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CHARACTERIZATION OF EXPOSURES TO WORKERS COVERED UNDER THE U.S. ENERGY EMPLOYEES COMPENSATION ACT

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Abstract

Since the mid-1940s, hundreds of thousands of workers have been engaged in nuclear weapons-related activities for the U.S. Department of Energy (DOE) and its predecessor agencies. In 2000, Congress promulgated the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA), which provides monetary compensation and medical benefits to certain energy employees who have developed cancer. Under Part B of EEOICPA, the National Institute for Occupational Safety and Health (NIOSH) is required to estimate radiation doses for those workers who have filed a claim, or whose survivors have filed a claim, under Part B of the Act. To date, over 39,000 dose reconstructions have been completed for workers from more than 200 facilities. These reconstructions have included assessment of both internal and external exposure at all major DOE facilities, as well as at a large number of private companies [known as Atomic Weapons Employer (AWE) facilities in the Act] that engaged in contract work for the DOE and its predecessor agencies. To complete these dose reconstructions, NIOSH has captured and reviewed thousands of historical documents related to site operations and worker/workplace monitoring practices at these facilities. Using the data collected and reviewed pursuant to NIOSH's role under EEOICPA, this presentation will characterize historical internal and external exposures received by workers at DOE and AWE facilities. To the extent possible, use will be made of facility specific coworker models to highlight changes in exposure patterns over time. In addition, the effects that these exposures have on compensation rates for workers are discussed.

Keywords

dose reconstruction; exposure; radiation; health effects; National Council on Radiation Protection and Measurements

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INTRODUCTION

Since the mid-1940s, it has been estimated that 650,000 workers have been engaged in nuclear weapons-related activities for the U.S. Department of Energy (DOE) or its predecessor agencies. In 2000, Congress promulgated the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA 2000), which was enacted after epidemiologic research indicated associations between work-related exposures to potential hazards at DOE facilities and elevated rates of cancers and other illnesses incurred by this workforce. EEIOCPA, which is administered by the U.S. Department of Labor (DOL), provides monetary compensation and medical benefits to certain energy employees who have developed cancer. Part B of the Act, supplemented by a Presidential Executive Order (2000), established a program for providing a lump-sum payment of $150,000 and medical benefits as compensation to people who have suffered or are suffering from designated illnesses (i.e., cancer, chronic beryllium disease, or silicosis), provided these were shown to have developed from exposures incurred during employment involving nuclear weapons-related activities at one or more facilities or sites operated by DOE or its predecessor agencies. The Act also included coverage for what is estimated as >100,000 employees of commercial facilities that were contracted by DOE to perform work related to the nuclear weapons programs. Under the Act, these facilities have been designated as Atomic Weapons Employers (AWEs). A complete listing of all facilities covered under part B of EEOICPA can be viewed at the following web address: energy.gov/hss/information-center/department-energy-technical-standards-program/former-worker-medical-screeni-0 (USDOE 2012).

Although the Presidential Executive Order assigned primary responsibility for administration of the program to the DOL, the U.S. Department of Health and Human Services (DHHS) was assigned the task of fulfilling several important supporting technical and policymaking roles. The National Institute for Occupational Safety and Health (NIOSH), a component of the Centers for Disease Control and Prevention, is named under EEOICPA to assist the Secretary of DHHS to implement her responsibilities under the Act. Under EEOICPA, the NIOSH is required to reconstruct radiation doses for those workers who have filed a claim, or their survivors who have filed a claim, under Part B of the Act. The DOL uses the results of these dose reconstructions to determine eligibility for compensation under the Act. Under Part B, compensation decisions for a covered cancer are made by DOL based on a probability of causation calculation. Using the Interactive RadioEpidemiology Program (Kocher et al. 2008), a cancer must have been “at least as likely as not” (i.e., a probability of causation of ≥50%) due to the worker’s radiation exposure at a covered facility (DHHS 2002). To date, >39,000 dose reconstructions have been completed for workers from over 200 covered facilities. These reconstructions include assessment of both internal and external exposure at all major DOE facilities, as well as at a large number of AWE facilities. A detailed discussion of the technical and administrative aspects of the NIOSH dose reconstruction program under EEOICPA has been published previously (Moeller and Toohey 2008).

DEMOGRAPHICS AND SOURCE TERM FOR CASES RECEIVED

Of the >39,000 cases received for dose reconstruction thus far, most are men, but a significant proportion of the cases (13%) are women. Given that EEOICPA covers exposures going back to the early 1940s, a significant portion of the claims (28%) have been filed by survivors (i.e., spouses or children) of former workers. As also might be expected, given the size of the DOE complex, the majority of the cases (84%) are from workers or former workers at DOE (or its predecessor agencies) facilities. Fig. 1 provides the distribution of cases received from DOE facilities. As can be seen, more than one-quarter of the cases are from the three DOE sites located in Oak Ridge, Tennessee. The distribution of cases by employment start date is provided in Fig. 2. The distribution is fairly uniform from 1960–1989 with a notable spike in the 1950s and the number of cases trending downward in the 1980s and 1990s. Slightly >10% of the cases were first employed in the 1940s.

Beginning with the establishment of the Manhattan Engineer District (MED) in 1942 and continuing through the present, the activities involved in the production of nuclear weapons encompass a wide range of technologies. As discussed in the DOE publication, *Linking Legacies* (USDOE 1997), the basic weapons-related activities that created an exposure potential for workers are varied. These activities are summarized in Table 1. Each activity has the potential to expose workers to a variety of internal and external sources of radiation. Table 2 provides a summary of the types of exposure associated with weapons-related activities. Based on past dose reconstruction experience, the exposures that provide a large amount of dose in most claims are the external exposure to penetrating gamma radiation in the early years of operations and the internal exposure associated with the inhalation of uranium and plutonium. Attention will be focused on these modes due to the need to limit the scope of this publication to a reasonable length. This is not to say that the other exposure types are unimportant. In fact, for many cases, exposure to other types of radiation (e.g., neutron, beta dose to skin, and inhalation of other actinides) have constituted a large part of the reconstructed dose. It is anticipated that a discussion of these additional types of exposures not covered in this presentation will be summarized and discussed in a future publication.

EXPOSURE DURING THE EARLY YEARS OF URANIUM PROCESSING

1942 through the mid-1950s

Starting with the creation of the MED in 1942 and continuing through the early 1950s, there was a demand for large quantities of purified uranium that would be turned eventually into uranium metal and rolled into rods. To meet this early demand, the MED [subsequently the Atomic Energy Commission (AEC) beginning in 1946] contracted with a number of commercial facilities to develop processes for separating uranium from ore, converting the purified compounds of uranium metal, and shaping the metal into rods.

Chemical separation and purification

There are a number of processes involved in the refinement of uranium, including ore handling, chemical extraction, denitration, oxide reduction, and reduction to metal. While there were several commercial facilities involved in the refinement process, the

Mallinckrodt Chemical Company serves as a good example of the types of exposures encountered at these early facilities. The MED asked the Mallinckrodt Chemical Works in April 1942 to begin research on uranium refining and processing operations that could lead to large-scale uranium production operations. The work began immediately, and by July 1942, Mallinckrodt was producing almost a ton of UO_2 per day (ORAU 2010). In addition to Mallinckrodt, some of the other major early facilities involved in the refining of uranium from ore included the Linde Ceramics Plant in Tonawanda, New York, and the Harshaw Chemical Company in Cleveland, Ohio.

The exposures at these early AWE facilities that refined uranium were characterized by high concentrations of airborne uranium, with airborne levels exceeding hundreds of times the then maximum allowable concentration of 70 dpm m^{-3}.† In the very early years of uranium refining, prior to the establishment of the AEC in 1946, monitoring data are sparse. Even when data are available, the monitoring techniques employed are not well documented, making the results difficult to interpret. With the creation of the AEC, however, the Health and Safety Laboratory was formed to provide radiation monitoring support to the sites involved in uranium processing. This laboratory, located in New York City, developed and standardized workplace exposure assessment techniques for the existing AEC facilities. For an 8-y period between 1948 and 1956, the Health and Safety Laboratory completed 60 workplace evaluations at seven uranium refining facilities. Based on their published data, a graph depicting air concentration data at these facilities as a function of time has been constructed (Strom 2007). This graph, provided in Fig. 3, shows the decreasing trend of geometric mean exposures over an 8-y period, along with estimates of the associated uncertainties. From inspection of Fig. 3, it can be seen that there is about a 30-fold drop in the geometric mean value over the decade.

On a number of occasions, the uranium extraction operations during this period involved the processing of high-grade uranium ore, which contained equilibrium quantities of uranium progeny. Because of this, the external exposure environment had levels of gamma radiation that could easily produce annual exposures of 20 R y^{-1}. As an example, Table 3 provides a summary of the annual external exposures received by Mallinckrodt workers between 1947 and 1956. Although there is some component of this exposure that can be attributed to the gamma emissions associated with the purified uranium product, most of this is due to the gamma radiation from the short-lived gamma-emitting progeny of ^{226}Ra (i.e., ^{214}Pb and ^{214}Bi).

The ore refining process separated the progeny that was originally in secular equilibrium into several waste streams, creating isolated pathways where one or more of the progeny could become concentrated. Notably, ^{230}Th was known to concentrate in the filter cake in one portion of the refining process. Thus, the potential for unmonitored exposure to this source term was created. In addition, ^{222}Rn was also present at any facility that handled uranium ore in equilibrium with its progeny. Radon, being a chemically unreactive gas, would readily accumulate in areas where ore was processed and stored, particularly in

†Because this paper recounts historical exposures to workers over an extended period of time, the traditional units employed at the time the measurements were made are reported.

locations with minimal ventilation. An example of the levels of radon that existed at early ore processing facilities is provided in Table 4. Here it can be seen that the upper radon levels at the Mallinckrodt Facility between 1949 and 1957 were well into the hundreds of pCi L^{-1}. Assuming an average progeny equilibrium ratio of 50% for indoor air, this equates to a work environment of several working levels.

Metal production

Subsequent to the production of purified uranium compounds, much of the material was converted to metal and eventually shaped into rods for use as targets in reactors. As with the chemical processing operations, the AEC relied on existing commercial or research facilities to perform this conversion. Early in 1942, faculty members in the Chemistry Department at Iowa State College in Ames, Iowa, with expertise in rare earth metallurgy, were called on to develop a method to produce uranium metal. By November 1942, successful methods had been developed, and approximately one-third of the uranium used in the Chicago pile was supplied by the Ames Project. Between mid-1942 and August 1945, >1,000 tons of pure uranium metal was supplied to the Manhattan Project. Eventually, uranium production was established at a number of commercial facilities, including Harshaw Chemical Company, Mallinckrodt, and Electromet. Given that the uranium had been separated from its progeny during the refining process, radiation exposures during the production of uranium metal were almost entirely due to the three naturally occurring isotopes of uranium, ^{234}U, ^{235}U, and ^{238}U.

Once the immediate need for uranium metal was fulfilled, the Ames Project began to develop methods for purifying thorium in 1943. By late 1944, a large-scale process for thorium metal production was developed. Between 1950 and 1953, when thorium production was turned over to commercial operations, >65 tons of pure thorium metal and thorium compounds were produced by the Ames Laboratory (Ames 1960). The production of thorium was not limited to Ames, and in fact, a number of the early AWE facilities that processed uranium also processed thorium, although on a more limited basis. In the MED (prior to 1946) and early AEC years, air samples were not collected with sufficient frequency to quantify worker intakes, but urine samples were collected occasionally. Unfortunately, the high detection limit for the urinalysis method employed, in conjunction with the low urinary excretion of insoluble thorium, rendered these data unusable for reconstruction of workers exposure to thorium. Because of the limited sampling that was conducted and the technology shortfall associated with thorium bioassay, NIOSH has determined that thorium doses cannot be reconstructed with sufficient accuracy at several of the early processing facilities.‡

Metal rolling

Several steel mills contributed to the production of uranium metal rods used by Hanford as targets for the production of plutonium. Rolling of uranium metal rods was investigated at Joslyn Manufacturing and Supply during and after the war effort to evaluate methods to

‡At facilities where it has been determined that dose reconstructions cannot be performed with sufficient accuracy, EEOICPA provides for the addition of certain classes of workers to a Special Exposure Cohort. For those classes of workers added to the Special Exposure Cohort, dose reconstructions are not required, and causation is presumed, for any of the 22 cancers prescribed in the Act.

improve product quality and reduce losses of product during the manufacturing process. Another development that promised improvements in the production of uranium metal rods was the successful rolling of lead-dipped uranium billets by Joslyn in 1948, which, according to the early AEC reports, were far superior to the Hanford[§] materials in terms of blistering (USDOE 1997). Blistering of the uranium surface not only led to loss of product but also created the potential for the generation of high concentrations of airborne uranium in the workplace.

During the late 1940s, uranium metal was delivered as billets to Simonds Saw and Steel Company, Lockport, New York, and Vulcan Crucible Steel Company, Aliquippa, Pennsylvania, where they rolled the billets into rods that were shipped to Hanford. Although it is known that other rolling mills also participated in rolling operations during this early time period, Simonds Saw and Steel became the principal manufacturer of rods as Vulcan was unable to roll the larger billets coming from Mallinckrodt. The levels of airborne uranium during these early years reached >500 times the then maximum allowable concentration of 70 dpm m^{-3}. The distribution of air samples taken at the Simonds Saw and Steel facility is provided in Fig. 4. It can be seen that in 1948, the measured air concentrations are characterized by a log-normal distribution with a median value of approximately 1,200 dpm m^{-3} and a geometric standard deviation of eight (ORAU 2011). These levels were associated with the rolling of uranium that had been heated in an open furnace. As new techniques were developed that heated the uranium billets in molten salt baths, the levels of uranium in air were reduced substantially.

EXPOSURE AT DOE PRODUCTION AND PROCESSING FACILITES

With the advent of the larger DOE owned and operated facilities, the levels of exposure were better controlled, and worker monitoring programs were established and/or expanded. At these facilities, most external exposures were reduced by about an order of magnitude over that seen in the early AWE operations. The initiation of routine bioassay sampling programs, along with more standardized methods, also provided for better documentation of internal exposure in the workplace. The variety and types of exposure, however, increased dramatically. Potential exposures now included a growing inventory of actinide elements, such as plutonium, americium, and neptunium. Furthermore, a number of new reactors were constructed that increased exposure potential to photons, neutrons, and mixed fission and activation products. To support ongoing research activities, new accelerators and cyclotrons were put in service that also added to the complexity of the exposure profile.

To complete dose reconstructions at these facilities, the Division of Compensation Analysis and Support within NIOSH has collected and reviewed thousands of historical documents related to site operations and worker/workplace monitoring practices at these facilities. When individual monitoring data are available (i.e., external badge and bioassay results), NIOSH uses these preferentially to reconstruct a worker's dose. Absent these data, NIOSH

[§]Construction of the Hanford Site, located in Richland, Washington, began in 1943. The Hanford Site played an important role in the development of the U.S. nuclear weapons program. Operations at the site included the construction of nine reactors to produce plutonium for weapons and seven physical testing, research, and demonstration reactors. Facilities for the separation of uranium and plutonium, for uranium and tritium extraction, and for many support functions evolved over the years.

has developed co-worker models to evaluate exposures. These co-worker models, which characterize the distribution of a worker's facility-specific exposure potential over time, have been used to establish reasonable estimates of dose for unmonitored workers. As with AWE operations, the levels of external and internal exposures have generally decreased over time, but there are some facility-specific exceptions. While it is not possible to provide a detailed summary for all DOE facilities evaluated by NIOSH, a few sites have been chosen for discussion that are considered to be representative of the types of exposures routinely encountered in dose reconstructions at DOE production and processing facilities.

External exposure

The Feed Materials Production Center located near Cincinnati, Ohio, started operation as a uranium production facility in 1952. As such, the Fernald facility in Ohio took on the role of uranium refinement that was performed previously by commercial AWE facilities. In 1952, construction also began on the gaseous diffusion plant in Piketon, Ohio, which later became known as the Portsmouth Gaseous Diffusion Plant. Uranium enrichment, which was the primary activity at Portsmouth, Ohio, began in 1954. Fig. 5 provides an example of the magnitude of the 50th percentile annual external exposures at the Fernald and Portsmouth facilities between their startup in the early 1950s through the 1990s. Although both facilities processed primarily uranium, the Fernald site mostly handled natural or depleted uranium, while the Portsmouth site is a gaseous diffusion plant that was engaged in the enrichment of uranium. Given the differences in the uranium source terms, it is interesting that the initial magnitude of the annual external exposure at these facilities was in the 10 mSv range with exposures dropping to nondetectable levels starting around the end of the 1980s. It should be noted that the annual exposures plotted in these graphs include "missed dose." That is, for every badge result that was reported to be below the limit of detection, it was considered to have received a dose that is equal to one-half the limit of detection.

As with most occupational exposure datasets, the annual distribution of external doses was found to be log-normally distributed. Based on the geometric standard deviation that was calculated for each year, Fig. 6 provides a plot of the time-dependent 95th percentile external doses. While the 95th percentile exposures at Portsmouth tend to follow the general decline of the 50th percentile exposures over time, the 95th percentile exposures at Fernald increase dramatically in the early 1960s and stay elevated at around 10 mSv through the early 1980s. A review of the activities at Fernald revealed that the elevated exposures correspond to the receipt and processing of thorium at the site. Although exposures for most workers were reduced over this time period, as indicated by the decreasing 50th percentile exposure, those workers associated with thorium handling continued to receive elevated exposures.

External exposures at the Hanford and Oak Ridge X-10[**] Facilities are examples of large facilities with a variety of external exposure source terms. As shown in Fig. 7, exposures decrease over time from their initial annual exposures in the mid-1940s of (~14 and 8 mSv)

[**]Site operations at the Oak Ridge X-10 facility began in 1943. Much of the early site work was devoted to the development and operation of the original plutonium production reactor and associated chemical separation facility to test the larger production reactors that were being built on the Hanford Site.

at Hanford and X-10, respectively. While X-10 exposures continue to decrease through the middle of 1960, exposures at Hanford decrease through the end of 1950, then start rising to a peak in 1965. This trend corresponds to the years of peak plutonium production at the facility. The 95th percentile doses do not decline as dramatically at Hanford and X-10. As seen by comparing Fig. 7 with Fig. 8, the 50th percentile doses drop over time by more than an order of magnitude, while the 95th percentile typically stay within a band of about a factor of three.

Internal exposure

Using the bioassay monitoring information that NIOSH has collected from a number of DOE facilities, the urinary excretion of various radionuclides has been characterized as a function of time. As they predominate the internal exposure potential at DOE facilities, the radionuclides with the most monitoring data are uranium and plutonium. As with the external monitoring data, the bioassay samples for a given time period were found to be log-normally distributed, which allows the data to be described by 50th and 84th percentile excretion rates, where the 84th percentile corresponds to the excretion at one geometric standard deviation. To date, NIOSH has used these data to develop coworker exposure models at a dozen facilities. While it is not possible to discuss all these facilities during this publication, an example of a site with uranium and plutonium excretion curves is provided.

Fig. 9 provides a graph depicting the 24 h urinary excretion of ^{239}Pu at the Hanford facility between 1946 and 1988. As shown, the 50th percentile for the 24 h urinary excretion decreased by more than an order of magnitude over this time period, decreasing from ~0.3 dpm d^{-1} to levels at or near the detection limit around the mid-1950s. The geometric standard deviation tracks closely with the 50th percentiles and was ~2.6. The sharp drop in the mid-1980s is associated with an improvement in the analytical sensitivity of the measurement technique and not a reduction in intakes. As will be discussed in a subsequent section of this presentation, the sensitivity of the measurement technique has a direct effect on the level of internal dose that could have been received by a worker yet undetected by the bioassay sample.

Fig. 10 provides a graph depicting urinary excretion of uranium for workers at the Fernald site between 1952 and 1990. After a fairly steep rise in excretion at the onset of production, there is a peak median output of 35 μg L^{-1} in 1955 followed by a gradual decline. Starting in about the mid-1960s, the 50th percentile values are at about the detection limit of the fluorometric fusion technique employed. As was the case in the early years at AWE facilities, the reduction in internal exposure was mostly the result of improvements in administrative and engineering controls. In fact, some of the technical staff from the AEC's Health and Safety Laboratory who were responsible for recommending improvements at AWE facilities eventually joined the health and safety staff at the Fernald site.

CONSIDERATION OF MISSED DOSE

For the purposes of NIOSH's role under EEOICPA, missed dose is defined as the potential dose that could have been received by a person who wore a personal monitoring badge or submitted a bioassay sample, but because of technical limitations, the dose was undetected.

In all cases processed by NIOSH, missed dose is explicitly included in the external and internal dose reconstructions (Bracket et al. 2008; Merwin et al. 2008). Although missed dose for external exposure can be substantial for the early years when the detection limit for film badges was higher than that for currently employed thermoluminescent dosimeters and the badges were exchanged more frequently, the most significant missed dose is that associated with persons monitored for internal exposure to insoluble actinides. The low urinary excretion rate associated with insoluble forms of the actinides (e.g., uranium and plutonium) creates a situation where fairly large intakes could have occurred that went undetected in the bioassay sample (i.e., routine bioassay samples were below the analytical detection limit). In cases where a worker is monitored routinely and all the bioassay samples are at on below the detection limit, NIOSH assumes (in most cases) that the worker was chronically exposed over the duration of the monitoring period.

The assumptions described above lead to the assignment of dose to workers that could far exceed their recorded workplace exposure. Specifically, this would be most notable in cases where the dose to the lung was being reconstructed and, to a lesser extent, to one of the organs that tend to concentrate actinides (e.g., the liver for plutonium). For lung cancer cases especially, the missed doses assigned to workers are of sufficient magnitude to produce a probability of causation of ≥50%, even when there is no evidence of a positive bioassay sample.

COMPENSATION RATES FOR CANCER CLAIMS

Given the characteristics of the exposures described above, it is of interest to examine the overall compensation rate for the cases reconstructed by NIOSH thus far, as well as the rate for various types of cancers. As provided in Table 5, the overall compensation rate for claims with a single primary cancer is 26.2%.†† For cases with multiple cancers, the compensation rate increases to 35.2%. For all cases combined, the overall compensation rate is 28.8%.

Of the 22,233 cases with a single primary cancer, lung, prostate, and skin cancer make up >50% of the cases. Lung cancer has the highest compensation rate with 2,940 dose reconstructions out of 4,521 (65%), producing a probability of causation >50%. As discussed in the previous section, this is largely a result of the missed internal dose assigned by NIOSH for cases that had the potential for inhalation exposure to the plutonium or uranium. Three forms of leukemia have three of the top six cancer compensation rates, which are primarily related to the elevated excess relative risk per Sievert associated with leukemia as compared to other solid tumors. Cancers of organs with low uptakes of actinides (e.g., brain and digestive tract) have relatively low, but not zero, compensation rates. For these cancers to be compensated, it usually requires a fairly high cumulative external exposure to penetrating gamma radiation. These types of conditions were more predominant in the early AWE periods during the processing of uranium ores.

††This value is based on 31,467 claims with a single primary cancer and with dose reconstructions approved and submitted to DOL through 21 September 2012.

SUMMARY AND CONCLUSION

Under the EEOICPA, NIOSH has received from the DOL >39,000 cases for dose reconstruction. The dose reconstructions performed by NIOSH are used by DOL to determine if a worker's cancer was at least as likely as not (i.e., a probability of causation of ≥50%) caused by their exposure to ionizing radiation while employed at a DOE or AWE facility. To conduct these dose reconstructions, NIOSH has collected large amounts of information on the exposure conditions at over 200 different facilities. The exposures covered under EEOICPA span a considerable time period, beginning with the creation of the MED in 1942 and continuing through the present. Given the wide variety of operations associated with the production of nuclear weapons, the radiation source term consists of a wide range of internal and external exposure. Based on past dose reconstruction experience, the exposures that provide a large amount of dose to many claims are the external exposure in the early years (both actual and missed dose) and the internal exposure associated with the inhalation of uranium and plutonium (both actual and missed dose).

The uranium processing operations during the MED and early AEC time periods produced high internal and external exposures that were many times greater than those currently allowed under existing regulations. In addition to uranium, workers in this era were also exposed to high levels of radon gas and uranium progeny, including ^{226}Ra and ^{230}Th. Over time, these exposures were reduced greatly due to improvements in administrative and engineering controls. At the same time, the introduction of reactors and chemical processing plants increased the variety of the source term.

Over time, large purpose-built DOE facilities were constructed. These facilities established monitoring programs that included the routine issuance of external dosimeter badges and collection of bioassay samples. An evaluation of the data collected over time allows for the characterization of internal and external exposures at these facilities. Several examples provided in this presentation demonstrate the overall trend in the reduction of exposures over time, with deviations in this pattern related to site-specific activities.

By including missed dose and using other favorable assumptions, almost 30% of all claims have dose reconstructions that result in a probability of causation ≥50%. Incorporation of missed dose into lung cancer cases results in a compensation rate of more than two times that of the average.

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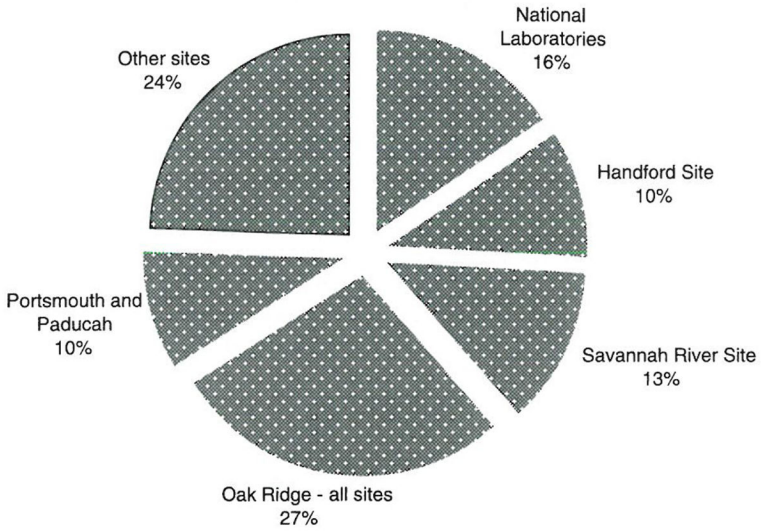

Fig. 1.
Distribution of DOE facility cases by site.

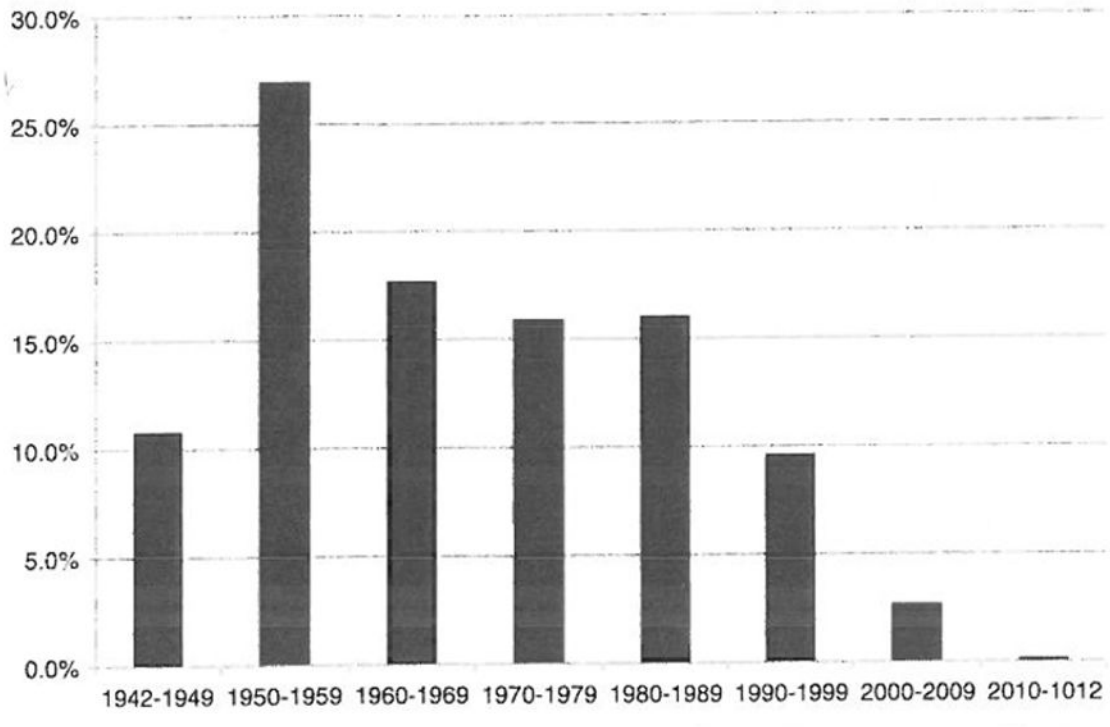

Fig. 2.
Distribution of employment start dates for cases received.

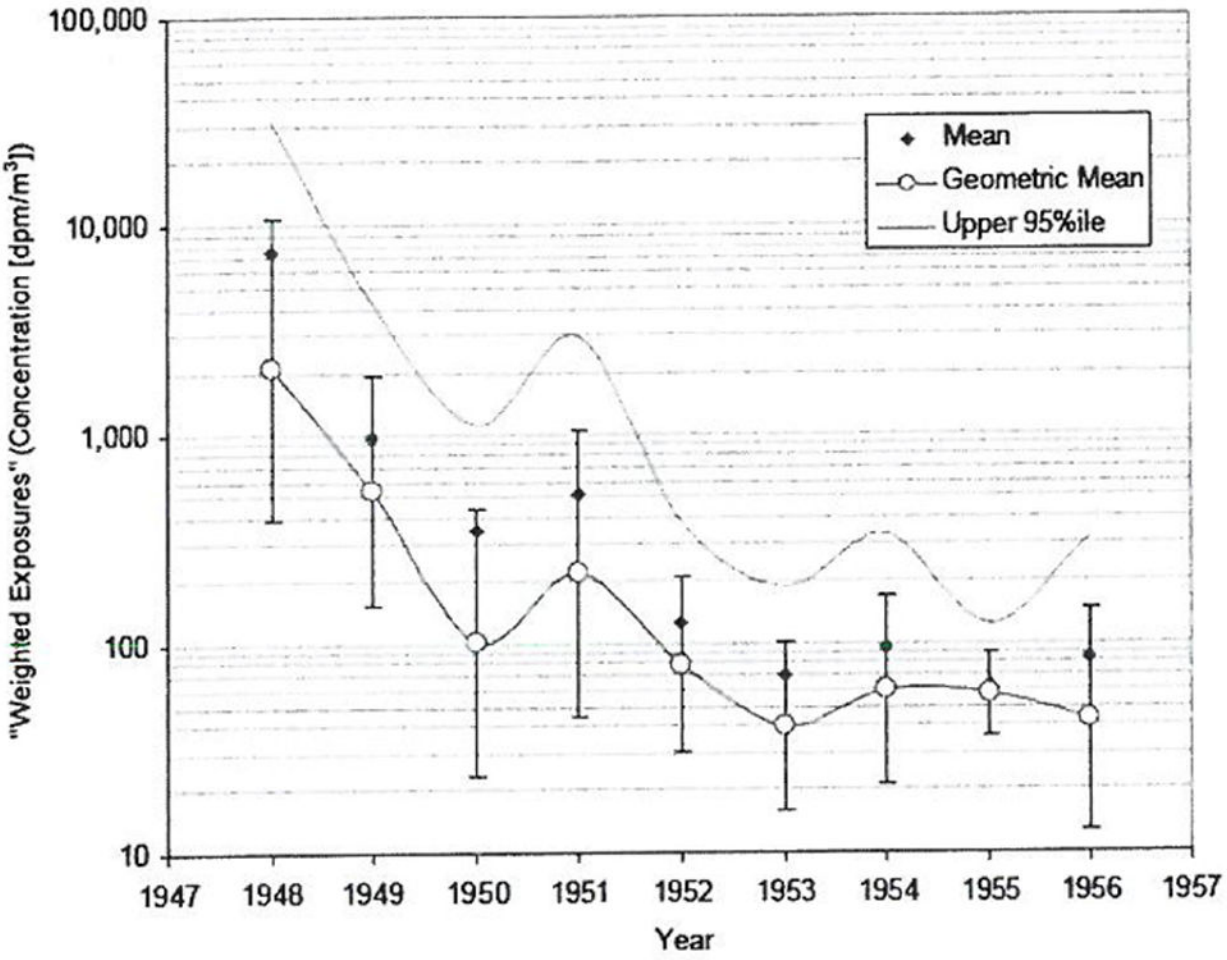

Fig. 3.
Gross alpha air concentration at early uranium refining facilities.

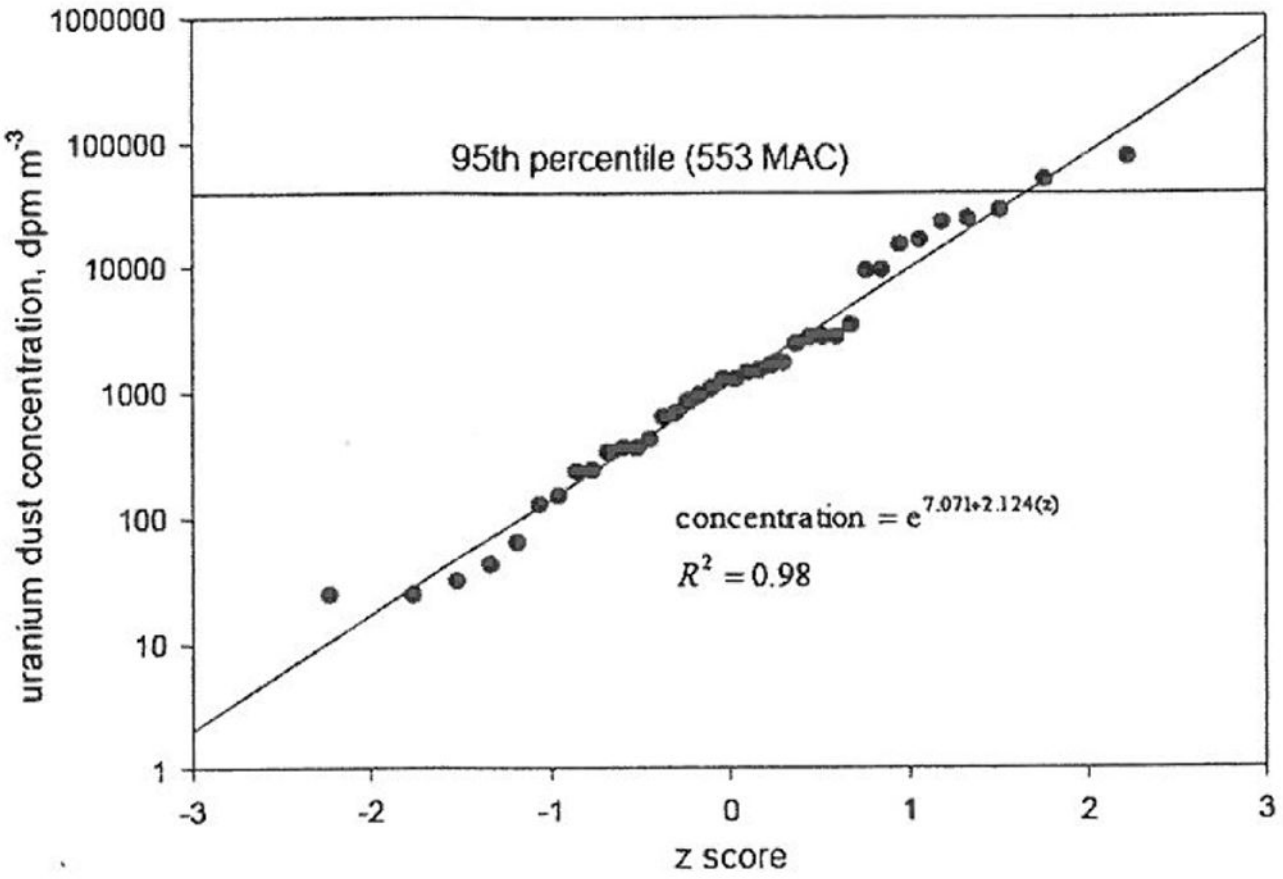

Fig. 4.
Distribution of air samples at Simonds Saw and Steel, 1948.

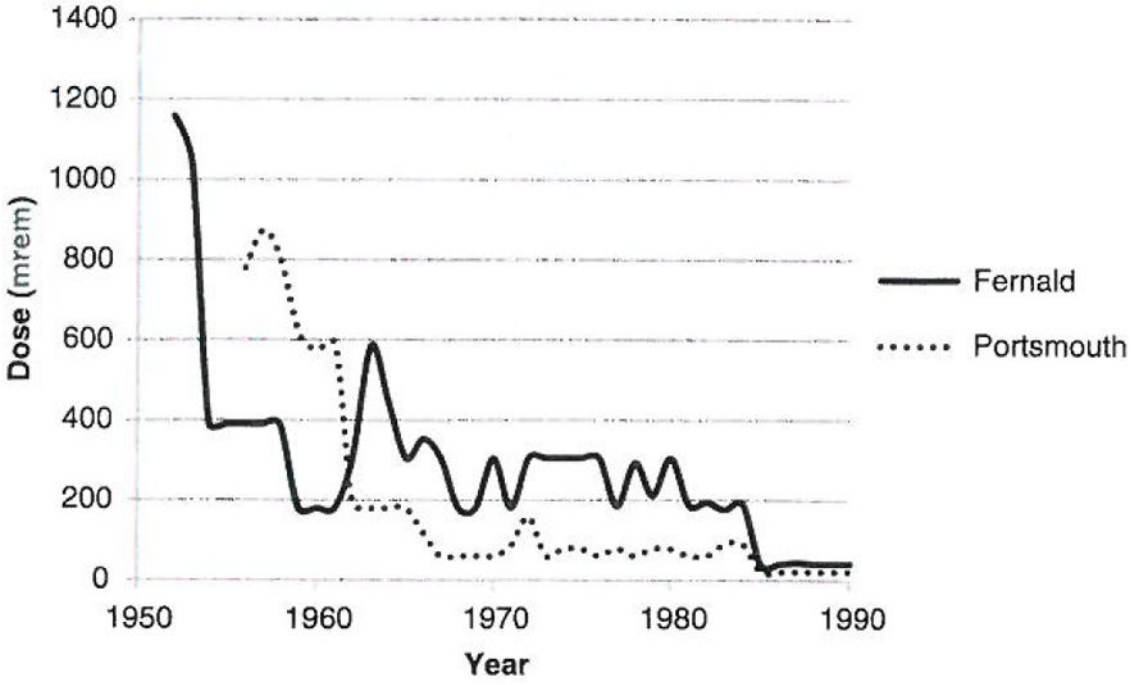

Fig. 5.
50th percentile external gamma doses as measured by personnel dosimeters (includes missed dose).

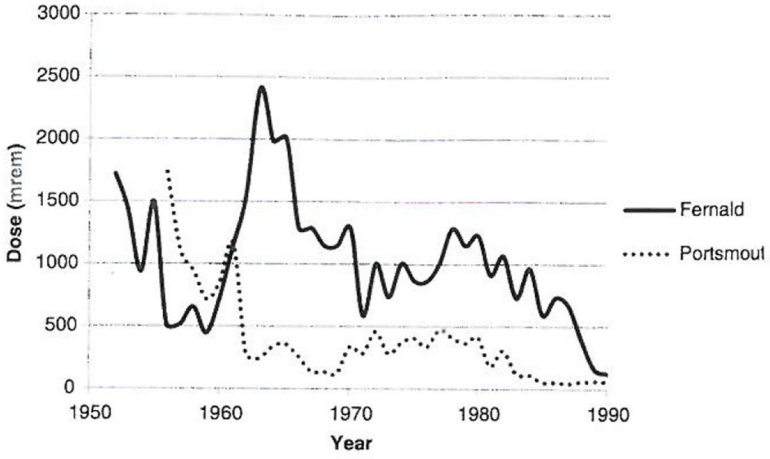

Fig. 6.

95th percentile external gamma doses as measured by personnel dosimeters (includes missed dose).

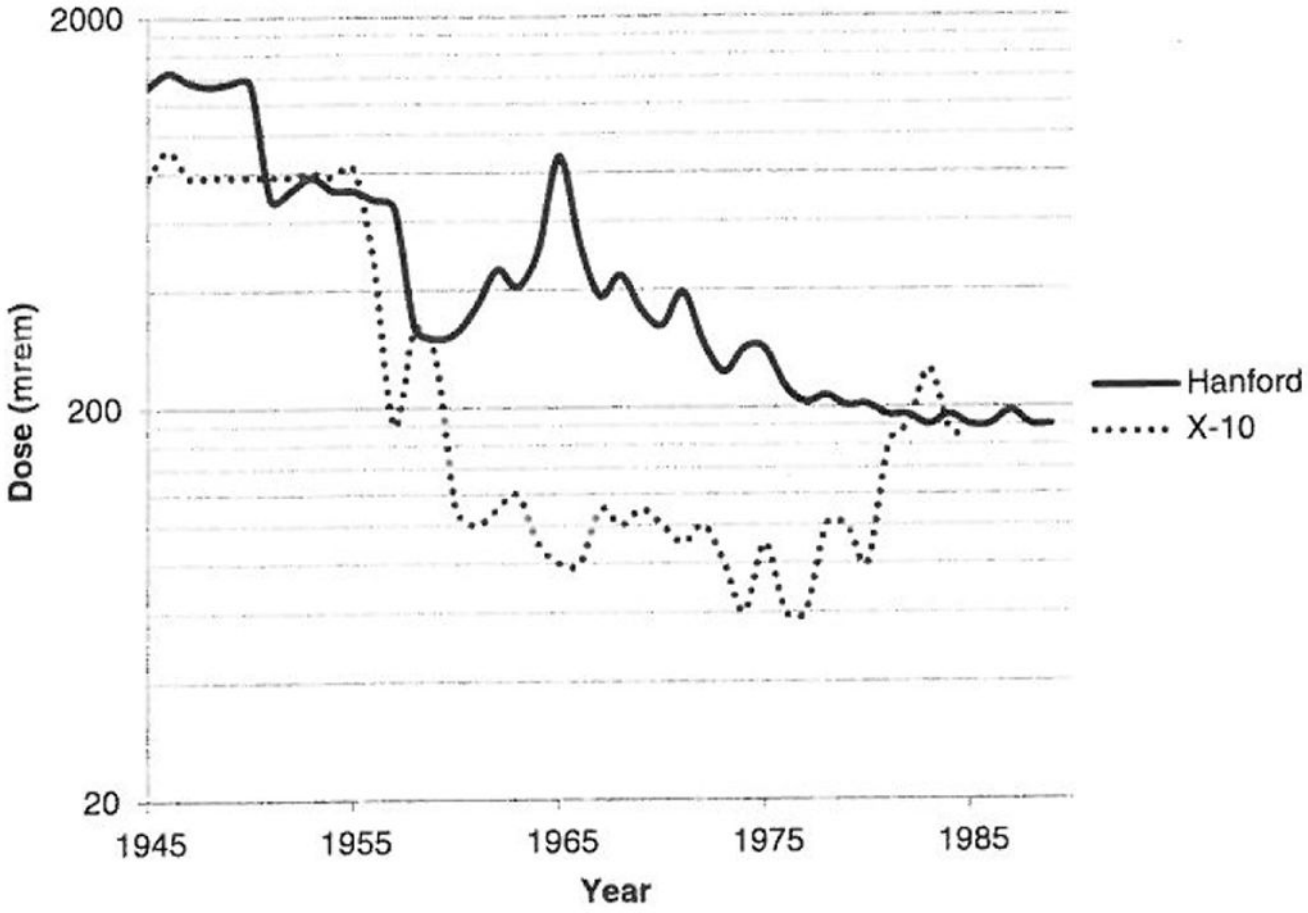

Fig. 7.

50th percentile external gamma doses as measured by personnel dosimeters (includes missed dose).

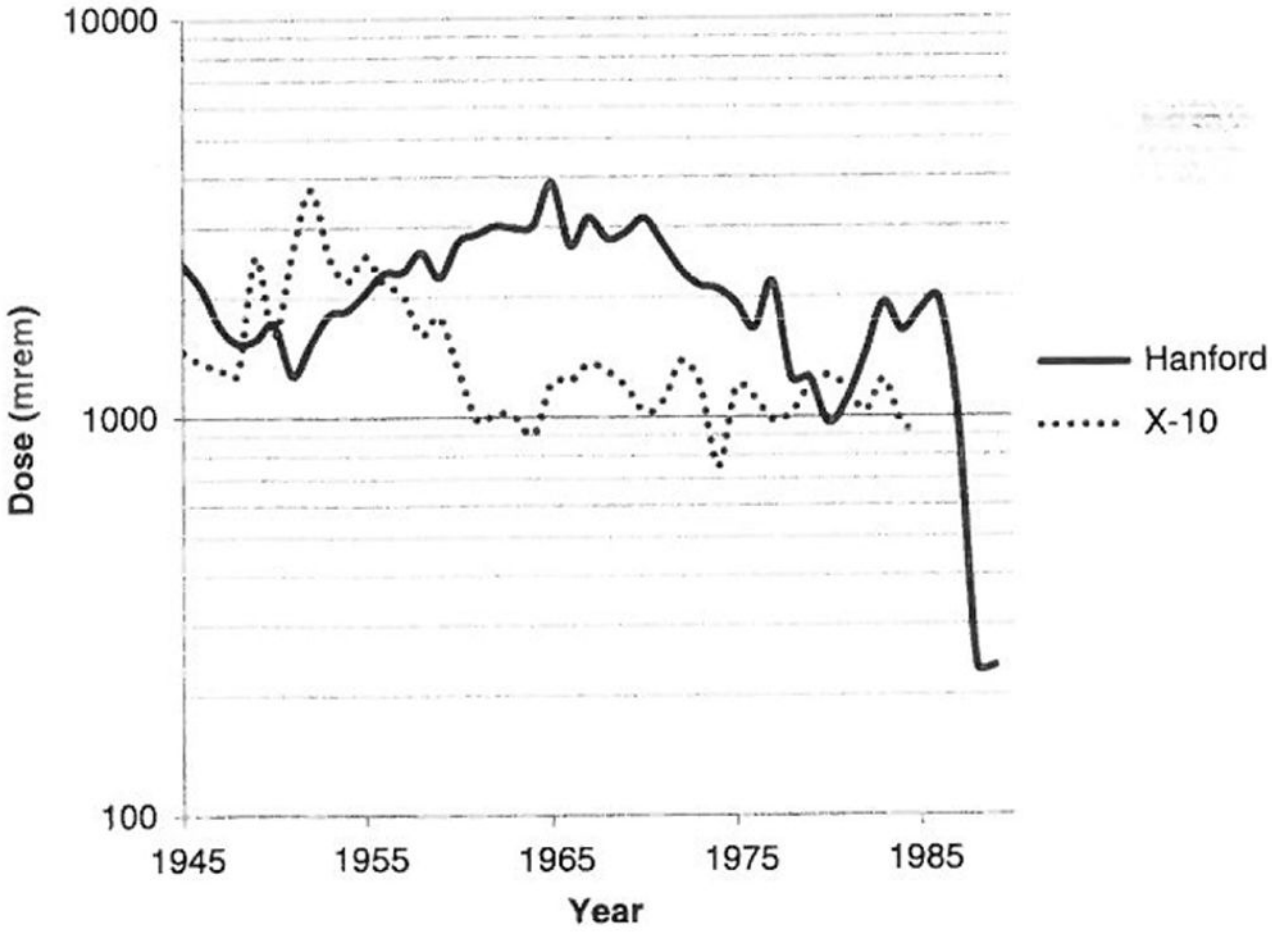

Fig. 8.
95th percentile external gamma doses as measured by personnel dosimeters (includes missed dose).

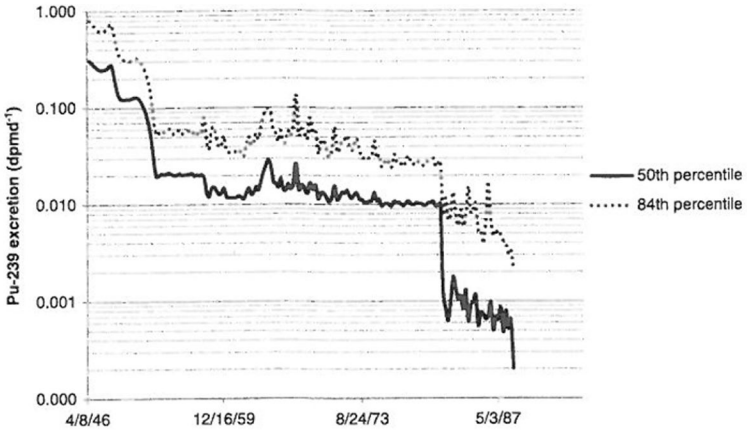

Fig. 9.
Measured ^{239}Pu excretion in urine at Hanford.

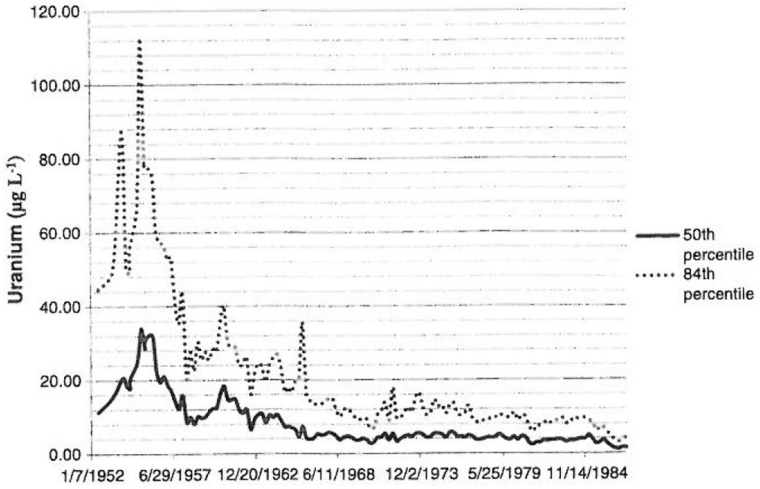

Fig. 10.
Measured uranium excretion in urine at Fernald.

Table 1

Weapons production activities that created an exposure potential.

Uranium milling and refining	Chemical separations
Enrichment	Weapons fabrication
Metal fabrication	Weapons operations
Reactor operations	Research and development

Table 2

Types of exposures associated with weapons production activities.

External
• Gamma
• Beta
• Neutron
• Medical x-rays
Internal
• Uranium (depleted, natural, and enriched)
• Thorium
• Uranium and thorium progeny
• Plutonium
• Other actinides (e.g., americium and curium)
• Mixed fission and activation products

Table 3

External gamma exposures — Mallinckrodt Chemical Works.

	Annual exposure (R)		
Year	**Minimum**	**Average**	**Maximum**
1947	14.4	16.1	23.5
1948	14.9	17.0	20.3
1949	7.7	9.0	13.3
1950	4.5	5.4	7.1
1951	5.0	5.9	7.1
1952	5.1	5.9	6.6
1953	4.0	4.6	5.7
1954	3.9	4.4	5.1
1955	3.9	4.4	5.1
1956	1.1	1.4	1.9

Table 4

Reported radon levels — Mallinckrodt Chemical Works (1949–1957).

Location	Median (pCi L^{-1})	Geometric standard deviation	95th percentile (pCi L^{-1})
Plant 6	3–19	3–7	59–244
Ore filtration areas	4–35	2–10	33–1,012
K-65 centrifuge	3–13	2–8	24–192
Ore storage	1–26	4–22	41–590
Scale house	1–59	3–8	10–680

Table 5

Compensation results by the NIOSH Interactive Radio Epidemiology Program (IREP) cancer model based on claims with dose reconstruction approval and submitted to DOL through 21 September 2012 (31,467 claims).

	NIOSH-IREP cancer model (ICD-9 code)	Compensated (PC ≥ 50%)		Not compensated (PC < 50%)		Total claims	
Rank by compensation rate	**Claims with a single primary cancer**	***N***	**%**	***N***	**%**	***N***	**%**
1	Lung (162)	2,940	65.0	1,581	35.0	4,521	20.3
2	Chronic myeloid leukemia (205.1)	48	53.3	42	46.7	90	0.4
3	Non-melanoma skin—basal cell (173)	947	52.8	846	47.2	1,793	8.1
4	Acute lymphocytic leukemia (204.0)	41	50.0	41	50.0	82	0.4
5	Liver (155.0)	75	43.1	99	56.9	174	0.8
6	Acute myeloid leukemia (205.0)	73	37.4	122	62.6	195	0.9
7	Lymphoma and multiple myeloma (200–203)	626	36.9	1,071	63.1	1,697	7.6
8	Malignant melanoma (172)	226	35.4	412	64.6	638	2.9
9	Other respiratory (160, 161, 163–165)	186	30.4	426	69.6	612	2.8
10	Leukemia, excluding chronic lymphocytic leukemia (204–208, excluding 204.1)	42	30.2	97	69.8	139	0.6
11	Oral cavity and pharynx (140–149)	98	22.1	346	77.9	444	2.0
12	Bone (170)	41	18.3	183	81.7	224	1.0
13	Thyroid (193)	52	16.5	264	83.5	316	1.4
14	Gallbladder (155.1, 156)	17	15.2	95	84.8	112	0.5
15	Eye (190)	5	9.8	46	90.2	51	0.2
16	Stomach (151)	49	9.3	479	90.7	528	2.4
17	Colon (153)	91	7.5	1,116	92.5	1,207	5.4
18	Urinary organs, excluding bladder (189)	41	6.8	559	93.2	600	2.7
19	Bladder (188)	41	6.7	570	93.3	611	2.7
20	Other endocrine glands (194)	1	3.7	26	96.3	27	0.1
21	All male genitalia (185–187)	136	3.2	4,177	96.8	4,313	19.4
22	Esophagus (150)	4	2.9	136	97.1	140	0.6
23	Connective tissue (171)	4	2.8	137	97.2	141	0.6
24	All digestive (150–159)	3	2.7	108	97.3	111	0.5
25	Other and ill-defined sites (195)	1	1.9	51	98.1	52	0.2
26	Breast (174–175)	16	1.8	897	98.2	913	4.1

	NIOSH-IREP cancer model (ICD-9 code)	Compensated (PC ≥ 50%)		Not compensated (PC < 50%)		Total claims	
Rank by compensation rate	**Claims with a single primary cancer**	***N***	**%**	***N***	**%**	***N***	**%**
27	Non-melanoma skin–squamous cell (173)	11	1.7	622	98.3	633	2.8
28	Pancreas (157)	5	0.9	575	99.1	580	2.6
29	Rectum (154)	3	0.6	516	99.4	519	2.3
30	Nervous system (191–192)	1	0.2	414	99.8	415	1.9
31	Female genitalia, excluding ovary (179)	0	0.0	242	100.0	242	1.1
32	Ovary (183)	0	0.0	113	100.0	113	0.5
Subtotal for Claims with a Single Primary Cancer		**5,824**	**26.2**	**16,409**	**73.8**	**22,233**	**70.7**
Subtotal for Claims with Multiple Primary Cancers		**3,248**	**35.2**	**5,986**	**64.8**	**9,234**	**29.3**
GRAND TOTAL (all claims)		**9,072**	**28.8**	**22,395**	**71.2**	**31,467**	**100.0**

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