Historical Evaluation of the Film Badge Dosimetry Program at the Y-12 Facility in Oak Ridge, Tennessee
Part 2 – Neutron Radiation

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Acknowledgement

This report is the second in the series of reports documenting the film badge dosimetry program at Y-12; the first report focused on gamma radiation dosimetry during the film badge period. Funding and oversight for this work have been provided by the National Institute for Occupational Safety and Health (NIOSH) through Contract No. 200-2002-00593 to support the NIOSH Office of Compensation Analysis and Support activities to assist claimants and support the role of the Secretary of Health and Human Services under the Energy Employees Occupational Illness Compensation Program Act of 2000. The authors wish to express thanks to B. Jolene Jones for typing and editorial assistance in manuscript preparation and to Y-12 personnel who assisted in obtaining background memos and reports.

Summary

This report provides background information on aspects of the Y-12 external dosimetry program related to film badge monitoring of neutron radiation. The potential for Y-12 workers to have occupational exposure to neutron doses was largely confined to the years 1952-1962 and to certain departments. During this period, however, there were only 375 positive quarterly neutron doses among 143 workers. Thus, only a small fraction of the Y-12 workers had a significant potential for exposure to neutron radiation and those with a notable potential appear to have been monitored for neutron radiation.

Graphical methods were used to evaluate the quarterly neutron dose data to determine how they might be used to derive neutron-to-gamma ratios. Included are estimates of neutron-to-gamma ratios for specific departments and a summary of neutron sources at the Y-12 Plant. The only known source of information on neutron-to-gamma dose ratios that is applicable to radiation exposures at the Oak Ridge 86-Inch Cyclotron is the data generated by this historical evaluation document. Also provided are recommendations on how this information may be used to estimate a claimant favorable neutron dose for quarters with no positive quarterly neutron doses. These estimated doses may be used for dose reconstruction as specified by the Energy Employees Occupational Illness Compensation Program Act of 2000.

All analyses were carried out using the R statistical computing system (R, 2004). Detailed documentation on R is available at the R home page (http://www.r-project.org).

1. Introduction

The purpose of this series of reports is to present definitive documentation regarding the development of the Y-12 external dosimetry film badge program from its beginnings half a century ago through 1979, the end of the film badge period. This information provides the background for appropriate use of recorded film badge doses in dose reconstruction. This report, Part 2, deals with neutron exposures.

As discussed in detail in Part 1, the film badge period began when Union Carbide Corporation-Nuclear Division (UCCND) assumed management of the Y-12 Plant in May of 1947 and continued until film dosimeters were largely replaced by thermoluminescence dosimeters (TLD dosimeters) in 1980 (Watkins et al., 2004).

The potential for Y-12 workers to have occupational exposure to neutron doses was largely confined to the years 1952-1962 and to certain departments. During this period, however, there were only 375 positive quarterly neutron doses among 143 workers. Thus, only a small fraction of the Y-12 workers had a significant potential for exposure to neutron radiation, and those with a notable potential appear to have been monitored for neutron radiation.

2. Y-12 Neutron Dose Measurement in the Film Badge Program

2.1 Y-12 Neutron Exposures

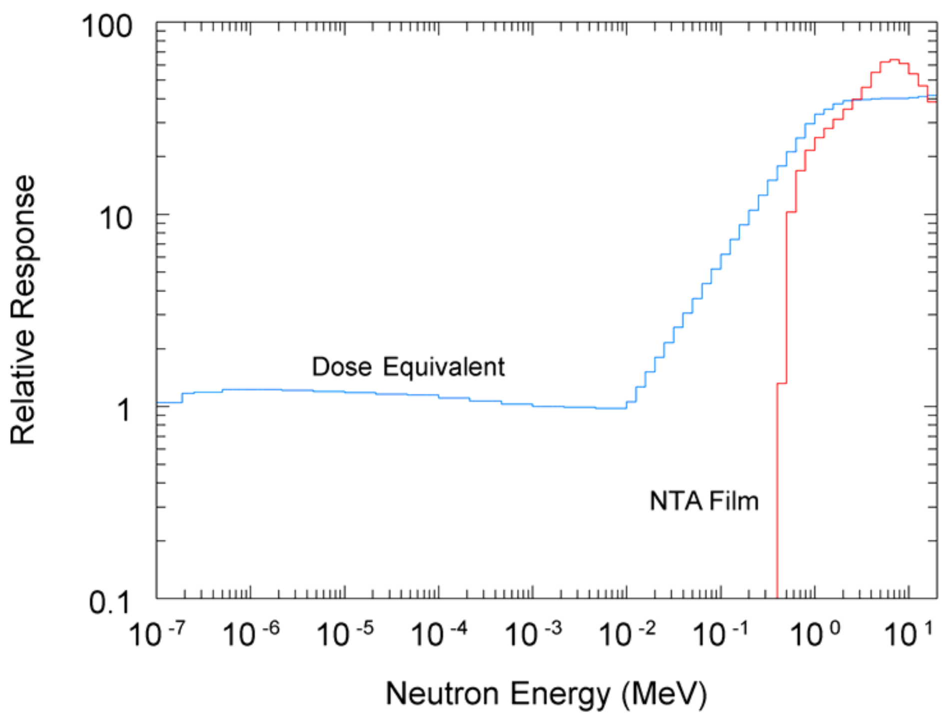
Part 1 discussed in detail the routine film badge exchange frequency over time and the composition of the various film dosimeters used at Y-12 (Watkins et al., 2004). It was noted that in 1949 neutron sensitive films were added to the film badge, and these films were exchanged on a biweekly schedule (Souleyrette, 2003). Starting in 1958, the neutron films were exchanged on a monthly schedule, and starting in 1961, on a quarterly (or three month) schedule (Souleyrette, 2003; Watkins et al., 2004).

During the 1950s, the neutron films were calibrated in air (no phantom) using neutrons from a polonium-beryllium (^{210}Po-Be) neutron source (Souleyrette, 2003). Neutrons produced recoil-ion tracks in the film that could be seen by using appropriate imaging capability such as oil immersion and a high powered microscope. For nuclear track emulsions, type A (or so-called NTA films), it was found that twenty-two tracks per twelve microscope fields viewed at approximately 900x magnification in the portion of the NTA film behind the open window of the film badge was equivalent to 100 mrep (~100 mrem), while eighteen tracks per twelve microscope fields viewed at approximately 900x magnification in the portion of the NTA film behind the cadmium shield of the film badge was equivalent to 100 mrep (~100 mrem) (Struxness, 1949a; Long, 1950). Starting in 1962, the neutron films were calibrated in air (no phantom) using neutrons from an americium-beryllium (^{241}Am-Be) neutron source (Y-12 Plant, 1963). The minimum detectable limit (MDL) was believed to be about 50 mrem for all years of usage (Kerr, 2003).

Film badges containing an NTA film were assigned to all workers who had a notable potential for exposure to a neutron source at the Y-12 Plant from 1950 through 1961 (Kerr, 2003). After 1961, film badges containing an NTA film were assigned to all workers, although there were no positive neutron doses for Y-12 workers after 1960 except for Department 2345 in 1962. An NTA film was processed and read only if a worker entered an area with a neutron source and the health physics staff recommended processing. If the NTA film indicated that the neutron dose to the worker was less than the MDL, the general guideline was to record either a zero or the MDL. The MDL of 50 mrem may have been recorded when the health physics staff had reason to believe that a neutron exposure had occurred. If a worker with an NTA film did not enter an area with a neutron source, the film was not processed and a zero was recorded for the neutron dose during that monitoring period. A surprising result of this study is the number of recorded neutron doses that are greater that zero, but less than the MDL of 50 mrem (see Tables A1 and A2 of Appendix A).

The MDL of 50 mrem for the NTA film was based primarily on laboratory studies using ^{210}Po-Be and ^{241}Am-Be neutrons (Kerr, 2003). In other exposure situations, the MDL could be larger than 50 mrem because the NTA film only responded to fast neutrons with energies greater than approximately 0.5 MeV (IAEA, 1990) as shown in Figure 1. For comparison purposes, the multicollision dose equivalent near the surface of the body from a plane beam of neutrons normally incident on the body is also shown in Figure 1. The multicollsion dose equivalent from neutrons in Figure 1 is taken from Report 38 of the National Council on Radiation Protection and Measurements (NCRP, 1971) (also see Table 2-II on page 15 of IAEA, 1990). If a person was exposed in an area with a highly degraded energy spectrum of neutrons, then a significant part of the neutron dose below the effective 0.5-MeV threshold of the NTA film might be undetected and the MDL could be much larger than 50 mrem. However, exposure to a highly degraded energy spectrum of neutrons at the Y-12 Plant was the exception rather than the rule.

Figure 1. Comparison of dose equivalent from a beam of normally incident neutrons and energy response of a nuclear track emulsion, type A (NTA film).



Records from the time period indicate that the health physics staff placed NTA films in hundreds of film badges each quarter, although not all were processed, as described above. For example, 455 NTA films were developed and microscopically examined for neutron recoil-ion tracks during the last two quarters of 1952 (Struxness, 1954a) and 420 NTA films were developed and microscopically examined for neutron recoil-ion tracks during the first two quarters of 1953 (Struxness, 1954b). The number of films developed and read during these periods would provide continuous biweekly monitoring coverage for 30 to 35 workers. However, only two monitored workers had positive quarterly neutron doses in the last two quarters of 1952 and only two monitored workers had positive quarterly neutron doses in the first two quarters of 1953 (see Tables A1 or A2 of Appendix A). Thus, if a worker has no positive neutron doses before 1962, it is unlikely that the worker experienced neutron exposure and would require an estimated neutron dose.

Initially, the purpose of the radiation dosimetry program at Y-12 was simply to demonstrate compliance with radiation protection guidelines over periods as small as a day or a week (Table 1). In 1958, the radiation protection guidelines were modified to include an age limit on the accumulated radiation dose to a worker. The age-dependent cumulative dose limit placed on the penetrating whole-body dose from gamma rays and neutrons was 10(N-18) rem, where N was the age of the worker in years (see footnotes to Table 1). The biweekly recorded neutron doses, D_n (Biweekly), were summed to obtain quarterly neutron doses, D_n (Quarterly), using the following formula (West, 1958):

$$D_n(\text{Quarterly}) = \sum D_n(\text{Biweekly}) \times \frac{\text{Number of Issued Neutron Film Badges}}{\text{Number of Positive Neutron Doses}} . \qquad (1)$$

The above formula attempts to adjust the quarterly neutron dose for the missed neutron dose below the MDL of the NTA films. If a quarterly neutron dose to a worker was recorded as zero, then all biweekly neutron doses during the 13 week quarter for that worker were also equal to zero. Although gamma/beta and neutron films were read more frequently (generally weekly or biweekly) in earlier years, only quarterly dose summations are available for the penetrating doses from gamma rays and neutrons and for the skin doses from beta particles, gamma rays, and neutrons (Watkins et al., 2004). Only quarterly dose summations are also available for the monthly monitoring periods used from 1958 through 1961.

Table 1. Historic radiation protection guidelines for the Y-12 facility (Wiley, 2004).

Dates	Exposure periods	Dose* to lens of the eye	Dose* to extremities[a]	Shallow or skin dose*	Deep or penetrating whole-body dose*	Total effective dose equivalent[b]
1944-1948	Day			0.1	0.1	
1949-1950	Week			0.3	0.3	
1951-1953	Week		1.5	0.3	0.3	
1954-1957	Week	0.3		0.6	0.3	
1958	Week	0.3	1.5	0.6[c]	0.3[d]	
1959-1960	Quarter Year	1.2	25 75	6[c]	3[d]	
1961 to 03/29/1977	Quarter Year	 5	25 75	10 30	3[d]	
03/30/1977 to 1988	Quarter Year	 15	25 75	5 15	3 5	
1989 to 11/30/1992	Year	15	50	50		5
12/01/1992 to 2004	Year	15	50	50		5[e]

* All doses are given in rem. This table also appears as Table 1 in Watkins et al. (2004).
a. The extremities are defined typically as the hands and arms below the elbow and the feet and legs below the knee.
b. The Department of Energy has used the total effective dose equivalent (TEDE) to limit the sum of the internal and external whole-body (effective) doses since 1989.
c. Accumulated dose not to exceed 10(N-18) rem, where N is the age in years.
d. Accumulated dose not to exceed 5(N-18) rem, where N is the age in years.
e. Accumulated dose not to exceed N rem, where N is the age in years.

2.2 Sources of Neutron Exposure

Table 2 presents data on the major sources for neutron exposure at the Y-12 Plant and physical locations of these sources within the Y-12 Plant. The sources are characterized in the following parts of this section using parameters of interest in the dose reconstructions for Y-12 workers (NIOSH, 2002). These parameters are (1) the neutron-to-gamma ratios for exposures to these various sources, (2) the missed neutron dose below the MDA of the NTA films in the Y-12 film badge dosimeters, and (3) the energy spectrum of the neutrons that are incident on a Y-12 worker's body during exposure to one of these sources. The neutron source spectra are characterized in terms of the broad neutron energy groups of < 10 keV, 10-100 keV, 0.1-2 MeV, 2-20 MeV, and > 20 MeV that are used in dose reconstruction for workers at Y-12 and other DOE facilities (NIOSH, 2002).

Two other neutron sources not listed in Table 2 are a Cockcroft-Walton linear accelerator capable of producing a maximum of 1×10^{10} fast neutrons per second (Struxness, 1954b) and a 5-MeV Van de Graff accelerator capable of producing a fast neutron flux as high as 560 fast neutrons per cm^2 second near the target (Struxness, 1951b; Struxness, 1952). The Cockcroft-Walton was installed in the Oak Ridge National Laboratory (ORNL) Biology Division (Building 9207) in early 1953, and the 5-MeV Van de Graff was installed in an unknown location at Y-12 in late 1951. The 5-MeV Van de Graff was operated at Y-12 during 1951 and 1952 while a permanent structure was being built for the accelerator at the ORNL site (Johnson and Schaffer, 1994). At present, very little is known about the operation or shielding of either of these accelerators at the Y-12 site.

Table 2. Location of major sources for neutron exposure at the Y-12 Plant during the film badge dosimetry program.

Location	Y-12 building	Neutron source
Assay Laboratory[a]	9203 (Room 8), 9205	Ra-Be, Po-Be
Criticality Experiments Facility[b]	9213	Po-Be, Pu-Be
		Fission neutrons
Electromagnetic Research[c]	9201-2, 9204-3	Po-Be
		86-Inch Cyclotron
Health Physics[d]	9983 (Calibration Laboratory)	Po-Be, Am-Be
Instrument Department[e]	9737	Po-Be
Chemical Operations[f]	9202, 9206, 9212	Highly enriched uranium fluoride and oxide compounds

[a]Struxness (1949b), Stuxness (1951a)
[b]Struxness (1951a), Struxness (1951b), Struxness (1954b), CEF Staff (1962, 1967)
[c]Struxness (1951a), Struxness (1951b), Livingston (1951); Livingston and Boch (1952), Livingston (1952), Struxness (1952), Struxness (1953), Livingston (1958)
[d]Struxness (1951a), Struxness (1953), Y-12 Plant (1963)
[e]Struxness (1951a)
[f]Jessen (2004), DOE (2000)

Radionuclide Sources.

Radionuclide sources that produced neutrons by alpha particle reactions in boron (B) or beryllium (Be) provide a convenient source of neutrons for a number of applications (Reese, 1967). Their use at the Y-12 Plant has been summarized in Table 2. From this table, it can be seen that such sources were used in basic research (Buildings 9201-2 and 9204-3), critical assembly and reactor research (Building 9213), calibration of radiation dosimeters and radiation detection instruments (Buildings 9737 and 9983), and material assay (Buildings 9203 and 9205). Shielding was used to protect workers from unnecessary exposures to the radionuclide sources, but some dose was received even in shielded areas, and some dose was also received from the bare sources. However, the largest exposure would occur while sources were withdrawn from their shields during the calibration of radiation instruments or during periodic tests for leakage of radioactive materials from the sealed containers about the sources. For individuals working around ^{226}Ra-Be sources, exposures would be predominately from gamma rays due to the very small neutron-to-gamma dose ratio for these sources (Table 3). Thus, the neutron exposures to these individuals would probably be very small or even non-detectable compared to their gamma-ray exposures. For individuals working around ^{210}Po-Be, ^{239}Pu-Be, and ^{241}Am-Be sources, however, exposures would be predominately from neutrons because the neutron-to-gamma dose ratios for these sources are typically greater than unity (one) (see footnote to Table 3).

Table 3. Neutron emission rates, neutron and gamma dose rates, and neutron-to-gamma dose ratios for several common (α, n) neutron sources.

Source	Neutron emission (n/sec/curie)	Neutron dose at 10 cm (rem/hr/curie)	Gamma dose at 10 cm (rem/hr/curie)[a]	Neutron-to-gamma dose ratio
^{226}Ra-Be[b]	$1.0\text{-}1.5 \times 10^7$	1.3	85	0.015
^{239}Pu-Be[b]	1.5×10^6	0.15	0.26	0.58
^{210}Po-Be[b]	2.5×10^6	0.25	0.10	2.5
^{241}Am-Be[c]	2.5×10^6	0.26	0.25	1.1

[a]Not including self-absorption in source (Kiefer and Maushart, 1972). If self-absorption of gamma rays in the source is taken into account then all of the above sources, except Ra-Be, have neutron-to-gamma dose ratios greater than unity (one). The neutron-to-gamma dose ratio depends to some extent on the construction of the source (Kiefer and Maushart 1972).
[b]Kiefer and Maushart (1972), Nachtigall (1967), Reese (1967), Handloser (1959),
[c]IAEA (1985), Kerr et al. (1978), Nachtigall (1967), Reese (1967).

The neutron spectra from all radionuclides using the (α, n) reaction in Be are quite similar; the neutron energies range from about 1 MeV to a maximum of about 12 MeV (Kiefer and Maushart, 1972), and the average energy of the neutrons is about 4 MeV (Nachtigall, 1967; Kerr et al., 1978). Thus, the spectral distribution of dose equivalent from a plane neutron beam normally incident on the front of the body was calculated using the ^{241}Am-Be source spectra measured by Kluge and Weise (1981) (also see Table 4 of IAEA, 1990) and the neutron fluence-to-dose equivalent coefficients from Report 38 of the NCRP (1971) (also see Table 2 of IAEA, 1990). Figure 2 presents the calculated results using twenty-two neutron energy groups for the measured neutron spectra (IAEA, 1990). Also shown are three neutron energy groups used in the dose reconstruction for Y-12 workers, namely, 10-100 keV, 0.1-2 MeV, and 2-14 MeV. The dose equivalent per source neutron obtained by summing the values given in the graph for these three groups is 3.73×10^{-5} mrem. This value is in excellent agreement with other values derived for radionuclide sources using the (α,n) reaction in beryllium (Nachtigall, 1967; Kerr et al., 1978). The calculated results in Figure 2 also indicate that the dose equivalent below the NTA threshold energy of 0.5 MeV was less than 3% of the total dose equivalent per source neutron. The dose fractions recommended for use in dose reconstruction for Y-12 workers exposed to neutrons from (α,n) sources are shown in Table 4.

Figure 2. Dose equivalent distribution for neutrons produced in a radionuclide source by the (α,n) reaction in beryllium (Be).

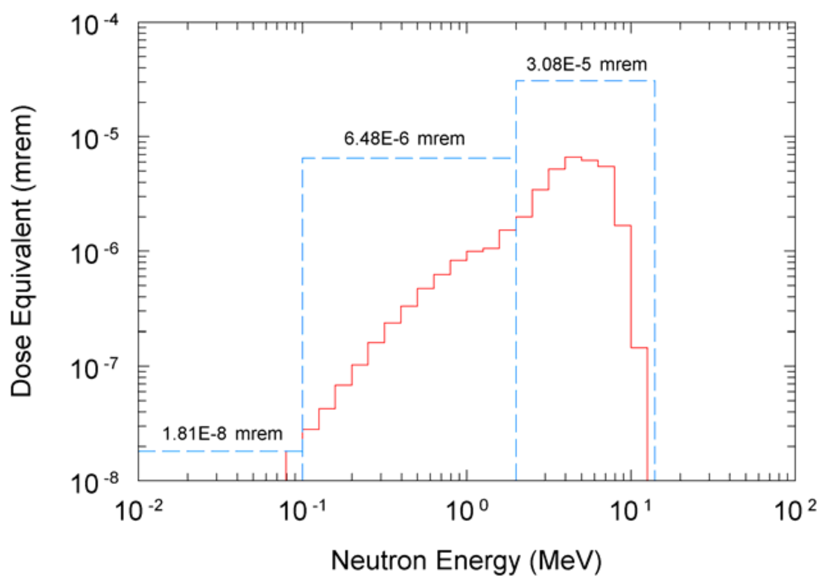


Table 4. Dose fractions for exposure to neutrons produced by radionuclide sources using the (α,n) reaction in beryllium (Be).

Neutron energy group[a]	Dose fraction
0.1 – 2 MeV	0.18
2 – 14 MeV	0.82

[a]The fraction of the neutron dose below 0.1 MeV is insignificant.

<u>Alpha-Neutron Reactions in Uranium Compounds</u>

From about 1949 to 1964, the Y-12 Plant received cylinders of UF_6 containing highly enriched uranium as feed material for the manufacturing of nuclear weapon parts (Jessen, 2003). After 1964, the majority of enriched uranium processed at Y-12 was recycled from nuclear weapon stockpiles. These operations were confined primarily to Buildings 9202, 9206, and 9212. The recycled uranium program involved the processing of other material forms, including UO_2, UO_3, and UF_4 (Jessen, 2003). The interaction of alpha particles from uranium with the nuclei of fluorine, oxygen, and other low-Z atoms generates neutrons with energies of approximately 2 MeV (DOE, 2000). The magnitude of the neutron flux varies, based on the total activity of the uranium (a function of enrichment) and the chemical compound in question (mixing of U with F or O). In the case of UF_6, the typically measured neutron dose equivalent rates for storage containers are as follows:

Natural to 5% enrichment:	0.01-0.02 mrem/hr,
Very high enrichment (97+%):	2-4 mrem/hr (contact) 1-2 mrem/hr (3 feet).

In general, the exposure potential of workers to neutrons generated by (α,n) reactions in uranium compounds is not very high, unless workers spend a significant amount of time near containers of uranium fluoride or oxide compounds, or storage or processing areas for large quantities of uranium fluoride or oxide compounds (DOE, 2000). At very high ^{235}U enrichments, the neutron-to-gamma dose ratio can be as much as 2 and the neutrons can be the limiting source for whole body exposure. Neutron radiation from low ^{235}U-enriched compounds or from uranium metal is considerably lower than the gamma-ray component and, consequently, is not limiting.

Measurements were made recently by the Pacific Northwest Laboratory (PNL) at a height of 39 inches (1 meter) above the floor and 2 feet from the shelf at a location near the center of a rack that was filled with 20 containers of UF_4 (PNL, 1990; McMahan, 1991; BWXT Y-12, 2001). The neutron dose equivalent rate from the PNL measurements was 1.65 mrem/hr, which is in good agreement with the above values from the *Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities* (DOE, 2000).

The PNL measurements of the neutron energy spectrum near the center of the UF_4 storage rack are shown by the solid line in Figure 3, and the dose fractions for the neutron energy groups shown by the dashed line in this figure are provided in Table 5. The dose fraction for the lower (< 10 keV) and intermediate (10-100 keV) energy neutron groups were less than 2% of the total dose from these PNL measurements. Thus, combining the lower and intermediate energy groups with the fast neutron group from 0.1-2 MeV provides a reasonable and claimant favorable simplification of the neutron dose reconstruction for a Y-12 worker. The recent PNL measurements also indicate that approximately 95% of the neutron dose was above the 500-keV threshold of the NTA emulsions used in the Y-12 film badge dosimeters, and the neutron-to-gamma dose ratio from the enriched uranium fluoride containers was approximately unity (one).

Figure 3. Dose equivalent from a one-hour exposure to neutrons from highly enriched UF_4 storage containers.

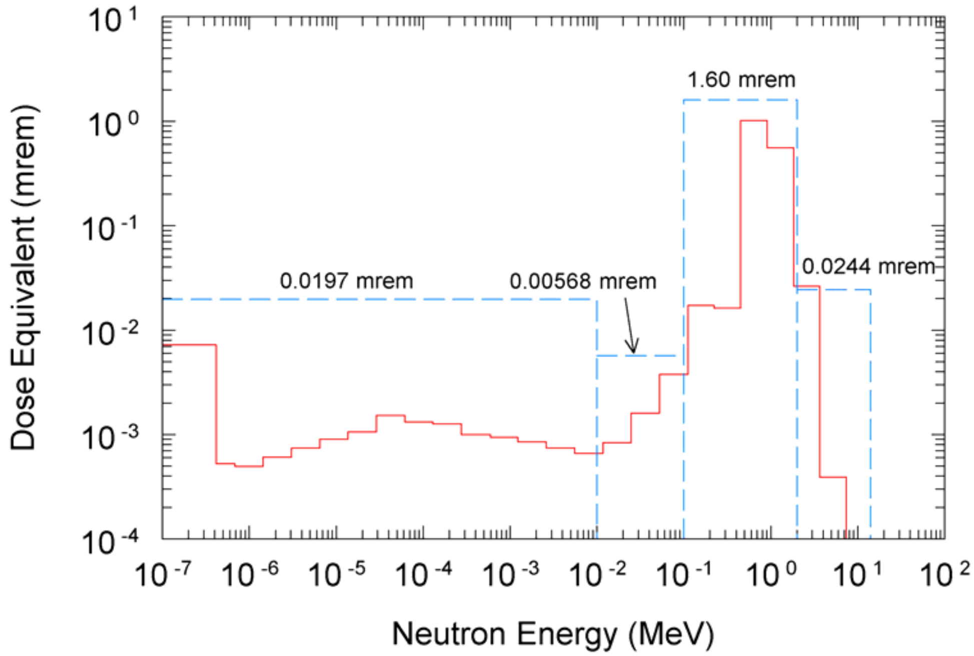


Table 5. Dose fractions for exposure to neutrons from highly enriched uranium compounds (Buildings 9202, 9206 and 9212).

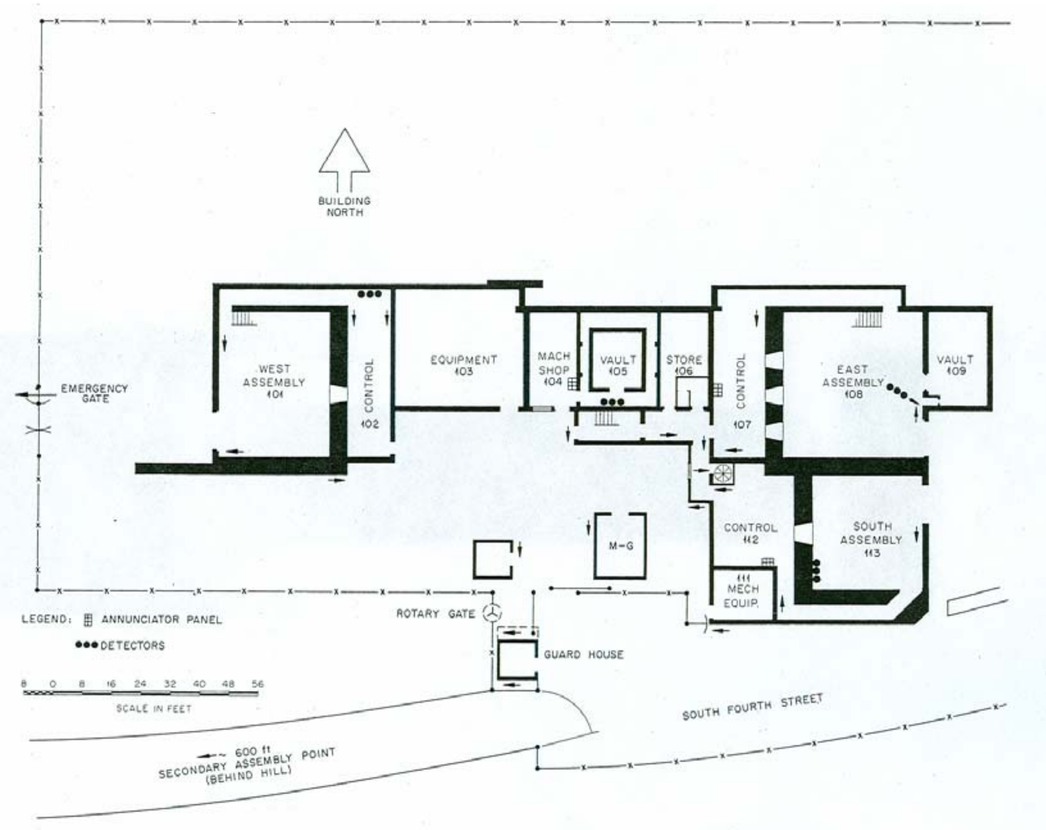
Neutron energy group	Dose fraction
< 10 keV	0.012
10 - 100 keV	0.003
0.1 - 2 MeV	0.970
2 - 14 MeV	0.015
Claimant favorable dose fractions	
0.1 - 2 MeV	1.00

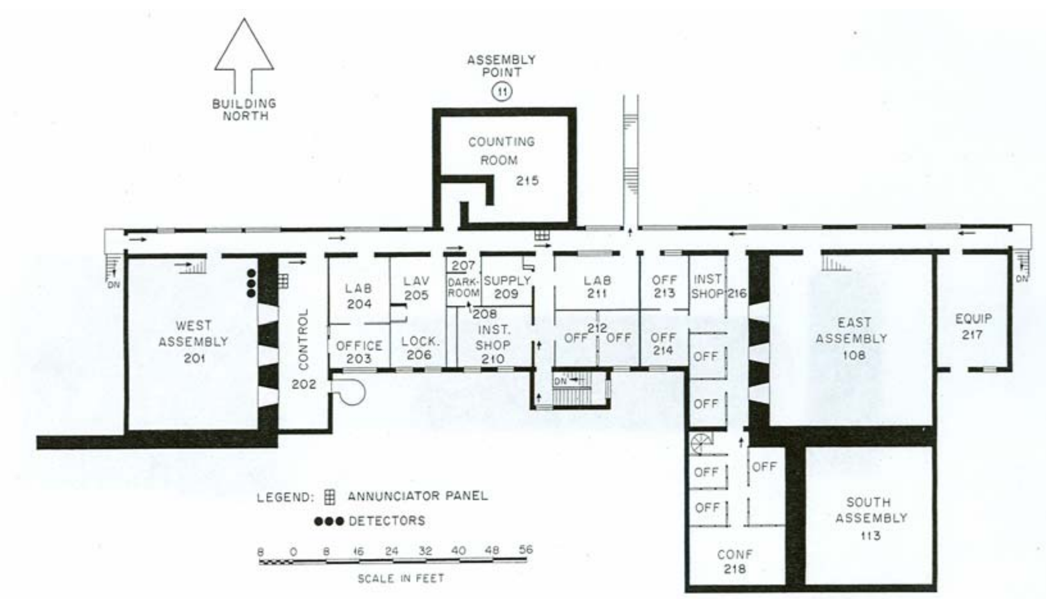
Critical Experiments Facility

Prior to the construction of the Critical Experiments Facility (CEF), several critical experiment programs had been carried out at ORNL and the Oak Ridge Gaseous Diffusion Plant (K-25 Plant) (CEF Staff, 1967). The inadequacy of the facilities at these two locations was recognized in 1949 due to the expected demands for further experimentation in (1) the safety of metallurgical and chemical processes and (2) the support of new reactor designs. The latter need was further emphasized by a then-active program in Oak Ridge on the development of nuclear propulsion for aircraft (Johnson and Shaffer, 1994). It was decided, therefore, that a laboratory adequate for a wide variety of critical experimentation be established, that the various programs of critical experiments in Oak Ridge be combined, and that the work be administered by ORNL (CEF Staff, 1967). Near critical and criticality experiments were started at the CEF facility in late August and early September 1950.

The CEF facility is located at a remote site in the southwest portion of the Y-12 complex in a pocket formed by surrounding hills as much as 200 feet higher than the CEF building itself (CEF Staff 1962, 1967). The projected ground distance to the nearest work areas was more than 2,000 feet and to the nearest public highway was 4,200 feet. The facility operated until March 1987 and was shut down permanently in 1992 (Stapleton, 1993). During its operational years, access to the CEF was restricted by means of a chain link fence (CEF Staff, 1962, 1967). Gates in the fence, except the one at the entrance to the facility were kept locked. The facility was a two-story concrete and concrete block structure about 200 feet long and 80 feet wide as shown in Figure 4. The original building construction included only two assembly areas or test cells for critical experiments, one on the east end and one on the west end of the building. A third assembly area, or test cell, separated from the east test cell by a 5-foot-thick wall of concrete, was added in 1957. A control room was associated with each test cell and was separated from it by a 5-foot-thick ordinary concrete wall with a specific density of about 2.5. Communication between the control rooms and test cells was provided by the use of water-filled windows, intercom, and closed circuit television. Necessary office, laboratory and other support space were provided in the central portion of the building, mainly on the second floor of the building as shown in Figure 4 (CEF Staff, 1967). The size of the CEF staff was limited to keep potential radiation exposures at the facility to a minimum.

Figure 4. Schematic showing fenced exclusion area and first floor (upper portion of figure) and second floor (lower portion of figure) of the Oak Ridge Critical Experiments Facility at the Y-12 complex.





The walls of the test cells on the south side of the building adjacent to the roadway were of 5-foot-thick concrete. The cell walls on the north side were 12 to 18 inches thick, established by structural needs, and provided significant shielding at the boundary of the fenced exclusion area to the north of the CEF. The walls to the east and west sides of the building were also 12 to 18 inches thick, for structural purposes. However, personnel on the roadway and in other accessible areas were protected from leakage radiation through these walls by earth bunkers and additional concrete walls as shown in Figure 4. The scattering of radiation by air (or skyshine) was originally underestimated, and the original roof met structural requirements only. The need for additional shielding against skyshine radiation was recognized, and each test cell was covered with concrete at least one foot thick. The central general purpose area of the building and guard shelter were covered by concrete at least 3.5 inches thick. Of course, the effective thickness of the roof shields was somewhat greater because of the angle at which the radiation must traverse them in order to be scattered into the central area of the building or onto the road.

Many data collected over the years provide an evaluation of the protection afforded both inside and outside the facility (CEF Staff, 1967; Callihan, 1968; Dickens and Fleming, 2003). For example, measurements were made at a number of locations both outside and inside the facility during extended operations of critical assemblies at relatively high power. During a measurement collection session in January 1960, a critical volume of a uranium solution, located in the West Assembly Area (Figure 4), was operated in a steady state mode to produce 7×10^{12} fissions per second. Because the results were intended for use in accident dosimetry, the absorbed dose measurements for fast neutrons were converted to a dose equivalent using a relative biological effectiveness (RBE) of two. A value of 10 was applied here to make the dose measurements for fast neutrons applicable in routine radiation protection dosimetry. The results are presented in Table 6 for seven normally occupied sites on the second floor of the CEF. It is important to note that approximately one-half of the neutron dose is from low energy neutrons below the cutoff of the NTA films. Thus, the MDL of NTA films used for routine radiation protection measurements at this facility was approximately 100 mrems, and the total neutron-to-gamma dose ratio was approximately twice what would be derived by comparing the recorded doses obtained with NTA and gamma films in a film badge dosimeter (Table 7). The total neutron-to-gamma dose ratio observed at normally occupied sites within this facility varied from a low of unity (one) near the south wall of the West Assembly Control Room to a high of three near the Equipment Room in the building's north hall (Figure 4).

Table 6. Data on dose equivalent for routine radiation protection purposes developed from measurements made inside the Critical Experiments Facility, while a critical volume of a uranium solution was operated in a steady state mode in the West Assembly Area.

Location of measurement	Dose equivalent (mrem/10^{16} fissions)		
	Fast neutrons	Thermal neutrons	Gamma rays
Near south wall of West Assembly Control Room (Room 202)	6.0	8.3	13.9
North hall near West Assembly Control Room (Room 202)	27.8	27.4	39.7
Near south wall of Office (Room 303)	6.0	10.3	9.9
North hall near Lavatory (Room 205)	6.0	17.1	12.7
North hall near Laboratory (Room 211)	11.9	14.3	11.9
North hall near Instrument Shop (Room 216)	2.0	2.4	2.0
North hall near Equipment Room (Room 217)	4.0	3.2	2.4

Table 7. Neutron-to-gamma dose ratios for routine radiation protection purposes from measurements made inside the Critical Experiments Facility, while a critical volume of a uranium solution was operated in a steady state mode in the West Assembly Area.

Location of measurement	Fast neutron-to-gamma dose ratio	Total neutron-to-gamma dose ratio
Near south wall of West Assembly Control Room (Room 202)	0.43	1.03
North hall near West Assembly Control Room (Room 202)	0.70	1.39
Near south wall of Office (Room 303)	0.61	1.64
North hall near Lavatory (Room 205)	0.47	1.82
North hall near Laboratory (Room 211)	1.00	2.20
North hall near Instrument Shop (Room 216)	1.00	2.20
North hall near Equipment Room (Room 217)	1.67	3.00

The neutron dose fractions recommended for use in the dose reconstruction for Y-12 workers exposed to fission neutrons at the Oak Ridge Critical Experiments Facility are shown in Table 8. To simplify the dose reconstruction to the Y-12 workers, it is recommended that the <10 keV neutron energy group and the 2-14 MeV neutron energy group be combined with other nearby neutron energy groups. This provides a reasonable and claimant favorable simplification in neutron dose reconstruction for Y-12 workers.

Table 8. Dose fractions for exposure to fission neutrons at the Critical Experiments Facility at Y-12 (Building 9312).

Neutron energy group	Dose fraction
<10 keV and 10 - 100 keV	0.50
0.1 - 2 MeV and 2 - 14 MeV	0.50
Claimant favorable dose fractions	
10 - 100 keV	0.50
0.1 - 2 MeV	0.50

Oak Ridge 86-Inch Cyclotron

The Oak Ridge 86-Inch Cyclotron became operational in November 1950 (Livingston, 1952a; Livingston and Boch, 1952). The availability of large magnetic and vacuum components at the Y-12 Plant greatly simplified the planning of the cyclotron and facilitated its fabrication (Johnson and Schaffer, 1994). A study of available buildings at the Y-12 Plant resulted in the selection of the Alpha Process Building 9201-1, which had been in "standby" condition since 1945 (Livingston and Boch, 1952). The design and fabrication of the 86-Inch Cyclotron was a cooperative ORNL and Y-12 effort (Johnson and Schaffer, 1994). The construction of the cyclotron required approximately one year. Ground was broken for the magnet footings on September 21, 1949, and the machine was ready for test operations the following September. The first proton beam was observed on November 11, 1950. By the end of the year, a proton beam of a few microamperes had been obtained at proton energies of approximately 20 MeV, and by September 1951, proton currents above one milliampere at proton energies of 20 MeV were possible. The Oak Ridge 86-Inch Cyclotron was supervised initially by the Electromagnetic Research Division of the Oak Ridge National Laboratory (ORNL). The ORNL Electromagnetic Research Division was later renamed the Electronuclear Research Division to better reflect its changing interest.

One of the original uses of the Oak Ridge 86-Inch Cyclotron was the production of polonium-208 (^{208}Po) (Livingston and Martin, 1952; Butler, 1963; Johnson and Schaffer, 1994). In 1952, internal revisions of the position and mounting of the ion source resulted in an increase in proton energy to 23 MeV. At the higher energy, the ^{208}Po yield was more than doubled and a total of approximately 9 curies of ^{208}Po was produced before the project was terminated in August 1952 (Livingston and Martin, 1952). During the next few years, the ground work was laid for the production of neutron deficient radioisotopes (Butler, 1963). From 1952 to 1961, however, the 86-Inch Cyclotron was used primarily for nuclear physics research by the ORNL Electronuclear Division (Howard, 1954; Livingston, 1958), and isotope production time was made available only when it did not interfere with the primary program (Butler, 1963). Following completion of the construction and testing of the Oak Ridge Isochronous Cyclotron at ORNL in 1961, the responsibility for operation and maintenance of the 86-Inch Cyclotron was shifted on the first day of December from the ORNL Electronuclear Division to the ORNL Isotope Division (Livingston and Zucker, 1962; Johnson and Schaffer, 1994). The 86-Inch Cyclotron was used primarily as a production facility for medical radioisotopes until it was shut down permanently in the early 1980s.

Fast neutrons are the radiation of most concern in occupied areas near cyclotrons operated at proton beam energies between 15 MeV and 50 MeV (Shleien et al., 1998, p. 11-71). The shielding for the 86-Inch Cyclotron consisted of 5-foot-thick concrete walls supporting a 5-foot-thick concrete ceiling (Livingston and Boch, 1952). Two mazes were the only openings into the cyclotron vault. Early 1950 measurements indicated the presence of an excessive stray neutron flux outside the entrance to the maze, and a shielded door was added to reduce the neutron flux in this area to acceptable levels. A maximum permissible flux of 250 neutrons per cm^2 second was established to limit the neutron exposure of cyclotron personnel to less than 300 mrem per 40-hour work week which was the radiation protection guideline at that time (Table 1). The measured neutron flux in most occupied areas outside the shielding for the cyclotron was typically smaller than the maximum permissible flux of 250 neutrons per cm^2 second by one to two orders of magnitude (Livingston, 1952b; Struxness, 1952; Howard, 1952). Beginning on June 26, 1952, NTA emulsions were included in the film badges worn by workers at the cyclotron (Struxness, 1953). These emulsions were carried for two weeks, exchanged, and microscopically examined for proton recoil tracks after processing.

The neutron energy spectra in work areas near the 86-Inch Cyclotron, like the neutron energy spectra near other early proton accelerators, is not well-known. To simulate the stray neutron fields near the 86-Inch Cycloton, a Maxwellian thermal neutron spectrum was used at energies less than 0.125 eV, and an E^{-1} slowing down spectrum was used at energies from 0.125 eV to 20 MeV, where E represents the neutron energy. The fraction of the dose equivalent from neutrons below the threshold energy of 0.5 MeV for the NTA film was calculated to be approximately 20%. The dose fractions in the neutron energy groups used in the dose reconstruction for Y-12 workers are also shown in Table 9. The results in Table 9 appear to be consistent with observations by others (IAEA, 1988). For example, it has been found that most of the dose at early proton accelerators came from neutrons with energies between 0.1 and 10 MeV, and the neutron dose contributions from both thermal neutrons and fast neutrons with energies above 10 MeV were quite small. The results in Table 9 suggest that neutrons with energies less than 0.1 MeV and neutrons with energies from 14 to 20 MeV contribute only 11% and 8.7%, respectively, to the total neutron dose equivalent in the stray radiation fields at the 86-Inch Cyclotron. Thus, combining the dose from these neutron energy groups with other nearby neutron energy groups is a reasonable and claimant favorable simplification of the neutron dose reconstruction for Y-12 workers (Table 9).

Much of the neutron dose to workers at the Y-12 Plant in the 1950s appears to be associated with research activities at the 86-Inch Cyclotron. The neutron-to-gamma dose ratios may have been quite large in the stray neutron fields in normally occupied areas near the cyclotron, but they were probably moderated by additional exposures to gamma rays from neutron activated materials in the cyclotron vault. The only known source of information on neutron-to-gamma dose ratios that is applicable to radiation exposures at the Oak Ridge 86-Inch Cyclotron is the data generated by this historical evaluation document.

Table 9. Dose fractions for exposure to stray neutrons from the Oak Ridge 86-Inch Cyclotron at Y-12 (Building 9201-1).

Neutron energy group	Dose fraction
< 10 keV	0.076
10 – 100 keV	0.044
0.1 - 2 MeV	0.336
2 - 14 MeV	0.457
14 - 20 MeV	0.087
Claimant favorable dose fractions	
0.1 - 2 MeV	0.46
2 - 14 MeV	0.54

3. Neutron Doses in the Y-12 External Dose Database

Quarterly neutron doses in mrem were among the variables contained in electronic files which the Y-12 site delivered to ORAU/CER from 1978 through the 1980s. These records for more than 17,000 Y-12 workers begin with 1950 data and have resided in a Microsoft © SQL Server database since 2002, as described in Part 1 (Watkins et al., 2004). Neutron doses in the files were summations of biweekly or monthly doses (or blanks) that are no longer available.

4. Statistical Methods

Let n_i denote the recorded neutron dose and g_i the recorded gamma dose for each quarter for one of the four departments described in Section 5.2. If one or more of the gamma doses is zero, it is considered to be left censored (i.e. a non-detect) and is represented as $g_i^* =$ MDL indicating that g is in the interval (0, g^*). An MDL of 30 mrem for the quarterly gamma dose was assumed to assure that the calculated neutron-to-gamma dose ratios would be claimant favorable. The calculated neutron-to- gamma ratio for the i^{th} quarter is $r_i = n_i / g_i$, $i = 1,..., m$, where m is the number of detected gamma doses and $r_i^+ = n_i / g_i^*$, $i = m + 1,\ldots, N$, when the gamma dose is a non-detect and N is the number of quarters with data. If the gamma dose is a non-detect (i.e. left censored) then the ratio $r_i^+ = n_i / g_i^*$ is right censored, i.e., r_i^+ indicates that r_i is greater than or equal to r^+ . If, for example, the neutron dose is 60 mrem and gamma dose is zero, then the ratio r^+ is at least 2. Assuming the ratios are a random sample from a lognormal distribution, the log of the likelihood function for the unknown parameters μ and σ, given the data $\{r_i \quad i = 1,\ldots, m; \; r_i^+ \quad i = m+1,\ldots,N\}$, is

$$L(\mu,\sigma) = \sum_{i=1}^{m} \log\left[g(r_i \,; \mu, \sigma)\right] + \sum_{i=m+1}^{N} \log\left[1 - G(r_i^+ \,; \mu, \sigma)\right], \qquad \textbf{(2)}$$

where $g(r;\mu,\sigma) = \exp[-½ (\log(r) - \mu)^2/\sigma^2] (\sqrt{2\pi}\,\sigma r)^{-1}$ is the probability density function for the lognormal distribution and $G(r^+, \mu,\sigma)$ is the lognormal cumulative distribution function. The maximum likelihood (ML) estimates of μ and σ are obtained using the approach described by Cohen (1991) for a lognormal distribution with random right censored data. The numerical approach used to calculate the ML estimates is based on the R (2004) function **optim**( ). The R driver function **rclnml**( ) is used to calculate the ML estimates $\hat{\mu}$, $\hat{\sigma}$, and their standard errors. Note that when all of the gamma doses are greater than zero, m = N and the second term in Equation (2) is not present. In this case, the solution of the likelihood equations results in the well-known estimates: $\hat{\mu} = \Sigma y_i /N$, $\hat{\sigma} = [\Sigma(y_i - \hat{\mu}_i)^2 /N]^{1/2}$, where $y_i = \log(r_i)$.

5. Evaluation of Film Badge Data

5.1 Quarterly Neutron Dose Distribution

A zero quarterly dose for a worker in the database meant that there were no positive neutron dose readings in the monitoring periods that were summed to produce the quarterly dose. Zero neutron doses may have arisen from any of these three sources: (1) the worker was monitored with NTA film but all measured neutron doses during the quarter were less than the MDL; (2) NTA film was included in the film badge but was not processed because the worker did not enter an area of potential neutron exposure during the quarter; and (3) NTA film was not included in the worker's film badge because the job did not involve entering an area of potential exposure. Table 10 summarizes the distribution of positive neutron quarterly doses and cumulative neutron doses by year, and Table 11 further summarizes the cumulative neutron doses by year and department of exposure.

Because only 143 Y-12 employees had at least one positive quarterly neutron dose, individual neutron doses and additional data, including department of exposure, are presented for each of these workers in Tables A1 and A2 of Appendix A. All of these 143 workers were employed in only 25 departments, which comprised approximately 10% of the total number of Y-12 departments in this time period, and only seven departments had 10 or more workers with at least one positive quarterly neutron dose. There are a total of 375 positive quarterly neutron doses from all departments. These doses are shown schematically in Figure 5. Maximum likelihood estimates of the lognormal parameters and additional summary statistics are also shown. The median quarterly neutron dose was 46 mrem, and only 41.6 percent of the quarterly neutron doses were greater than 50 mrem, with 191 quarterly neutron doses (50.9 percent) less than 50 mrem and 28 (7.5%) equal to 50 mrem.

Table 10. Data on positive quarterly neutron doses and cumulative neutron dose by year.

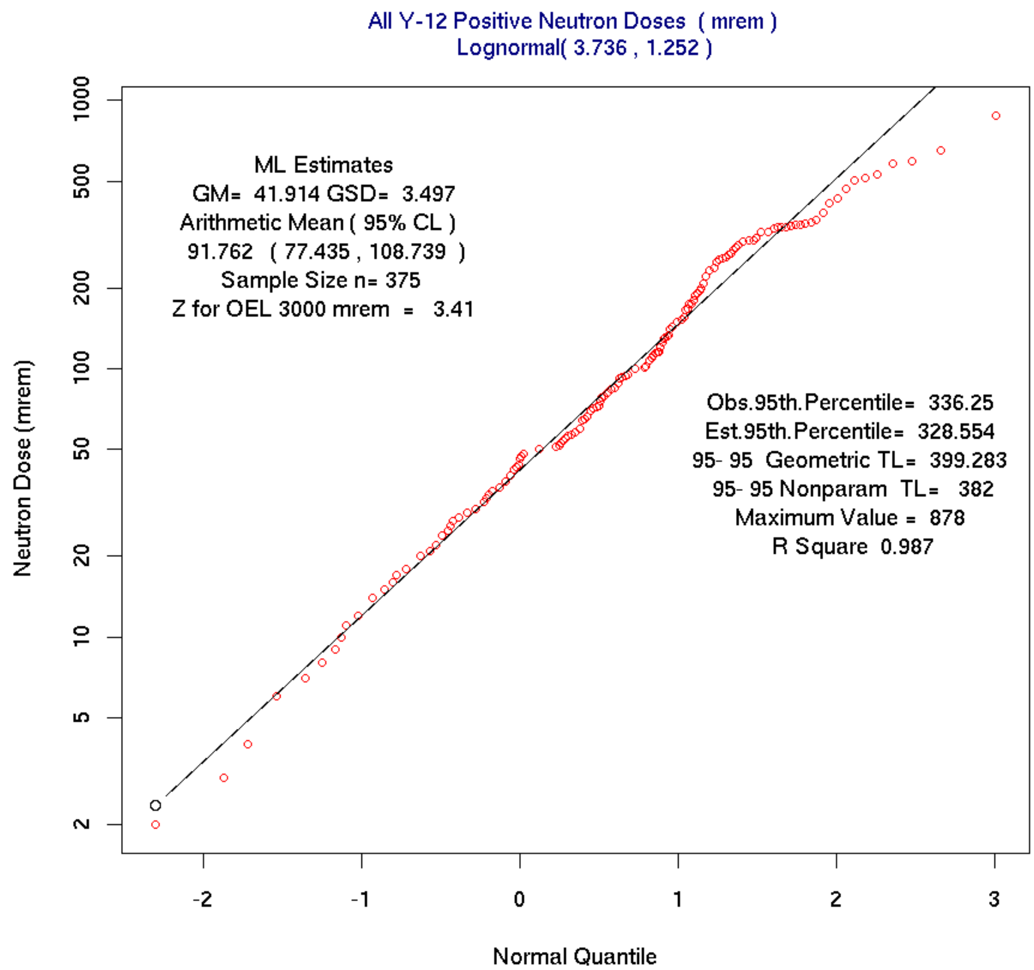
Year	Number of employees	Number of positive neutron doses	Cumulative neutron dose (mrem)
1952	3	3	338
1953	3	3	434
1954	42	48	5927
1955	57	99	17631
1956	32	66	2458
1957	34	76	1650
1958	19	22	530
1959	19	54	3009
1960	2	2	81
1961	0	0	0
1962	2	2	210
Total	143	375	32268

Table 11. Cumulative neutron dose (mrem) by department and year from 1952 to 1962.[a]

Dept.	Year										
	1952	1953	1954	1955	1956	1957	1958	1959	1960	1962	Total
2000			348								348
2001					38	18					56
2003				471							471
2018			16		44	99	18				177
2044				300			30				330
2070		94	142								236
2077			22	714	246	86	15				1083
2091			50								50
2108			262	1923	257	142	41	259			2884
2158					288	168	12				468
2159				6424	759						7001
2160				2556	33						2589
2231			200			334					534
2260			50								50
2301				1128	703	743	283	2750			5607
2303				1016							1016
2345										210	210
2616	18		2552								2570
2617			2235	3231							5466
2618	320	340	50						66		776
2685				50							50
2687						60					60
2701							131				131
2703									15		15
2791					90						90
Total	338	434	5927	17631	2458	1650	530	3009	81	210	32268

a. There were no recorded positive neutron doses for 1961.

Figure 5. Lognormal Q-Q plot of positive neutron doses from all Y-12 departments.



5.2 Neutron-to-Gamma Dose Ratios

One problem in the calculation of neutron-to-gamma dose ratios from the 375 positive quarterly neutron doses available for Y-12 workers is that over 30% of the corresponding quarterly gamma doses are zero (see Tables A1 and A2 of Appendix A). Whenever the corresponding quarterly gamma dose was greater than zero, Table A1 presents the neutron-to-gamma ratios for individual worker/quarters grouped by worker and Table A2 shows these ratios grouped by department. Table A2 reveals that there can be substantial variation in the neutron-to-gamma ratio even for an individual worker from one quarter to the next while working in the same department.

Only four of the 25 departments had sufficient positive neutron dose data for calculating a departmental neutron-to-gamma dose ratio. These four departments are Health Physics (2108), Alloy Maintenance (2159), Material Engineering (2160), and Developmental Operations (2301). Figures 6-9 present the quantile-quantile (Q-Q) plots for the four departments, along with ML estimates for lognormal parameters and other statistical information. In these analyses if a gamma dose is zero (i.e., a non-detect), the neutron-to-gamma dose ratio is obtained by dividing the neutron dose by the MDL of 30 mrem for the quarterly gamma-ray doses and treating the ratio as right censored (see Section 4 for details). This procedure assures that the ratios derived from the available data in Tables A1 and A2 of Appendix A are claimant favorable values. The percent of non-detects or gamma doses equal to zero varied from a low of zero for Departments 2159 and 2160 (Figures 7 and 8) to a high of 41% for Department 2301 (Figure 9).

The neutron-to-gamma dose ratio based on the combined data for all 25 departments is presented in Figure 10. It should be noted that the neutron-to gamma ratio for all departments combined appears to be unreasonably large when compared with the ratios obtained for the four specific departments in Figures 6-9. It was determined that the unacceptably large value was due primarily to two departments, the Product Chemical Department (2616) and Product Processing Department (2617). Departments 2616 and 2617 have data for 32 workers but their positive neutron doses occurred mainly in 1954 and 1955 and include 25 quarterly neutron doses that are multiples of 50 mrem. These positive neutron dose are likely to have been composed of assigned biweekly doses of 50 mrem substituted for below MDL readings.

Figure 11 presents data on the neutron-to-gamma dose ratio obtained using combined data on all workers with positive neutron doses, except those in Departments 2616 and 2617. It is recommended that this lognormal prediction density of neutron-to-gamma dose ratios be used as a default for workers in departments other than the four departments listed in Table 12. The expected values (means) of the ratios in Table 12 of the lognormal prediction densities appear to be reasonable when compared to what is known about neutron-to-gamma dose ratios of the major sources for neutron exposure at the Y-12 Plant during the film badge dosimetry program (Section 2.2). For example, most of the neutron sources in use at Y-12 during the film badge dosimetry program had neutron-to-gamma dose ratios ranging from about 1 to 3. These values may be moderated to some extent by an additional exposure of an individual to pure gamma-ray sources within the workplace.

Figure 6. Lognormal Q-Q plot of neutron-to-gamma dose ratios for the Health Physics Department (2108).

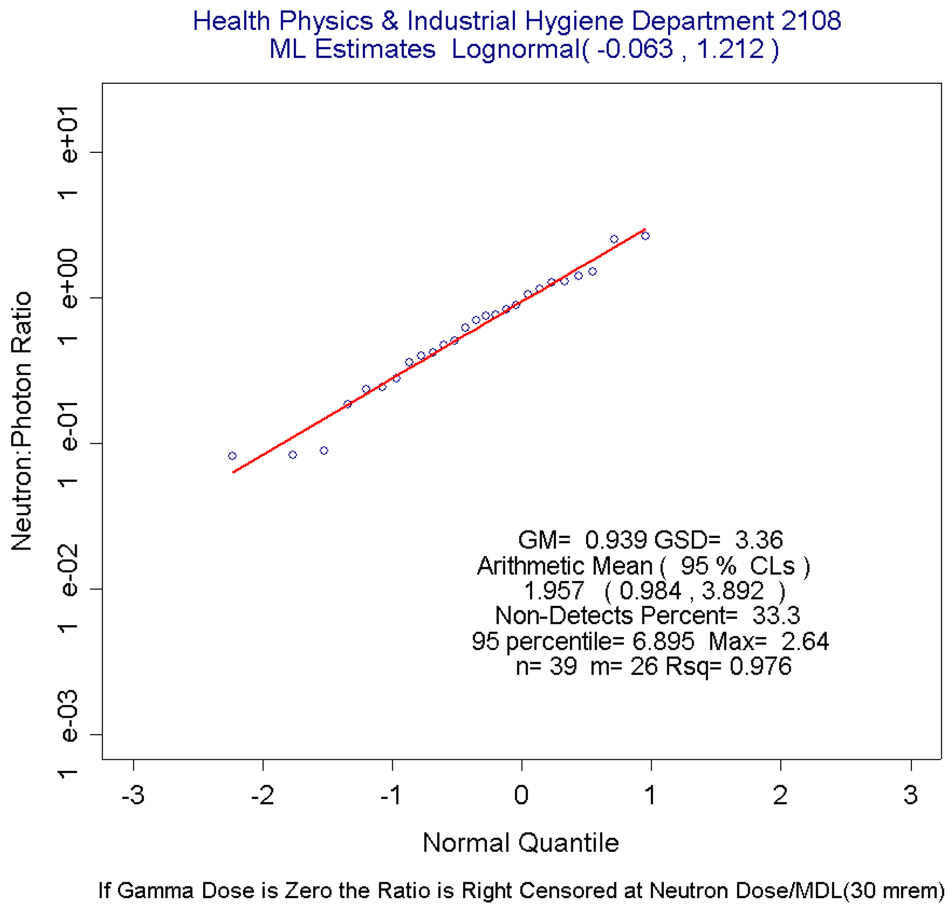


Figure 7. Lognormal Q-Q plot of neutron-to-gamma dose ratios for the Alloy Maintenance Department (2159).

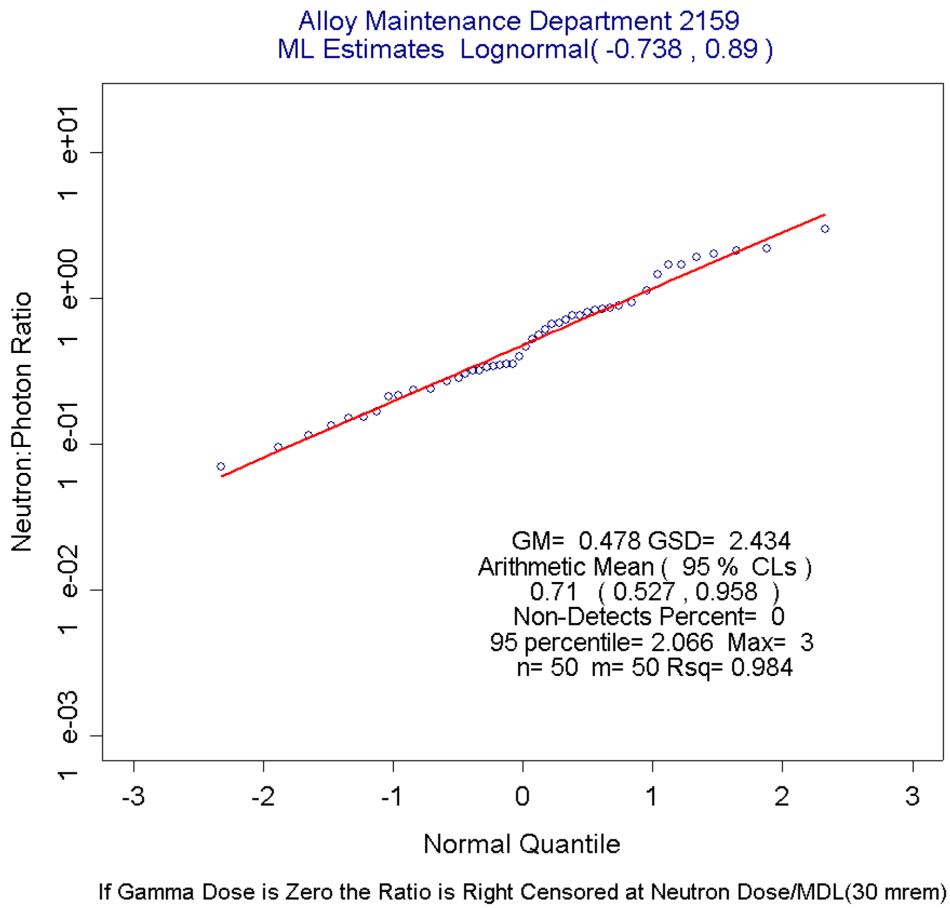


Figure 8. Lognormal Q-Q plot of neutron-to-gamma dose ratios for the Material Engineering Department (2160).

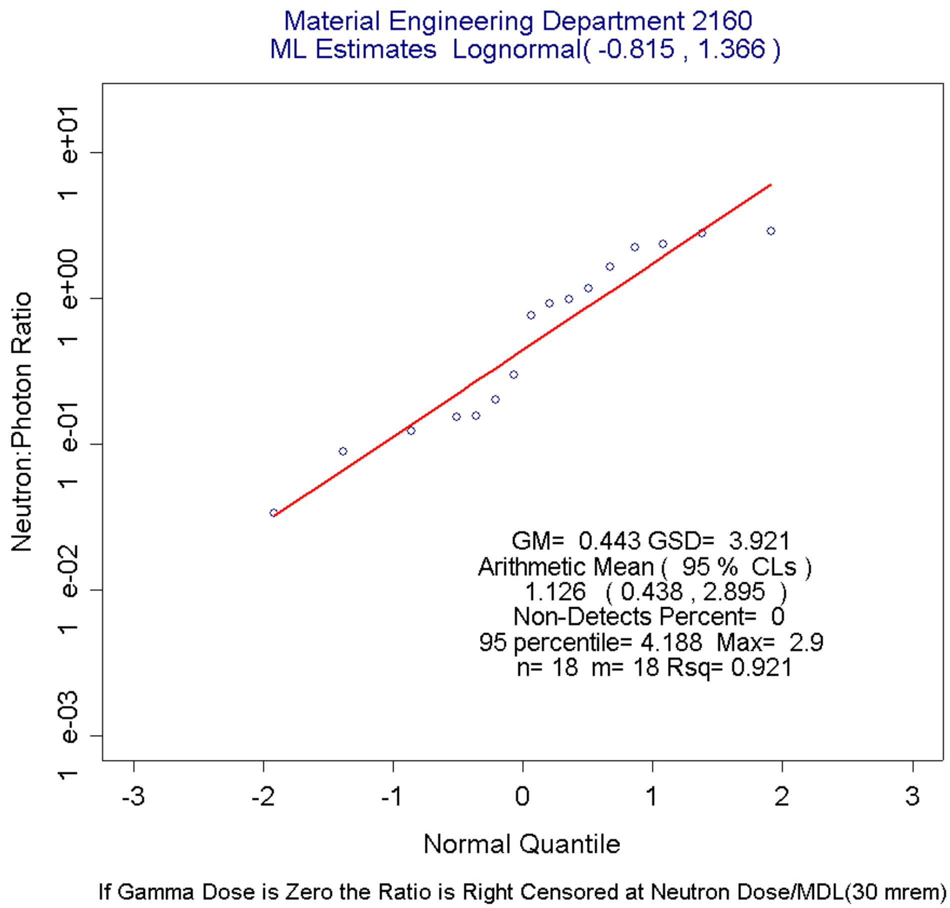


Figure 9. Lognormal Q-Q plot of neutron-to-gamma dose ratios for Developmental Operations Department (2301).

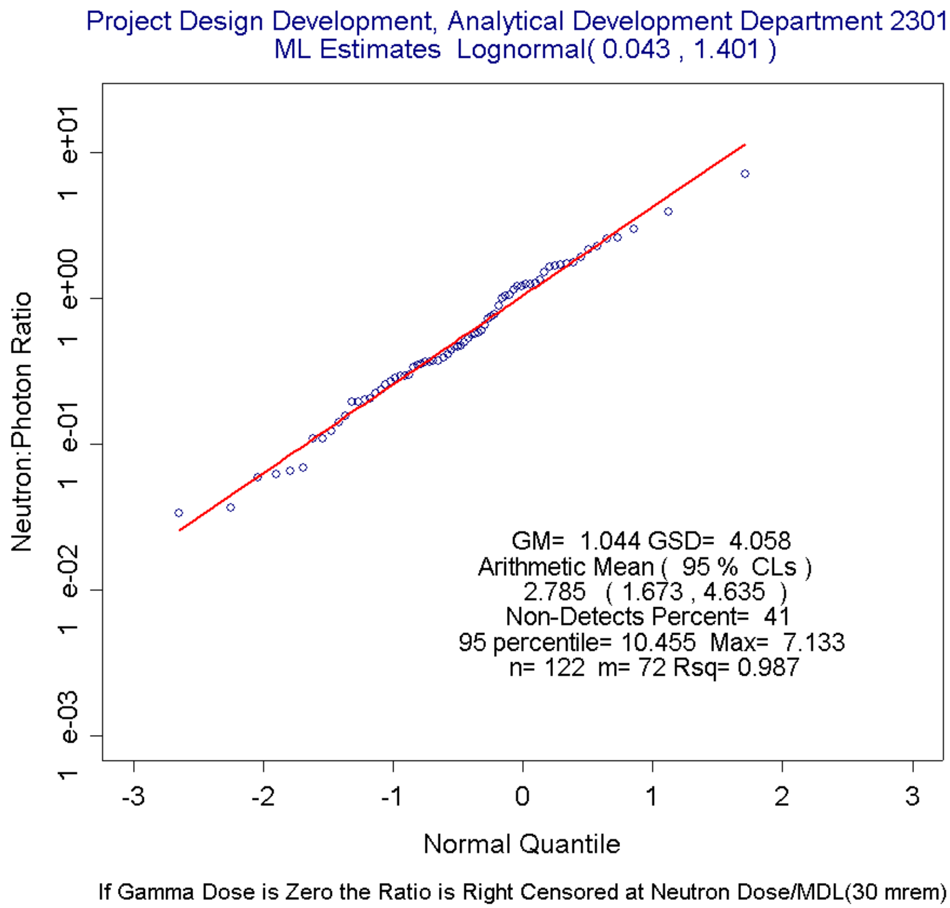


Figure 10. Lognormal Q-Q plot of neutron-to-gamma dose ratios using data from all Y-12 departments.

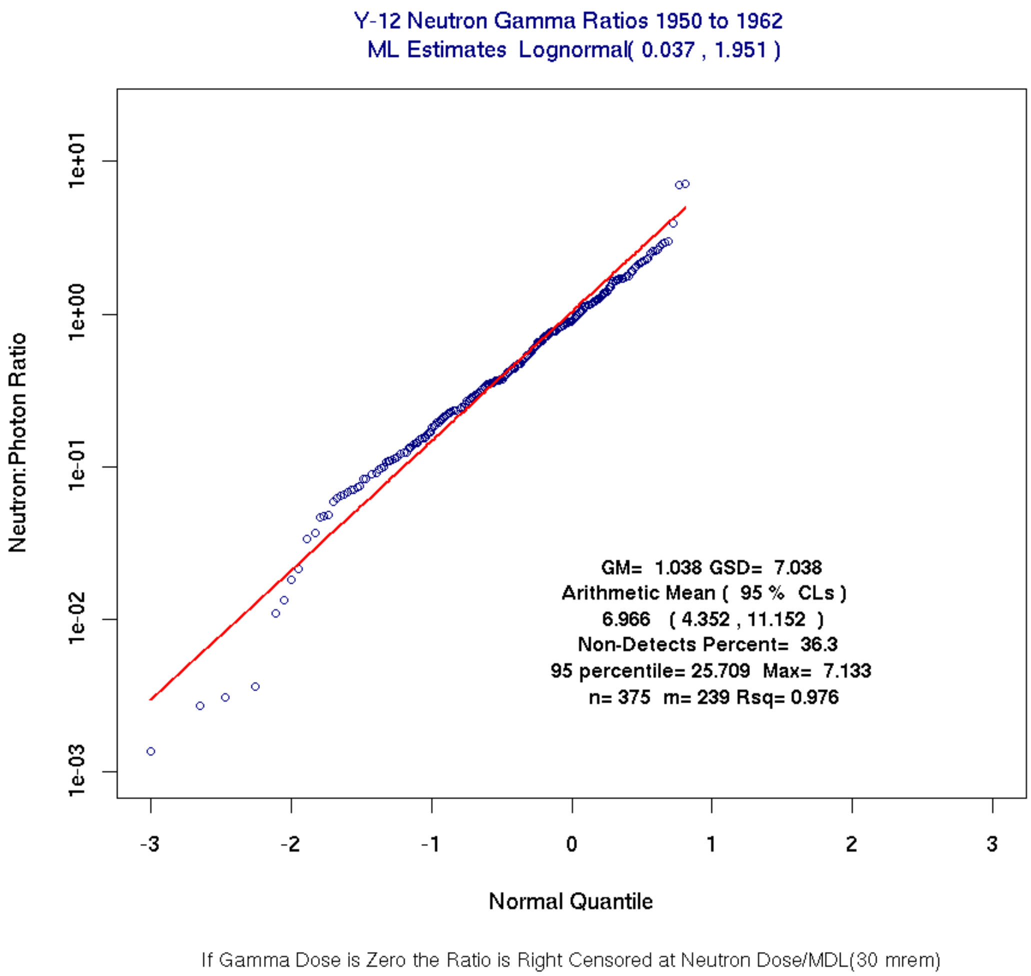


Figure 11. Lognormal Q-Q plot of neutron-to-gamma dose ratios using data from all Y-12 departments except the Product Chemical Department (2616) and Product Processing Department (2617).

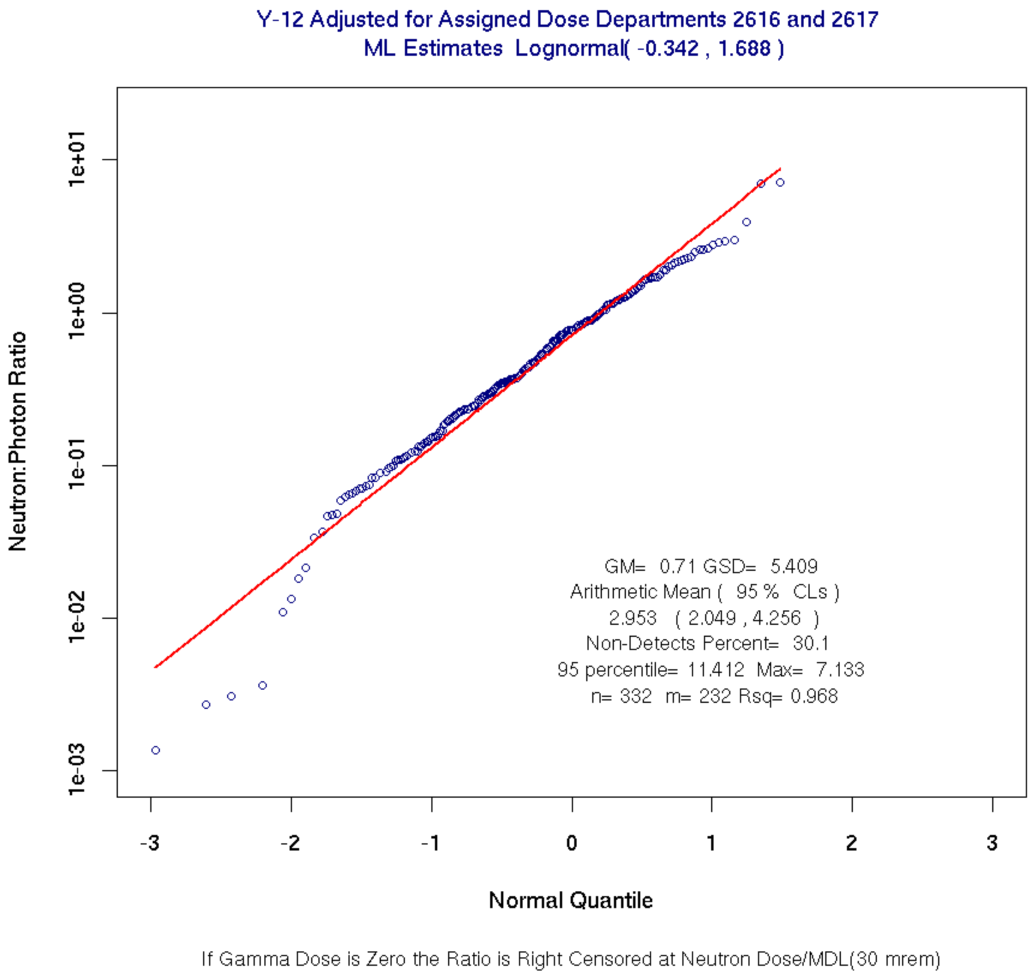


Table 12. Parameter estimates for a lognormal prediction density of neutron-to-gamma dose ratios.

Department[a]	μ	σ	GM	GSD	ER[b]
2108	-0.0629	1.2306	0.9391	3.4235	2.0025
2159	-0.7377	0.8984	0.4782	2.4557	0.7159
2160	-0.8151	1.4038	0.4426	4.0705	1.1855
2301	0.0430	1.4084	1.0439	4.0895	2.8146
Default value	-0.3421	1.6911	0.7103	5.4254	2.9678

[a]See Figures 6-9 and Figure 11.
[b]ER is the expected neutron-to-gamma dose ratio (mean) of the distribution.

6. Estimating Dose for Quarters with No Recorded Positive Neutron Dose

Neutron doses should be estimated using methods developed in this report only during the film badge period prior to 1980. To estimate the dose for a quarter with no recorded positive neutron dose for a worker in Departments 2108, 2159, 2160, or 2301 use the appropriate lognormal parameters for the neutron-to-gamma dose ratio distribution listed in Table 12. Otherwise, use the recommended default parameters of the lognormal distribution on the last line of Table 12. Assigning neutron doses from monitored workers to other workers in the same departments, but who have no record of neutron exposure, is not recommended unless clearly indicated by the unmonitored workers' work history. If a worker has no positive neutron doses before 1962, it is unlikely that the worker experienced neutron exposure and would require an estimated neutron dose.

Discussion

The purpose for this series of reports was to provide important background information on the film badge dosimetry program through 1979 at the Y-12 site as a resource for dose reconstruction. This report focused on neutron exposures and developed neutron-to-gamma ratios that can be used during the process of neutron dose estimation for quarters when a worker was employed and potentially exposed but did not have a positive neutron dose.

Only four departments had sufficient positive neutron dose data for calculating a departmental neutron-to-gamma dose ratio (Table 12). However, a default lognormal predictive density for the neutron-to-gamma dose ratio is recommended for application to workers in other departments at the Y-12 Plant. The expected values (means) of the neutron-to-gamma ratios of these various prediction densities appear to be reasonable when compared to what is known about neutron-to-gamma dose ratios for the different neutron sources in use at the Y-12 Plant during the film badge dosimetry program.

The potential for Y-12 employees to have occupational exposure to neutron dose was largely confined to the years 1952-1962 and to certain departments at the Y-12 Plant. During this period, however, there were only 375 positive quarterly neutron doses among 143 workers. Thus, only a small fraction of the Y-12 workers had a significant potential for exposure to neutron radiation and those with a notable potential appear to have been monitored for neutron radiation. If a worker has no positive neutron doses before 1962, it is unlikely that the worker experienced neutron exposure and would require an estimated neutron dose.

While the potential for exposure to neutrons was confined to a small area of the Y-12 site, it is important to include neutron doses in the exposure records of workers for whom neutrons were a relevant source of radiation. It is noted, however, that there are large variations in neutron doses and neutron-to-gamma dose ratios for individual workers from one quarter to the next. Thus, one should be wary of assigning neutron dose to other workers in the same departments if they have no record of neutron exposure, unless such exposures are clearly indicated by the worker's work records.

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Appendix A

Table A1. Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
001	54	3	2000	50	0	
002	54	3	2000	50	0	
003	54	4	2000	188	0	
004	54	3	2000	50	0	
005	54	1	2000	2	0	
	54	2	2000	8	0	
006	55	4	2160	11	90	0.12
	56	1	2077	12	135	0.09
	56	4	2077	34	0	
007	54	3	2231	50	675	0.07
008	54	3	2070	92	1925	0.05
009	53	1	2618	255	0	
010	54	3	2618	50	0	
011	55	1	2617	150	0	
012	54	1	2077	8	600	0.01
	54	2	2077	2	550	< 0.01
013	58	4	2077	15	23	0.65
014	57	2	2687	21	0	
	57	3	2687	3	0	
015	55	1	2617	100	220	0.45
016	52	2	2618	290	0	
017	57	2	2018	33	16	2.06
	57	3	2018	12	4	3.00
	57	4	2018	54	34	1.59
	58	1	2018	18	16	1.13
018	54	1	2018	10	0	
	54	2	2018	2	0	
019	55	1	2617	100	0	

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
020	57	1	2301	6	88	0.07
	57	2	2301	35	0	
	57	3	2301	9	0	
	57	4	2301	6	0	
	58	1	2301	6	0	
021	62	1	2345	126	18	7.00
022	57	1	2301	20	0	
	57	2	2301	33	29	1.14
	57	3	2301	15	17	0.88
	57	4	2301	30	30	1.00
	58	4	2301	50	177	0.28
	59	1	2301	50	101	0.50
	59	2	2301	57	100	0.57
	59	3	2301	29	236	0.12
	59	4	2301	28	139	0.20
	62	1	2345	84	61	1.38
023	55	1	2617	100	0	
024	55	1	2108	50	0	
	55	2	2108	28	100	0.28
	55	3	2108	414	360	1.15
025	54	4	2616	200	0	
026	57	2	2687	12	0	
027	54	4	2616	150	0	
	55	1	2617	300	0	
028	54	4	2617	100	0	
	55	1	2617	100	0	
029	55	2	2159	505	300	1.68

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
029	55	3	2159	120	60	2.00
030	54	1	2018	2	1485	< 0.01
031	55	1	2617	100	0	
032	54	4	2617	50	0	
033	54	3	2260	50	0	
034	56	3	2301	16	46	0.35
	56	4	2301	8	0	
035	56	3	2108	20	8	2.50
	56	4	2108	84	80	1.05
	57	1	2108	26	0	
	57	2	2108	12	0	
036	57	2	2231	20	118	0.17
037	55	1	2003	112	0	
038	57	1	2301	20	0	
	57	2	2301	18	0	
	57	3	2301	30	18	1.67
	57	4	2301	36	0	
	58	4	2301	36	0	
	59	1	2301	22	60	0.37
	59	2	2301	36	30	1.20
	59	3	2301	36	21	1.71
	59	4	2301	35	119	0.29
039	56	1	2791	30	303	0.10
040	57	2	2108	9	0	
	57	3	2108	21	34	0.62
	57	4	2108	12	0	
	58	1	2108	12	16	0.75

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
041	57	4	2301	36	0	
	59	1	2301	130	60	2.17
	59	2	2301	79	0	
	59	3	2301	21	63	0.33
	59	4	2301	28	59	0.47
042	57	1	2231	24	104	0.23
	57	2	2231	32	198	0.16
043	59	4	2108	36	0	
044	55	2	2160	306	400	0.77
	55	3	2160	174	60	2.90
045	59	4	2301	79	0	
046	53	4	2070	94	1042	0.09
	55	2	2044	300	253	1.19
047	56	4	2001	38	0	
	57	1	2001	18	0	
048	59	1	2301	21	54	0.39
	59	2	2301	94	0	
	59	3	2301	29	114	0.25
	59	4	2301	14	32	0.44
049	56	3	2301	48	74	0.65
050	59	1	2301	78	41	1.90
	59	2	2301	36	0	
051	55	2	2303	350	400	0.88
	55	3	2301	114	390	0.29
	55	4	2301	88	450	0.20
	56	1	2301	73	195	0.37
	56	2	2301	8	135	0.06

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
051	56	3	2301	42	0	
	56	4	2301	51	0	
	57	1	2301	53	30	1.77
	57	2	2301	12	54	0.22
	57	3	2301	18	0	
	57	4	2301	24	0	
	58	1	2301	6	16	0.38
	58	4	2301	29	268	0.11
	59	1	2301	65	62	1.05
	59	2	2301	79	0	
	59	3	2301	51	30	1.70
	59	4	2301	50	0	
052	55	2	2160	654	400	1.64
	55	3	2160	166	60	2.77
	57	2	2158	6	0	
	57	4	2158	60	44	1.36
	58	1	2158	12	0	
053	55	2	2159	340	400	0.85
	55	3	2159	344	390	0.88
	55	4	2159	110	360	0.31
	56	1	2159	52	195	0.27
	56	2	2159	85	75	1.13
	56	3	2159	7	30	0.23
054	55	2	2160	322	350	0.92
	55	3	2160	134	60	2.23
	55	4	2160	11	90	0.12
	56	1	2158	56	195	0.29

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
054	56	2	2159	42	75	0.56
	56	3	2159	4	30	0.13
055	55	4	2160	14	90	0.16
	56	1	2159	29	135	0.21
	56	2	2159	20	60	0.33
056	57	2	2687	9	0	
	57	3	2687	15	0	
057	54	4	2616	324	0	
058	59	1	2301	58	375	0.15
059	54	4	2617	532	300	1.77
	55	1	2617	348	840	0.41
060	56	2	2159	32	15	2.13
061	54	1	2077	6	550	0.01
	54	2	2077	2	550	< 0.01
062	55	2	2303	196	300	0.65
	55	3	2301	302	390	0.77
	55	4	2301	56	400	0.14
	56	1	2301	81	195	0.42
	56	2	2301	40	75	0.53
063	55	2	2685	50	50	1.00
064	55	2	2159	512	300	1.71
	55	3	2159	258	390	0.66
	55	4	2159	76	360	0.21
	56	1	2159	18	75	0.24
065	54	4	2108	60	0	
	55	4	2108	107	76	1.41

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
066	57	2	2077	18	0	
	57	3	2077	12	0	
067	55	1	2617	50	0	
068	55	2	2159	28	400	0.07
	55	3	2159	114	60	1.90
069	55	2	2159	38	400	0.10
	55	3	2159	298	390	0.76
	55	4	2159	54	360	0.15
	56	1	2159	55	195	0.28
	56	2	2159	30	75	0.40
070	60	1	2618	66	58	1.14
071	57	2	2231	3	65	0.05
	57	3	2231	3	140	0.02
072	55	2	2077	430	600	0.72
	55	3	2077	191	390	0.49
	55	4	2077	93	418	0.22
	56	1	2018	44	195	0.23
	56	2	2077	66	75	0.88
	56	3	2077	22	64	0.34
	56	4	2077	28	39	0.72
	57	1	2077	50	0	
	57	2	2301	17	0	
	57	3	2301	3	0	
	57	4	2301	24	0	
	58	1	2301	6	16	0.38
	58	4	2301	14	215	0.07
	59	1	2301	36	77	0.47

Table A1 (Cont.). **Data by worker for 143 Y-12 workers with positive neutron doses.**

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
073	55	2	2159	102	300	0.34
	55	3	2159	156	300	0.52
074	55	4	2160	8	90	0.09
	56	1	2301	40	195	0.21
	56	2	2159	46	60	0.77
	57	1	2301	28	0	
	57	2	2301	35	0	
	57	3	2301	9	0	
	57	4	2301	27	0	
	58	1	2301	15	0	
	59	1	2301	144	56	2.57
	59	2	2301	50	0	
	59	3	2301	51	0	
	59	4	2301	35	0	
075	56	1	2791	30	212	0.14
076	57	2	2077	6	0	
077	55	4	2160	11	90	0.12
	56	1	2160	30	195	0.15
	56	2	2160	3	15	0.20
078	55	2	2108	337	404	0.83
	55	4	2108	70	380	0.18
	56	1	2301	7	15	0.47
	56	4	2301	4	110	0.04
	57	1	2301	22	62	0.35
079	58	4	2301	29	0	
	59	1	2301	93	41	2.27
	59	2	2301	43	0	

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
079	59	3	2301	21	36	0.58
	59	4	2301	56	34	1.65
080	55	2	2159	878	400	2.20
	55	3	2159	334	390	0.86
	55	4	2159	84	360	0.23
	56	1	2158	48	195	0.25
	56	2	2159	70	75	0.93
081	54	3	2231	50	779	0.06
	57	1	2231	16	149	0.11
	57	2	2231	20	176	0.11
082	54	1	2077	2	650	< 0.01
	54	2	2077	2	550	< 0.01
083	56	2	2159	34	56	0.61
	56	3	2159	25	71	0.35
084	56	3	2301	8	0	
	56	4	2301	65	0	
	57	1	2301	15	0	
	57	3	2301	6	0	
	57	4	2301	24	0	
	58	4	2301	58	217	0.27
	59	1	2301	65	54	1.20
	59	2	2301	115	0	
	59	3	2301	7	0	
085	55	1	2617	50	0	
	55	2	2617	175	100	1.75
086	56	2	2159	14	15	0.93

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
087	55	2	2159	268	400	0.67
	55	3	2159	180	60	3.00
	55	4	2160	27	90	0.30
	56	1	2158	84	195	0.43
	56	2	2159	24	75	0.32
088	55	1	2617	50	0	
089	57	1	2231	20	152	0.13
090	54	3	2231	50	683	0.07
091	54	4	2617	470	0	
	55	1	2617	116	0	
092	52	3	2616	18	0	
093	52	3	2618	30	0	
094	54	3	2091	50	0	
095	54	4	2617	152	0	
	55	1	2617	232	0	
096	54	3	2108	100	0	
	54	4	2108	102	0	
097	58	4	2301	14	25	0.56
	59	1	2301	101	39	2.59
	59	2	2301	72	0	
	59	3	2301	50	33	1.52
	59	4	2301	21	28	0.75
098	55	2	2108	132	50	2.64
	55	3	2108	7	30	0.23
	58	4	2108	29	0	
	59	1	2108	51	129	0.40
	59	2	2108	72	0	

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
098	59	3	2108	57	44	1.30
099	58	4	2301	7	0	
	59	1	2301	36	29	1.24
100	54	4	2617	258	0	
101	54	4	2617	208	0	
102	57	1	2231	28	35	0.80
103	57	1	2231	32	170	0.19
	57	2	2231	18	186	0.10
104	56	3	2301	16	44	0.36
105	54	4	2616	592	0	
	55	1	2617	336	0	
106	54	4	2617	100	0	
107	55	2	2108	221	250	0.88
	55	3	2108	298	390	0.76
	55	4	2108	25	300	0.08
	56	1	2108	70	195	0.36
	56	2	2108	38	75	0.51
	56	3	2108	21	86	0.24
	56	4	2108	24	0	
	57	1	2108	38	80	0.48
	57	2	2108	18	12	1.50
	57	4	2108	6	73	0.08
108	58	4	2044	15	0	
109	54	4	2616	250	0	
	55	1	2617	150	140	1.07
110	55	1	2617	100	0	

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
111	55	2	2108	42	100	0.42
	55	3	2108	17	0	
112	54	4	2616	338	0	
113	55	2	2108	167	239	0.70
114	55	1	2003	359	0	
115	54	4	2616	50	0	
	55	1	2617	50	0	
116	55	3	2159	52	150	0.35
	55	4	2159	54	474	0.11
	56	1	2158	72	195	0.37
	56	2	2159	60	75	0.80
117	55	2	2160	232	200	1.16
	55	3	2160	140	60	2.33
	55	4	2160	3	90	0.03
	56	1	2158	28	195	0.14
	56	2	2159	20	75	0.27
	56	3	2159	14	30	0.47
	57	1	2158	12	0	
	57	2	2158	57	0	
	57	3	2158	9	0	
	57	4	2158	24	30	0.80
118	54	4	2616	238	0	
	55	1	2617	150	0	
119	57	1	2231	28	76	0.37
	57	2	2231	14	102	0.14
120	54	4	2617	100	0	
	55	1	2617	50	279	0.18

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
121	58	4	2044	15	0	
122	57	1	2231	20	162	0.12
	57	2	2231	18	162	0.11
123	54	4	2616	260	0	
124	55	3	2108	8	90	0.09
125	56	1	2791	30	56	0.54
126	58	4	2701	131	144	0.91
127	55	2	2160	343	350	0.98
	55	3	2159	278	390	0.71
	55	4	2159	60	360	0.17
	56	1	2159	30	195	0.15
	56	2	2159	30	85	0.35
128	55	1	2617	324	594	0.55
129	54	4	2617	265	0	
130	59	4	2108	43	34	1.26
131	54	3	2070	50	2760	0.02
132	54	3	2231	50	708	0.07
133	53	2	2618	85	0	
134	54	4	2616	150	0	
135	55	2	2303	382	450	0.85
	55	3	2301	232	390	0.59
	55	4	2301	46	422	0.11
	56	1	2301	58	195	0.30
	56	2	2301	94	75	1.25
	56	3	2301	18	92	0.20
	56	4	2301	26	0	
	57	1	2301	40	30	1.33

Table A1 (Cont.). Data by worker for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
135	57	2	2301	47	12	3.92
	57	3	2301	3	48	0.06
	57	4	2301	42	0	
	58	1	2301	6	0	
	58	4	2301	7	210	0.03
	59	1	2301	79	62	1.27
	59	2	2301	50	0	
	59	3	2301	71	24	2.96
	59	4	2301	71	0	
136	57	1	2231	32	140	0.23
137	55	2	2159	582	400	1.46
	55	3	2159	322	390	0.83
	55	4	2159	95	300	0.32
	56	1	2077	84	195	0.43
	56	2	2159	18	75	0.24
138	57	2	2231	6	128	0.05
139	60	1	2703	15	0	
140	55	1	2617	100	0	
141	55	2	2303	88	200	0.44
	55	3	2301	283	390	0.73
	55	4	2301	7	30	0.23
142	59	1	2301	64	62	1.03
	59	2	2301	50	0	
	59	3	2301	107	15	7.13
	59	4	2301	57	0	
143	54	1	2108	2	735	< 0.01

Table A2. Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2000: Special Monitoring					
005	54	1	2	0	
	54	2	8	0	
001	54	3	50	0	
002	54	3	50	0	
004	54	3	50	0	
003	54	4	188	0	
Department 2001: Janitor Department					
047	56	4	38	0	
	57	1	18	0	
Department 2003: Maintenance Shops					
037	55	1	112	0	
114	55	1	359	0	
Department 2018: Research Services Department					
143	54	1	2	735	< 0.01
030	54	1	2	1485	< 0.01
018	54	1	10	0	
	54	2	2	0	
072*	56	1	44	195	0.23
017	57	2	33	16	2.06
	57	3	12	4	3.00
	57	4	54	34	1.59
	58	1	18	16	1.13
Department 2044: Mechanical Inspection Department					
046*	55	2	300	253	1.19
108	58	4	15	0	
121	58	4	15	0	

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2070: Mechanical Engineering Department, Tool Engineering					
046*	53	4	94	1042	0.09
008	54	3	92	1925	0.05
131	54	3	50	2760	0.02
Department 2077: Electrical Maintenance Department					
012	54	1	8	600	0.01
	54	2	2	550	< 0.01
061	54	1	6	550	0.01
	54	2	2	550	< 0.01
079	54	1	2	650	< 0.01
	54	2	2	550	< 0.01
072*	55	2	430	600	0.72
	55	3	191	390	0.49
	55	4	93	418	0.22
	56	2	66	75	0.88
	56	3	22	64	0.34
	56	4	28	39	0.72
	57	1	50	0	
006*	56	1	12	135	0.09
	56	4	34	0	
137*	56	1	84	195	0.43
066	57	2	18	0	
	57	3	12	0	
076	57	2	6	0	
013	58	4	15	23	0.65
Department 2091: Guard Department					
094	54	3	50	0	

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2108: Health Physics & Industrial Hygiene, Health Physics					
096	54	3	100	0	
	54	4	102	0	
065	54	4	60	0	
	55	4	107	76	1.41
024	55	1	50	0	
	55	2	28	100	0.28
	55	3	414	360	1.15
113	55	2	167	239	0.70
111	55	2	42	100	0.42
	55	3	17	0	
107	55	2	221	250	0.88
	55	3	298	390	0.76
	55	4	25	300	0.08
	56	1	70	195	0.36
	56	2	38	75	0.51
	56	3	21	86	0.24
	56	4	24	0	
	57	1	38	80	0.48
	57	2	18	12	1.50
	57	4	6	73	0.08
098	55	2	132	50	2.64
	55	3	7	30	0.23
	58	4	29	0	
	59	1	51	129	0.40
	59	2	72	0	
	59	3	57	44	1.30

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2108 (Cont.): Health Physics & Industrial Hygiene, Health Physics					
078*	55	2	337	404	0.83
	55	4	70	380	0.18
124	55	3	8	90	0.09
035	56	3	20	8	2.50
	56	4	84	80	1.05
	57	1	26	0	
	57	2	12	0	
040	57	2	9	0	
	57	3	21	34	0.62
	57	4	12	0	
	58	1	12	16	0.75
043	59	4	36	0	
130	59	4	43	34	1.26
Department 2158: Area 5 Maintenance Department					
054*	56	1	56	195	0.29
080*	56	1	48	195	0.25
087*	56	1	84	195	0.43
116*	56	1	72	195	0.37
117*	56	1	28	195	0.14
	57	1	12	0	
	57	2	57	0	
	57	3	9	0	
	57	4	24	30	0.80
052*	57	2	6	0	
	57	4	60	44	1.36
	58	1	12	0	

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2159: Alloy Maintenance Department					
029	55	2	505	300	1.68
	55	3	120	60	2.00
053	55	2	340	400	0.85
	55	3	344	390	0.88
	55	4	110	360	0.31
	56	1	52	195	0.27
	56	2	85	75	1.13
	56	3	7	30	0.23
064	55	2	512	300	1.71
	55	3	258	390	0.66
	55	4	76	360	0.21
	56	1	18	75	0.24
068	55	2	28	400	0.07
	55	3	114	60	1.90
069	55	2	38	400	0.10
	55	3	298	390	0.76
	55	4	54	360	0.15
	56	1	55	195	0.28
	56	2	30	75	0.40
073	55	2	102	300	0.34
	55	3	156	300	0.52
080*	55	2	878	400	2.20
	55	3	334	390	0.86
	55	4	84	360	0.23
	56	2	70	75	0.93
087*	55	2	268	400	0.67
	55	3	180	60	3.00
	56	2	24	75	0.32

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2159 (Cont.): Alloy Maintenance Department					
137*	55	2	582	400	1.46
	55	3	322	390	0.83
	55	4	95	300	0.32
	56	2	18	75	0.24
116*	55	3	52	150	0.35
	55	4	54	474	0.11
	56	2	60	75	0.80
127*	55	3	278	390	0.71
	55	4	60	360	0.17
	56	1	30	195	0.15
	56	2	30	85	0.35
055*	56	1	29	135	0.21
	56	2	20	60	0.33
054*	56	2	42	75	0.56
	56	3	4	30	0.13
060	56	2	32	15	2.13
074*	56	2	46	60	0.77
083	56	2	34	56	0.61
	56	3	25	71	0.35
086	56	2	14	15	0.93
117*	56	2	20	75	0.27
	56	3	14	30	0.47
Department 2160: Material Engineering Department					
044	55	2	306	400	0.77
	55	3	174	60	2.90
052*	55	2	654	400	1.64
	55	3	166	60	2.77

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2160 (Cont.): Material Engineering Department					
054*	55	2	322	350	0.92
	55	3	134	60	2.23
	55	4	11	90	0.12
117*	55	2	232	200	1.16
	55	3	140	60	2.33
	55	4	3	90	0.03
127*	55	2	343	350	0.98
006*	55	4	11	90	0.12
055*	55	4	14	90	0.16
074*	55	4	8	90	0.09
077	55	4	11	90	0.12
	56	1	30	195	0.15
	56	2	3	15	0.20
087*	55	4	27	90	0.30
Department 2231: Special Testing					
007	54	3	50	675	0.07
081	54	3	50	779	0.06
	57	1	16	149	0.11
	57	2	20	176	0.11
090	54	3	50	683	0.07
132	54	3	50	708	0.07
042	57	1	24	104	0.23
	57	2	32	198	0.16
089	57	1	20	152	0.13
102	57	1	28	35	0.80
103	57	1	32	170	0.19
	57	2	18	186	0.10

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2231 (Cont.): Special Testing					
119	57	1	28	76	0.37
	57	2	14	102	0.14
122	57	1	20	162	0.12
	57	2	18	162	0.11
136	57	1	32	140	0.23
036	57	2	20	118	0.17
071	57	2	3	65	0.05
	57	3	3	140	0.02
133	57	2	6	128	0.05
Department 2260: Laboratory Operations					
033	54	3	50	0	
Department 2301: Development Operations					
051*	55	3	114	390	0.29
	55	4	88	450	0.20
	56	1	73	195	0.37
	56	2	8	135	0.06
	56	3	42	0	
	56	4	51	0	
	57	1	53	30	1.77
	57	2	12	54	0.22
	57	3	18	0	
	57	4	24	0	
	58	1	6	16	0.38
	58	4	29	268	0.11
	59	1	65	62	1.05
	59	2	79	0	
	59	3	51	30	1.70
	59	4	50	0	

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2301 (Cont.): Development Operations					
062*	55	3	302	390	0.77
	55	4	56	400	0.14
	56	1	81	195	0.42
	56	2	40	75	0.53
135	55	3	232	390	0.59
	55	4	46	422	0.11
	56	1	58	195	0.30
	56	2	94	75	1.25
	56	3	18	92	0.20
	56	4	26	0	
	57	1	40	30	1.33
	57	2	47	12	3.92
	57	3	3	48	0.06
	57	4	42	0	
	58	1	6	0	
	58	4	7	210	0.03
	59	1	79	62	1.27
	59	2	50	0	
	59	3	71	24	2.96
	59	4	71	0	
141*	55	3	283	390	0.73
	55	4	7	30	0.23
078	56	1	7	15	0.47
	56	4	4	110	0.04
	57	1	22	62	0.35

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2301 (Cont.): Development Operations					
074*	56	1	40	195	0.21
	57	1	28	0	
	57	2	35	0	
	57	3	9	0	
	57	4	27	0	
	58	1	15	0	
	59	1	144	56	2.57
	59	2	50	0	
	59	3	51	0	
	59	4	35	0	
034	56	3	16	46	0.35
	56	4	8	0	
049	56	3	48	74	0.65
084	56	3	8	0	
	56	4	65	0	
	57	1	15	0	
	57	3	6	0	
	57	4	24	0	
	58	4	58	217	0.27
	59	1	65	54	1.20
	59	2	115	0	
	59	3	7	0	
104	56	3	16	44	0.36

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2301 (Cont.): Development Operations					
020	57	1	6	88	0.07
	57	2	35	0	
	57	3	9	0	
	57	4	6	0	
	58	1	6	0	
022*	57	1	20	0	
	57	2	33	29	1.14
	57	3	15	17	0.88
	57	4	30	30	1.00
	58	4	50	177	0.28
	59	1	50	101	0.50
	59	2	57	100	0.57
	59	3	29	236	0.12
	59	4	28	139	0.20
038	57	1	20	0	
	57	2	18	0	
	57	3	30	18	1.67
	57	4	36	0	
	58	4	36	0	
	59	1	22	60	0.37
	59	2	36	30	1.20
	59	3	36	21	1.71
	59	4	35	119	0.29
072*	57	2	17	0	
	57	3	3	0	
	57	4	24	0	
	58	1	6	16	0.38
	58	4	14	215	0.07
	59	1	36	77	0.47

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2301 (Cont.): Development Operations					
041	57	4	36	0	
	59	1	130	60	2.17
	59	2	79	0	
	59	3	21	63	0.33
	59	4	28	59	0.47
079	58	4	29	0	
	59	1	93	41	2.27
	59	2	43	0	
	59	3	21	36	0.58
	59	4	56	34	1.65
097	58	4	14	25	0.56
	59	1	101	39	2.59
	59	2	72	0	
	59	3	50	33	1.52
	59	4	21	28	0.75
099	58	4	7	0	
	59	1	36	29	1.24
048	59	1	21	54	0.39
	59	2	94	0	
	59	3	29	114	0.25
	59	4	14	32	0.44
050	59	1	78	41	1.90
	59	2	36	0	
058	59	1	58	375	0.15
142	59	1	64	62	1.03
	59	2	50	0	
	59	3	107	15	7.13
	59	4	57	0	

Table A2 (Cont.). Data department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2301 (Cont.): Development Operations					
045	59	4	79	0	
Department 2303: Project Design Development, Analytical Development Department					
051*	55	2	350	400	0.88
062*	55	2	196	300	0.65
135*	55	2	382	450	0.85
141*	55	2	88	200	0.44
Department 2345: Laboratory Development					
021	62	1	126	18	7.00
022*	62	1	84	61	1.38
Department 2616: Product Chemical Department					
092	52	3	18	0	
025	54	4	200	0	
027*	54	4	150	0	
057	54	4	324	0	
105*	54	4	592	0	
109*	54	4	250	0	
112	54	4	338	0	
115*	54	4	50	0	
118*	54	4	238	0	
123	54	4	260	0	
134	54	4	150	0	
Department 2617: Product Processing Development					
028	54	4	100	0	
	55	1	100	0	
032	54	4	50	0	

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2617 (Cont.): Product Processing Development					
059	54	4	532	300	1.77
	55	1	348	840	0.41
091	54	4	470	0	
	55	1	116	0	
095	54	4	152	0	
	55	1	232	0	
100	54	4	258	0	
101	54	4	208	0	
106	54	4	100	0	
120	54	4	100	0	
	55	1	50	279	0.18
129	54	4	265	0	
011	55	1	150	0	
015	55	1	100	220	0.45
019	55	1	100	0	
023	55	1	100	0	
027*	55	1	300	0	
031	55	1	100	0	
067	55	1	50	0	
085	55	1	50	0	
	55	2	175	100	1.75
088	55	1	50	0	
105*	55	1	336	0	
109*	55	1	150	140	1.07
110	55	1	100	0	
115*	55	1	50	0	
118*	55	1	150	0	

* Workers with neutron exposures listed under multiple departments.

Table A2 (Cont.). Data by department for 143 Y-12 workers with positive neutron doses.

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
Department 2617 (Cont.): Product Processing Development					
128	55	1	324	594	0.55
140	55	1	100	0	
Department 2618: Uranium Chip Recovery, Waste Operations					
016	52	2	290	0	
093	52	3	30	0	
009	53	1	255	0	
133	53	2	85	0	
010	54	3	50	0	
070	60	1	66	58	1.14
Department 2685: Colex Operations, Alpha-5 Cascade Operations					
063	55	2	50	50	1.00
Department 2687: Beta-2 Department, Chemical Services					
014	57	2	21	0	
	57	3	3	0	
026	57	2	12	0	
056	57	2	9	0	
	57	3	15	0	
Department 2701: Assembly Operations, D Mechanical Operations, Z-Area Operations					
126	58	4	131	144	0.91
Department 2703: A Wing, H2 & F Areas					
139	60	1	15	0	
Department 2791: Mechanical Operations Department, Special Chemical Services					
039	56	1	30	303	0.10
075	56	1	30	212	0.14
125	56	1	30	56	0.54