.3E-01	1.4E-02	3.2E-02	6.4E-02
	Max	---	---	3.1E-01	---	---	1.1E-01	2.2E-01	4.3E-01	8.6E-01	3.7E-02	8.5E-02	1.7E-01
Thyroid	Min	---	---	6.8E-02	---	---	2.3E-02	4.7E-02	9.4E-02	1.9E-01	8.1E-03	1.8E-02	3.7E-02
	Mode	---	---	1.3E-01	---	---	4.6E-02	9.3E-02	1.8E-01	3.7E-01	1.6E-02	3.6E-02	7.2E-02
	Max	---	---	3.5E-01	---	---	1.2E-01	2.4E-01	4.8E-01	9.7E-01	4.2E-02	9.5E-02	1.9E-01
Uterus	Min	---	---	4.7E-02	---	---	1.6E-02	3.3E-02	6.5E-02	1.3E-01	5.6E-03	1.3E-02	2.5E-02
	Mode	---	---	9.3E-02	---	---	3.2E-02	6.4E-02	1.3E-01	2.5E-01	1.1E-02	2.5E-02	5.0E-02
	Max	---	---	2.4E-01	---	---	8.3E-02	1.7E-01	3.3E-01	6.7E-01	2.9E-02	6.5E-02	1.3E-01
Whole-body dose rate	Min	---	---	7.5E-02	---	---	2.6E-02	5.2E-02	1.0E-01	2.1E-01	8.9E-03	2.0E-02	4.0E-02
	Mode	---	---	1.5E-01	---	---	5.0E-02	1.0E-01	2.0E-01	4.0E-01	1.7E-02	3.9E-02	7.9E-02
	Max	---	---	3.9E-01	---	---	1.3E-01	2.7E-01	5.3E-01	1.1E+00	4.6E-02	1.0E-01	2.1E-01

Data in this table were calculated using measured data from MCW (1958; 1959; 1961a) as given in Table A-39 above. Both maximum average and typical average dose rates at 1 meter (3 feet) were taken into account in calculating the effective gamma (photon) whole-body exposure rates; it was assumed that a worker spent two hours per day (500 hours per year) in the area of maximum dose rate and six hours per day (1,500 hours per year) in the area of typical dose rate. The base gamma annual exposures are shown as the whole-body exposure rates above.

The Min, Mode, and Max values were taken to correspond to the effective dose rates at 1 m, 1 foot (30 cm), and 1 cm from the contaminated surface, as per NIOSH direction.

Organ dose conversion factors for the ambient dose equivalent ($H^*(10)$ to H_T) from NIOSH (2007) were applied to produce the organ doses from photons. A geometry of 50% AP and 50% ROT was used and it was assumed that 100% of the exposure was due to photons in the 30–250 keV range.

"High" exposure potential represents those working in the most contaminated areas, i.e., the former process areas; "Moderate" represents those accessing the less contaminated areas or infrequently accessing the former process areas; and "Low" represents those accessing the uncontaminated areas. Plants 1 and 2 did not have enough data for these classifications to be applied.

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Table A-42. Annual external electron organ doses during the decontamination and post-decontamination periods (rem per year).

Decontamination years (1959–1961)													
		Plant 4			**Plant 6**			**Plant 6E**			**Plant 7**		
Organ	**Type**	**Low**	**Moderate**	**High**	**Low**	**Moderate**	**High**	**Low**	**Moderate**	**High**	**Low**	**Moderate**	**High**
Skin	Min	2.0E+00	3.8E+00	7.4E+00	7.8E-02	1.6E-01	3.0E+00	1.9E-02	1.2E-01	1.1E+00	8.7E-03	1.5E-01	1.5E+00
	Mode	3.7E+00	6.8E+00	1.3E+01	1.4E-01	2.8E-01	5.5E+00	3.4E-02	2.2E-01	2.0E+00	1.6E-02	2.7E-01	2.8E+00
	Max	1.8E+01	3.3E+01	6.4E+01	6.8E-01	1.4E+00	2.6E+01	1.6E-01	1.1E+00	9.6E+00	7.6E-02	1.3E+00	1.3E+01
Breast	Min	8.0E-01	1.5E+00	2.9E+00	3.1E-02	6.1E-02	1.2E+00	7.5E-03	4.8E-02	4.3E-01	3.4E-03	5.8E-02	6.0E-01
	Mode	1.4E+00	2.7E+00	5.2E+00	5.5E-02	1.1E-01	2.2E+00	1.3E-02	8.7E-02	7.8E-01	6.2E-03	1.0E-01	1.1E+00
	Max	6.9E+00	1.3E+01	2.5E+01	2.7E-01	5.3E-01	1.0E+01	6.5E-02	4.2E-01	3.7E+00	3.0E-02	5.0E-01	5.2E+00
Testes	Min	3.9E-01	7.2E-01	1.4E+00	1.5E-02	3.0E-02	5.9E-01	3.7E-03	2.4E-02	2.1E-01	1.7E-03	2.9E-02	2.9E-01
	Mode	7.1E-01	1.3E+00	2.6E+00	2.7E-02	5.4E-02	1.1E+00	6.6E-03	4.3E-02	3.8E-01	3.0E-03	5.1E-02	5.3E-01
	Max	3.4E+00	6.3E+00	1.2E+01	1.3E-01	2.6E-01	5.1E+00	3.2E-02	2.1E-01	1.8E+00	1.5E-02	2.5E-01	2.5E+00
Post-decontamination years (1962–1995)													
		Plant 1			**Plant 2**			**Plant 6E**			**Plant 7**		
Organ	**Type**	**Low**	**Moderate**	**High**	**Low**	**Moderate**	**High**	**Low**	**Moderate**	**High**	**Low**	**Moderate**	**High**
Skin	Min	5.3E-02	1.0E-01	6.7E-01	1.4E-02	2.8E-02	6.0E-01	4.6E-02	8.7E-02	1.7E-01	3.2E-02	7.2E-02	1.4E-01
	Mode	9.6E-02	1.9E-01	1.2E+00	2.5E-02	5.0E-02	1.1E+00	8.3E-02	1.6E-01	3.1E-01	5.7E-02	1.3E-01	2.6E-01
	Max	4.6E-01	9.0E-01	5.8E+00	1.2E-01	2.4E-01	5.2E+00	4.0E-01	7.5E-01	1.5E+00	2.8E-01	6.3E-01	1.3E+00
Breast	Min	2.1E-02	4.1E-02	2.6E-01	5.4E-03	1.1E-02	2.4E-01	1.8E-02	3.4E-02	6.8E-02	1.2E-02	2.8E-02	5.7E-02
	Mode	3.7E-02	7.3E-02	4.7E-01	9.8E-03	2.0E-02	4.2E-01	3.3E-02	6.1E-02	1.2E-01	2.2E-02	5.1E-02	1.0E-01
	Max	1.8E-01	3.5E-01	2.3E+00	4.7E-02	9.4E-02	2.0E+00	1.6E-01	2.9E-01	5.9E-01	1.1E-01	2.5E-01	4.9E-01
Testes	Min	1.0E-02	2.0E-02	1.3E-01	2.7E-03	5.3E-03	1.2E-01	8.9E-03	1.7E-02	3.3E-02	6.1E-03	1.4E-02	2.8E-02
	Mode	1.8E-02	3.6E-02	2.3E-01	4.8E-03	9.6E-03	2.1E-01	1.6E-02	3.0E-02	6.0E-02	1.1E-02	2.5E-02	5.0E-02
	Max	8.8E-02	1.7E-01	1.1E+00	2.3E-02	4.6E-02	1.0E+00	7.7E-02	1.4E-01	2.9E-01	5.3E-02	1.2E-01	2.4E-01

Data in this table was calculated using measured data from MCW (1958; 1959; 1961a) as given in Table A-39 above. Both maximum average and typical average dose rates at about 1 cm were taken into account in calculating the effective electron (beta) base exposure rates; it was assumed that a worker spent two hours per day (500 hours per year) in the area of maximum dose rate and six hours per day (1,500 hours per year) in the area of typical dose rate. The base annual exposures are shown as the skin exposures above.

The Min, Mode, and Max values were taken to correspond to the effective dose rates at 1 cm, 1 foot (30 cm), and 1 meter from the contaminated surface, as per NIOSH direction.

Organ dose conversion factors for conversion from skin dose to breast and testes doses were taken from ICRP (996); these are 0.49 for the breast and 0 .24 for the testes. In addition, a factor of .8 was used to account for clothing coverage for the breast and testes doses.

“High” exposure potential represents those working in the most contaminated areas, i.e., the former process areas; “Moderate” represents those accessing the less contaminated areas or infrequently accessing the former process areas; and “Low” represents those accessing the uncontaminated areas. Plants 1 and 2 did not have enough data for these classifications to be applied.

ATTACHMENT B
U. S. DEPARTMENT OF LABOR CORRESPONDENCE TO NIOSH CONCERNING DOSE RECONSTRUCTION FOR MEMBERS OF THE MALLINCKRODT-DESIGNATED SPECIAL EXPOSURE COHORT
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U.S. Department of Labor

Employment Standards Administration
Office of Workers' Compensation Programs
Division of Energy Employees Occupational
Illness Compensation
Washington, D.C. 20210

DEC 7 2005

Larry J. Elliott
Director, Office of Compensation Analysis and Support
National Institute for Occupational Safety and Health
Centers for Disease Control and Prevention
Mail Stop C-46
4676 Columbia Parkway
Cincinnati, Ohio 45226

Re: Handling of Mallinckrodt Cases for New SEC Class for 1949 - 1957

Dear Larry:

On October 14, 2005, the Secretary of the Department of Health and Human Services (HHS), Michael Leavitt, designated the following class for addition to the SEC in a report to Congress:

> Department of Energy (DOE) employees or DOE contractor or subcontractor employees who worked in the Uranium Division of the Destrehan Street Facility of Mallinckrodt Chemical Works from 1949 to 1957 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 within the parameters (excluding aggregate work day requirements) established for other classes of employees included in the SEC.

This designation became effective on November 13, 2005, as provided for under 42 U.S.C. 7384l(14)(C).

A report attached to Secretary Leavitt's letter, entitled "HHS Designation of Additional Members of the Special Exposure Cohort," provided the supporting rationale for designating a class of employees from the Uranium Division of the Mallinckrodt Chemical Works, Destrehan Street Facility, St. Louis, Missouri, for the years 1949 through 1957.

ATTACHMENT B
U. S. DEPARTMENT OF LABOR CORRESPONDENCE TO NIOSH CONCERNING DOSE RECONSTRUCTION FOR MEMBERS OF THE MALLINCKRODT-DESIGNATED SPECIAL EXPOSURE COHORT

Section IV, "Designation Findings," summarized NIOSH's finding that "… there is insufficient information either to estimate the maximum radiation dose for every type of cancer for which radiation doses are reconstructed that could have been incurred under plausible circumstances by any member of the class, or to estimate the radiation doses of members of the class more precisely than a maximum dose estimate with sufficient accuracy."

The discussion noted, "There is not individual bioassay monitoring or other monitoring information that can be used to quantify internal exposures to thorium-230, protactinium-231, and actinium-227 for raffinate workers specifically at the Destrehan Street facility of Mallinckrodt Chemical Works."

In addition, "The specific air sample data that exists for the Destrehan Street facility of Mallinckrodt Chemical Works is insufficient to establish the internal doses from inhalation of thorium-230, protactinium-231, and actinium-227 at the site with sufficient accuracy. This is because 1) the air sample data found at the Destrehan Street facility of Mallinckrodt Chemical Works do not provide radionuclide-specific information for the site; and 2) very little data are available to characterize the degree of disequilibrium in the raffinate source term at the Destrehan Street facility of Mallinckrodt Chemical Works."

The discussion further noted, "Records from the Destrehan Street facility of Mallinckrodt Chemical Works indicate that during the time frame of 1949 through 1957, employees may have rotated through a number of different jobs. The changes in work assignments make it difficult to distinguish the raffinate-exposed workers from the workers who never worked with raffinate."

Finally, "It should be noted that the Board believes, and NIOSH concurs, that the available external dose monitoring information is adequate for the reconstruction of individual external exposures; where appropriate, individual external doses can be reconstructed for specific types of cancer (e.g., skin)."

In summary, the Secretary of Health and Human Services has determined that it is not feasible to undertake dose reconstructions for the class of employees employed at the Destrehan Street facility of Mallinckrodt Chemical Works from 1949 through 1957. However, NIOSH has determined that it is possible to reconstruct individual occupational external doses for certain cancers.

Thus, NIOSH should provide two lists of employees at the Destrehan Street facility of Mallinckrodt Chemical Works for the SEC class period. One list should cover employees with specified cancers and the other list should address employees with non-specified cancers. NIOSH should return all cases with specified cancers (with the administrative record on a CD) to the Department of Labor Denver District Office for the Office of Workers' Compensation Programs to complete adjudication as appropriate. Since NIOSH has determined that it is possible to estimate external exposure, it will continue to perform dose reconstructions for cases with non-specified cancers for the SEC class time period based solely on external occupational dose. DOL will review employment and

ATTACHMENT B
U. S. DEPARTMENT OF LABOR CORRESPONDENCE TO NIOSH CONCERNING DOSE RECONSTRUCTION FOR MEMBERS OF THE MALLINCKRODT-DESIGNATED SPECIAL EXPOSURE COHORT

medical information for both lists of employees. If the district office identifies a case with a specified cancer during its review of cases with non-specific cancers, DOL will request the return of that case from NIOSH on an individual basis.

Sincerely,

Peter M. Turcic
Director, Division of Energy Employees
Occupational Illness Compensation

ATTACHMENT C
NOTES ON HOW THE "TOLERANCE" OR "PREFERRED" LEVEL FOR INSOLUBLE URANIUM COMPOUNDS IN AIR WAS CALCULATED IN 1948
Page 1 of 2

(From AEC 1949b)

Assumptions

1. The "tolerance" alpha radiation level to the lung is 30 mrep/week or 4.3 mrep/day.
2. The fraction of inhaled material retained in the lungs and pulmonary lymphatic tissue is 0.25.
3. The biological half-life of insoluble uranium compounds in the lung is 90 days.
4. The weight of a pair of lungs is 1,000 grams.
5. An individual inhales 10 cubic meters per 8-hour working day.

Calculations

1. µCi/g in lung required to deliver 4.3 mrep/day: = $\frac{(5.2 \times 10^7)\ (0.0043)}{2.2 \times 10^6 \times 60 \times 24 \times 8.86}$

   where

5.2×10^7	=	number of MeV/g in one rep
0.0043 rep/day	=	daily acceptable dose rate
2.2×10^6	=	number of dis/min per µCi
60×24	=	number of minutes per day
8.86	=	sum of energies of alpha radiation from U-238 and U-234 in equilibrium, in MeV

   = 8×10^{-6} µCi/g

2. Total µCi in lungs for 4.3 mrep/day:

   = $1{,}000 \times 8 \times 10^{-6}$
   = 8×10^{-3} µCi

3. µCi per 10 m^3 (inhaled in 8 hours) which will give 8×10^{-3} µCi to the lung at equilibrium (assuming exposure every day) = 2.54×10^{-4} µCi per 10 m^3

   where

8×10^{-3}	=	µCi in lungs at equilibrium
0.25	=	fraction of inhaled material deposited in the lung
90	=	assumed biological half-life in the lungs, in days
1.4	=	factor to convert half-life to mean life

4. µCi per m^3:

   = 2.54×10^{-5}
   = 56 dpm per m^3

ATTACHMENT C
NOTES ON HOW THE "TOLERANCE" OR "PREFERRED" LEVEL FOR INSOLUBLE URANIUM COMPOUNDS IN AIR WAS CALCULATED IN 1948

5. Adjustment for actual exposure occurring up to 6 days a week, when 7 days was assumed:

   56 dpm * (7 days/6 days) = 65 dpm
   (i.e., 5–6 days per week actually, since 56 dpm * (7 days/5 days) = 78 dpm

   and

   = **70 dpm per m^3**
   = **50 µg per m^3**

Note: As AEC 1949b states, these calculations use no factor to account for nonuniform distribution in the lungs. It is also stated that the acceptable weekly dose rate for alpha dust exposures was going to be changed (presumably by AEC) to either 30 mrep/week or 15 mrep/week.

ATTACHMENT D
EXAMPLE CALCULATION OF DAILY WEIGHTED AVERAGE EXPOSURE (DWE)

Table D-1. Calculation for continuous experimental furnace operators (from MCW 1950s).

Operation	Minutes per event	# events, day shift	# events, night shift	Total time, day shift	Total time, night shift	Measured alpha conc, dpm/m^3	Conc times total time, day shift	Conc times total time, night shift
Filling hopper	1.75	10	10	18	18	131,000 (avg of 3) H 153,000 L 102,000	2,358,000	2,358,000
Removing bottle	3	16	15	48	45	1,640 (avg of 3) H 3,440 L 265	78,720	73,800
Dumping bottles into drum	3.5	3	3	10	10	181,000 (avg of 2) H 236,000 L 125,000	1,810,000	1,810,000
Sampling the drum	1	3	3	3	3	407 (avg of 3) H 569 L 234	1,221	1,221
General air, furnace area				276	259	238 (avg of 6) H 908 L 8.5	65,688	61,642
General air, sampling area				60	60	175 (avg of 4) H 191 L 131	10,500	10,500
General air, smoking room				50	40	314 (avg of 3) H 378 L 248	15,700	12,560
General air, locker room				15	5	4.2 (avg of 5) H 6.5 L 0.7	63	21
General air, change room				15	15	68 (avg of 5) H 101 L 19	1,020	1,020
General air, lunchroom				30	40	1.27 (avg of 8) H 2.0 L 0.56	38.1	50.8
TOTAL	---	---	---	525	495	---	4,340,950	4,328,815
Average	---	---	---	505		---		

Average alpha concentration = $\frac{4{,}340{,}950}{505}$ = **8,596** dpm/m^3

Average "times tolerance" exposure = $\frac{8{,}596}{70}$ = **123**

Note: H and L denote the high and low values respectively.