DOE Review Release 12/14/2009

Document Title:	Document Number: ORAUT-OTIB-0045
Historical Evaluation of the Film Badge Dosimetry Program at the Y-12 Plant in Oak Ridge, Tennessee: Part 2 – Neutron Radiation	Revision: 01 Effective Date: 11/30/2009 Type of Document: OTIB Supersedes: Revision 00 (ORAUT-RPRT-0033)

Subject Expert(s): George D. Kerr, Edward L. Frome, Janice P. Watkins, William G. Tankersley

Site Expert(s): N/A

Approval:	Signature on File George D. Kerr, Document Owner	Approval Date:	11/12/2009
Concurrence:	Signature on File John M. Byrne, Objective 1 Manager	Concurrence Date:	11/12/2009
Concurrence:	Keith A. McCartney Signature on File for Edward F. Maher, Objective 3 Manager	Concurrence Date:	11/23/2009
Concurrence:	Signature on File Kate Kimpan, Project Director	Concurrence Date:	11/12/2009
Approval:	Signature on File James W. Neton, Associate Director for Science	Approval Date:	11/30/2009

☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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

PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
04/13/2005	00	This report was previously published as an Oak Ridge Associated Universities document and is now being incorporated as an ORAU Team controlled document. Future revisions will be reviewed and approved by NIOSH. Initiated by George D. Kerr.
11/30/2009	01	ORAUT-RPRT-0033 Rev 00 converted to ORAUT-OTIB-0045 Rev 01-A. Revisions include formatting, editorial changes, addition of required language on page 6 in Section 1.0, and a complete rewrite of Section 3.0. New information was added on sources of neutron exposure at the Y-12 site in Table 3.1 of Section 3.0 and a large number of new references were added. Attachment B was also added which provides supporting data on neutron doses to Y-12 workers during the film badge period from another recent study. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by George D. Kerr, Edward L. Frome, Janice P. Watkins, and William G. Tankersley.

Trademark Information

FreeBSD is a registered trademark of The FreeBSD Foundation in the United States and/or other countries.

MacOS is a registered trademark of Apple, Inc. in the United States and/or other countries.

UNIX is a registered trademark of The Open Group in the United States and/or other countries.

Windows is a registered trademark of Microsoft Corporation in the United States and/or other countries.

TABLE OF CONTENTS

SECTION **TITLE** **PAGE**

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

CEF	Critical Experiments Facility
Ci	curie
cm	centimeter
D-D	deuterium-deuterium reaction
DOE	U.S. Department of Energy
eV	electron volt
ft	foot
HP	health physics or health physicist
hr	hour
in.	inch
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron volts (one thousand electron volts)
m	meter
MDL	minimum detection level
MeV	megaelectron volts (one million electron volts)
ML	maximum likelihood
mrem	millirem
mrep	millirep
n	neutron
NIOSH	National Institute for Occupational Safety and Health
NTA	nuclear track emulsion, Type A
ORAU	Oak Ridge Associated Universities
ORNL	Oak Ridge National Laboratory
Q-Q	quantile-quantile
s	second
TIB	Technical Information Bulletin
TLD	thermoluminescent dosimeter
TLND	thermoluminescent neutron dosimeter
U.S.C.	United States Code
Y-12	Y-12 Plant, now the Y-12 National Security Complex
α	alpha particle
§	section or sections

1.0 INTRODUCTION

Technical information bulletins (TIBs) are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance concerning the preparation of dose reconstructions at particular sites or categories of sites. They will be revised when additional relevant information is obtained about the affect site(s). TIBS may be used to assist the NIOSH staff in the completion of individual dose reconstructions.

In this document the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy (DOE) facility" as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [42 U.S.C. § 7384l(5) and (12)].

2.0 PURPOSE

The purpose of this TIB is to provide information on the Y-12 film badge for the monitoring of neutron radiation. Other reports have been prepared that deal with film badge dosimetry at the Y-12 facility for gamma radiation (ORAUT 2005a) and beta radiation (ORAUT 2007a). The Y-12 film badge program began shortly after the Union Carbide Corporation-Nuclear Division (UCCND) assumed management of the Y-12 Plant in May of 1947 and continued until the film badge dosimeters were replaced in 1980 by thermoluminescent dosimeters (TLDs) (McLendon et al. 1980; Howell and Batte 1982).

The potential for occupational exposure to neutron doses at the Y-12 Plant was largely confined to research activities at the Oak Ridge 86-Inch Cyclotron and to a few workers in certain departments during the film badge era at the Y-12 Plant. During this period, only 375 positive quarterly neutron doses were recorded among a total of 143 workers. Thus, only a small fraction of the Y-12 workers had a significant potential for exposure to neutrons, and in these cases, personnel monitoring was provided by the use of neutron sensitive films in the film badge dosimeters (Emlet 1956, p. 6).

A summary of the major neutron sources involved in radiation exposures to Y-12 workers is presented in this TIB. Graphical methods are used to evaluate available neutron dose data from quarterly exposures to Y-12 workers and to determine how the data could be used to derive neutron-to-gamma dose ratios for dose reconstruction purposes. This TIB provides estimates of neutron-to-gamma dose ratios for specific departments and a default value for the neutron-to-gamma dose ratio based on the pooled neutron dose data for all Y-12 departments.

All statistical analyses in this TIB were carried out using the R system (RDCT 2008). The R system is an integrated suite of free software for data manipulation, calculation, and graphic display. It can be run on a variety of UNIX® platforms and similar systems (including Linux or FreeBSD®), Windows®, and MacOS®. A detailed documentation on all aspects of the R system is available on the R web page (http://www.r-project.org).

3.0 NEUTRON FILM BADGE DOSIMETRY AT Y-12 FACILITIES

Early operations at Y-12 were managed by the Tennessee Eastman Corporation and involved the use of the electromagnetic separation process to enrich uranium in ^{235}U (Wilcox 2001, p. 3). Ground was broken for the first building at Y-12 in February 1943, and the first production unit was in use by January 1944 (Marsden 1945, p. 115; Jones 1985, pp. 130, 139). Until the latter part of 1945, Y-12 converted UO_3 to UCl_4, which was subsequently enriched by the electromagnetic separation process using two calutrons (termed “Alpha” and “Beta”). In late 1945, Y-12 discontinued the use of the Alpha calutron stage and began using partially enriched UF_6 from the K-25 Gaseous Diffusion Plant (Wilcox

2001, pp. 16-21). The UF_6 from K-25 was converted UCl_4, further enriched in ^{235}U using the Beta calutrons, converted to UF_4, and shipped to Los Alamos for weapon production. In May 1947, the management of Y-12 was transferred to UCCND, and the mission of Y-12 changed from uranium enrichment to nuclear material processing and fabrication (Watkins et al. 1993, p. 10; Watkins et al. 1997, pp. 195-196). Internal radiation exposure to alpha particles from inhaled dust of uranium was still the largest concern at Y-12, but there was increased concern over the external radiation exposure to gamma rays and beta particles in the metal handling departments.

The first experience with the machining of uranium metal at Y-12 occurred in December of 1947 (Murray 1948, p. 1; Emlet 1952, p. 1) and steps were taken in the spring of 1948 for the transfer of certain weapon fabrication functions from Los Alamos to Y-12 (Williams 1948, p. 1; Emlet 1952, p. 3). At this time, responsibility for studying and monitoring the uranium machining operations was transferred from a Special Hazards Group to a Health Physics (HP) Department set up under the Y-12 Medical Division (Emlet 1952, p. 3). The HP Department started an external monitoring program in 1948 to monitor exposures to Y-12 workers in the Assay Laboratories, Radiographic Shop, Spectrographic Shop, and Machine Shops, where uranium metals were handled (Struxness 1948, pp. 8-9). The first film badge dosimeter used at Y-12 in 1948 was identical to the badge that was used at ORNL in 1949 and described by Thornton, Davis, and Gupton (1961, pp. 2-5). This film badge was an AEC Catalog Number PF-1B film badge manufactured by the A. M. Samples Machine Company in Knoxville, Tennessee (Patterson, West, McLendon 1957, p. 21). The radiation-sensitive medium (dosimetry film) in the PF-1B badge was encased in a protective packet with a clip for attachment to clothing or a lanyard (Handloser 1959, p. 152, Figure 8-1). The film badge was normally worn on the front of the torso between the neck and waist. A portion of the film was covered by a 1-mm thick cadmium filter to determine the radiation dose from gamma rays and high-energy x-rays and the remaining uncovered portion of the film (open window) was used to determine the radiation dose from beta particles and low-energy x-rays (Handloser 1959, p. 152, Figure 8-1).

Neutron-sensitive films were added to the PF-1B film badge in 1949 with the inauguration of the so-called D-D Project in Building 9204-3 by the Beta Development Group (Struxness 1949a, p. 3). The high positive ion output of the calutron made it particularly attractive as a neutron source using the low energy deuteron-deuteron (D-D) reaction which produced neutrons with energies of approximately 2.5 MeV. As a temporary expedient, the measurements of neutron dose to the personnel involved in the D-D Project were made with alpha-sensitive film provided by the ORNL HP Division, and they also calibrated the film, developed the film, and microscopically counted the density of neutron-recoil ion tracks in the film to determine the neutron dose to each person (Struxness 1949a, p. 3). These alpha sensitive films were exchanged on a weekly basis (Souleyrette 2003a, p. 2). In June 1952, nuclear track emulsions, type A, or so-called NTA films were first used as neutron dosimeters in the PF-1B film badges worn by personnel operating the Oak Ridge 86-Inch Cyclotron (Struxness 1953, p. 31). These emulsions were carried for two weeks, exchanged, and microscopically examined to determine the density of recoil ions in the emulsion and neutron dose to the individual wearing the film badge (Struxness 1953, p. 31). Film badges containing an NTA film were assigned to all workers who had a notable potential for exposure to neutrons at the Y-12 Plant from 1952 to 1961 (Emlet 1956, p. 6).

On June 16, 1958, an unexpected nuclear excursion occurred in the C-Wing of Building 9212 at the Y-12 Plant (UCNC 1958; Callihan and Thomas 1959). Eight Y-12 employees, who did not have a notable potential for exposure to neutrons or gamma rays and were not wearing a film badge dosimeter, received estimated radiation doses ranging from 23 rem to 365 rem (Hurst, Ritchie, and Emerson 1959). As a result of this criticality accident at the Y-12 Plant, a newer dosimeter system was developed that was an integral part of each employee’s ID badge and contained components for both routine and accident-related dosimetry (Thornton, Davis and Gupton 1961, pp. 22-32). It had been found that the fading of the latent images of tracks from neutron-produced recoil ions was reduced by an appreciable factor when the NTA film was packaged in a moisture proof container

(Cheka 1954). Thornton, Davis, and Gupton (1961, pp. 24-29) experimented with moisture-proof pouch paper and found that the latent image of tracks from the neutron-produced recoil ions could be controlled while the NTA films remained in the film badge dosimeters for a calendar quarter (13 weeks). The fading of the latent image of the neutron recoil tracks in NTA films sealed in a moisture-proof pouch is shown as function of time in Figure 3-1 (Thornton, Davis and Gupton 1961, p. 28; Morgan, Davis, and Hart 1963, p. 69). After 1961, film badge dosimeters containing NTA films were assigned to all employees, but the NTA films were processed and read only if an employee entered an area with a neutron source and the HP staff recommended processing. If the NTA film indicated that the neutron dose was less than the minimum detectable limit (MDL), the general guideline was to record either a zero or the MDL. A surprising result of this study is the number of recorded neutron doses that are greater than zero, but less than the estimated MDL of 50 mrem (see Tables A-1 and A-2 of Attachment A).

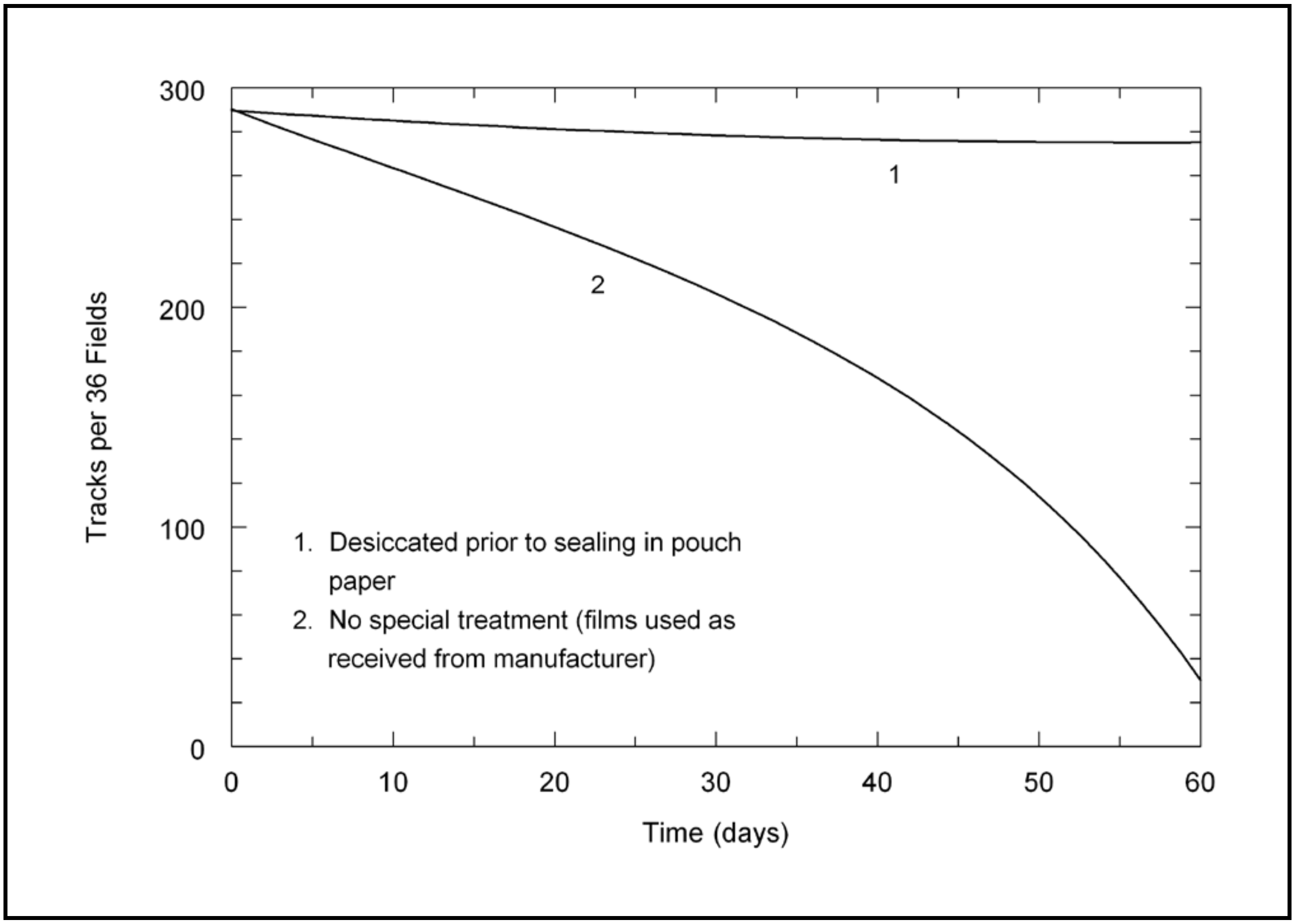

Figure 3-1. Effect of sealing NTA film in a moisture-proof pouch (Thornton, Davis, and Gupton 1961, p. 28; Morgan Davis, and Hart 1963, p. 69). Fading of latent images of tracks formed by neutron-recoil ions in NTA films sealed in moisture-proof paper (line 1) and NTA films as received from the manufacturer (line 2).

The NTA films were first calibrated at Y-12 using a ^{210}Po-Be neutron source (Struxness 1949a, p.7; Struxness 1953, p. 31) and later a ^{241}Am-Be neutron source (UCNC 1963, p. 19; McLendon 1963, p. 85; McRee, West and McLendon 1965, p.77). The film badge dosimeters containing the NTA films were exposed free in air (no phantom) to neutrons from the Po-Be or Am-Be source for pre-selected times to produce a range of track densities from neutron doses similar to those normally encountered in the workplace. Studies of backscattering from phantoms used to represent the human body have found an increase in track densities from reflected neutrons ranging from a low of zero to a high of

33% (Thomas et al. 1997, p. 3). To better define the effect of reflected neutrons on track density in NTA films exposed on a phantom, the National Physical Laboratory in England made a study using two different phantoms, two different neutron sources (^{252}Cf and ^{241}Am-Be), and two different track readers (Thomas et al. 1997, pp. 6-10). There was a systematic difference between the two track readers of about 10%; however, this difference was roughly the same for all irradiation conditions and the ratios determined by the two readers typically agreed to within about 3%. The final mean ratios from the different track readers suggested that the reflected neutrons added only about 5% on the average to the track reading of the NTA film and that there was no significant difference between the responses for NTA films calibrated with or without the use of a phantom (Thomas et al. 1997, pp. 6-10).

The NTA films were also calibrated with neutrons that were perpendicularly incident on the face of the film badge dosimeter and NTA film contained inside the film badge (Struxness 1949a, pp. 20-22; McLendon 1963, pp. 75-76; McRee, West and McLendon 1965, pp. 85-87). In most workplace environments, however, the neutrons are incident on the film badge and NTA film at widely variant angles. The angular dependence of NTA films has been studied experimentally by Kathren, Prevo, and Block (1965) and they suggest that multiplication of the tracks produced by perpendicularly incident neutrons from a calibration source should be multiplied by a factor of 0.75 to avoid the underestimation of the neutron dose to workers in most typical workplace environments. This is equivalent to multiplying the recorded neutron dose from a worker's NTA film by a factor of 1.3 (1 divided by 0.75). It is recommended, therefore, that dose reconstructors apply this factor to all recorded NTA film dosimeter results for Y-12 workers and an additional factor to account for the missed neutron dose due to the so-called energy threshold of the NTA film (ORAUT 2006). The threshold energy of the NTA film for fast neutron detection is typically quoted as having values ranging from 0.5 to 0.7 MeV (ORAUT 2006, Table 3-1, p. 10). A favorable to claimant value of 0.7 MeV is assumed in this report for the energy threshold of the NTA film.

The minimum detectable limit (MDL) depends on a number of parameters including the number of fields used in the evaluation of the neutron-produced recoil ion density of the exposed film and the energy of the neutrons used in calibrating the NTA film (Thomas, Horwood, and Taylor 1999; IAEA 1985, pp. 63-71). The minimum detectable limit (MDL) of the NTA film based on laboratory calibrations at the Y-12 Plant using ^{210}Po-Be or ^{241}Am-Be neutron sources is estimated to be approximately 50 mrem. In workplace exposure situations, the MDL could be much larger than 50 mrem because the NTA film responded only to fast neutrons with energies greater than the energy threshold of the NTA film as illustrated in Figure 3.2 (also see IAEA 1985, p. 64). 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 3.2 (NCRP 1971, also see IAEA 1990, p 15, Table 2-II). If a person was exposed in an area with a highly degraded spectrum of neutrons, then a significant part of the neutron dose below the effective 0.7-MeV threshold of the NTA film might have been undetected, and the MDL could have been larger than 50 mrem. Thus, it is important to correct a worker's recorded neutron dose for the missed neutron dose from neutrons with energies less than the measured or assumed energy threshold of the NTA film (ORAUT 2006).

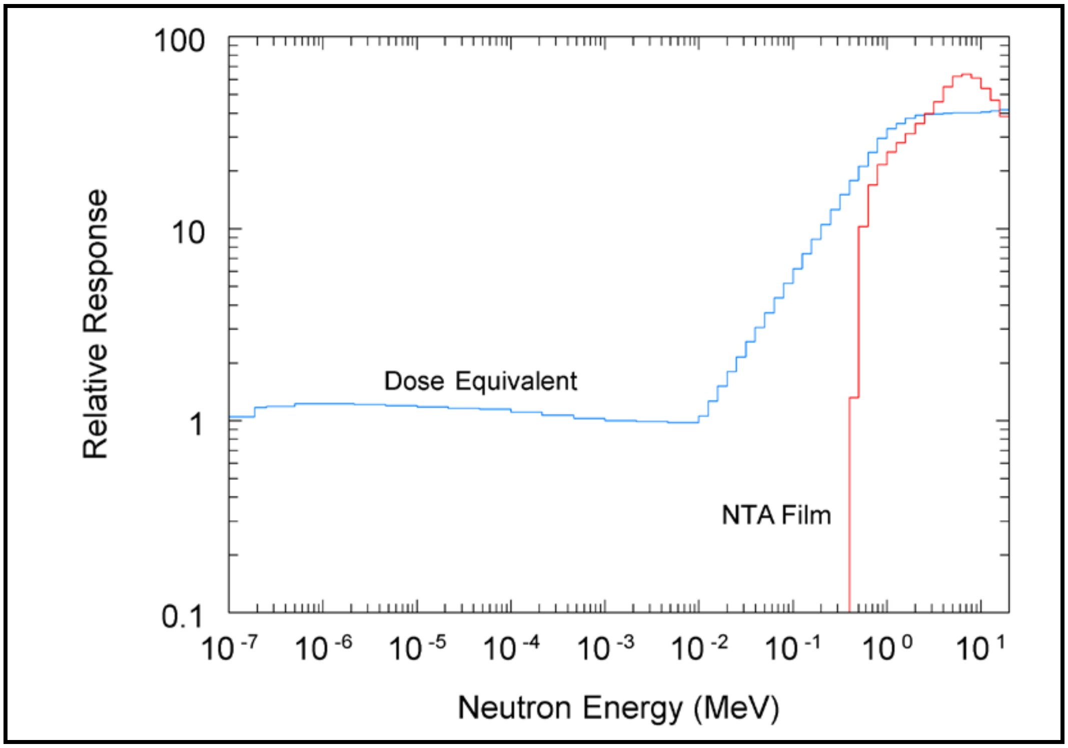

Figure 3-2. Comparison of dose equivalent (NCRP 1971) and NTA film energy response (IAEA 1985) for a beam of normally incident neutrons.

3.1 Y-12 AND ORNL MANAGED FACILITIES IN THE Y-12 AREA

After the Y-12 Plant transitioned from an electromagnetic uranium-enrichment plant to a weapon-component manufacturing plant (Williams 1948), its research divisions were transferred to ORNL and increased their staff by about 50% (Quist 2000, p. 21). These research divisions allowed everyone and everything to stay pretty much in place, but the former Y-12 researchers in these divisions now reported directly to ORNL management (Johnson and Shaffer 1994, pp. 63-64). The Y-12 buildings that were placed under ORNL management included: 9201-2 Thermonuclear or Fusion Energy Division (from Y-12 in 1951); 9201-3 Reactor Design and Engineering Development (from Y-12 in 1950); 9204-3 Electronuclear Research Division (from Y-12 in 1951); 9213 Criticality Experiments Facility (from Y-12 in 1949); 9207, 9210 Biology Division (from Y-12 in 1947); and 9204-3 Isotopes Research and Production Division (from Y-12 in 1951) (Markowitz et al. 2004, p. V-30; Quist 2000, p. 21; Johnson and Shaffer 1994, p. 63-64).

Building 9213 is located at a remote site in the southwest portion of the Y-12 Plant Site in a pocket formed by surrounding hills (UCC 1962, pp. 14-21; Stapleton 1992, p. 27). The building was constructed in 1946 for the storage of highly enriched uranium (HEU) while awaiting shipment from the Y-12 site and was expanded in 1949 to serve as a Criticality Experiments Facility (CEF) (Auerbach 1993, pp. 87-88). Prior to the construction of the CEF, several experimental criticality studies were carried out at the Oak Ridge Gaseous Diffusion Plant (K-25 Plant) and ORNL sites (UCC 1967, pp. 11-12). The inadequacy of the facilities at ORNL and K-25 was recognized in 1949 due to the expected demands for further experimentation dealing with (1) the safety of metallurgical and chemical processes and (2) the support of new reactor designs (UCC 1967, pp. 2-4). The latter need was further emphasized by an Oak Ridge program aimed at the development of nuclear propulsion for aircraft (Johnson and Schaffer 1994, pp. 58-63). It was decided, therefore, that a laboratory adequate for a wide variety of criticality studies be established, that the various criticality studies in Oak Ridge be combined, and that the work be managed by ORNL (UCC 1967, pp. 2-4). Critical and near-critical experiments began at the CEF in late August and early September 1950 (Struxness 1951a, p. 11; UCC 1967; pp. 2-4).

Because of established policies in 1950, it was decided at a June 14th meeting that the Y-12 Health Physics Department was to provide necessary auxiliary services for the CEF located in Building 9213 (CCCC 1950). These services were to include air sampling, surface contamination checking, area monitoring, and personal monitoring for both internal and external radiation exposure (CCCC 1950). The personal monitoring devices for external radiation exposure were to include neutron and gamma film badges, thermal neutron dosimeters, gamma pocket chambers, film rings for monitoring hand exposures to gamma and beta radiation, and hand counters for alpha radiation (CCCC 1950). The health physics services provided this facility required one full time Y-12 health physicist (Struxness 1951a, p. 11). Similar services were also provided at other ORNL buildings in the Y-12 area until July 1954 when the ORNL Health Physics Division assumed responsibility for the radiation monitoring of all ORNL personnel working at Y-12 (West 1956).

The administrative and service responsibility for ORNL employees working in the Y-12 area was addressed further in a 1958 Y-12 Plant Bulletin numbered AR-213 (Murray 1958, p. 3). This bulletin states: "Whenever processes involving radioactive materials are carried out in the Y-12 Area under the supervision of ORNL, the Laboratory shall assume responsibility for maintaining proper controls over all health physics problems which may arise, including the problem of detecting such hazards. Likewise whenever any phase of a Laboratory project is performed under Y-12 supervision, the Y-12 Health Physics Group will have sole responsibility for establishing the criteria for adequate employee protection, and shall conduct all necessary investigations. If personnel from both plants are involved in some particular Laboratory project, the investigating Health Physics Group will report all personnel-monitoring results to the Health Physics Group of the other plant." An ORNL Badge Office (Morgan and Davis 1965, p. 55) and four ORNL Health Physics Offices (Copenhaver et al. 1986, p. 12) were opened at Y-12 site to serve visitors and staff members at ORNL facilities located in the Y-12 area. While some Y-12 workers were used in the operation of the ORNL managed facilities in the Y-12 area, these facilities were minor sources for neutron exposures to Y-12 workers.

Table 3-1 provides a summary of the major and minor sources of neutron exposures to Y-12 workers at Y-12 and ORNL Buildings in the Y-12 area during the film badge period from 1950 to 1980. The major sources for neutron exposures to Y-12 workers were at facilities under Y-12 management with one exception. This one exception was the Oak Ridge 86-Inch Cyclotron which was originally built and operated by Y-12, but was placed under the management of ORNL in the early 1950s. All other facilities at Y-12 that were operated under ORNL management are classified as minor sources of neutron exposure to Y-12 workers in Table 3-1. For example, the U.S. Air Force agreed in March 1949 to purchase a 5-MeV Van de Graff accelerator for use in the Aircraft Nuclear Propulsion (ANP) project if ORNL would construct a permanent building to house it (Johnson and Schaffer 1994, pp. 65-67). This accelerator was temporarily housed in the east wing of Y-12 Building 9201-2 for about one and one-half years (Kerr 2007). In 1952, ORNL completed construction of the High Voltage Laboratory and moved the 5-MeV Van de Graff accelerator plus two other existing linear accelerators into the newly constructed High Voltage Laboratory (Building 5500) at ORNL (Johnson and Schaffer 1994, pp. 65-67; Snell and Wollan 1953, pp. 1 and 17). Thus, the ORNL Technical Basis Document on External Occupational Dose (ORAUT 2007b) should be consulted for data that can be used in the dose reconstruction for Y-12 workers who may have been exposed to neutrons while working at ORNL facilities listed in Table 3-1 as minor sources for neutron exposures during the film badge period from 1950 to 1980. Some information on these so-called minor sources for neutron exposure to Y-12 workers is provided by the references in the footnotes to Table 3.1.

Table 3-1. Major and minor sources for neutron exposures of Y-12 workers during the film badge period from 1950 to 1980.

Building	Location	Neutron sources
Major sources for neutron exposures of Y-12 workers		
9201-2[a]	West Wing	86-inch cyclotron (1950–1961), Po-Be neutron sources
9202, 9206, 9212[b]	Chemical Operations	(α,n) reactions in storage containers of highly enriched uranium fluoride and oxide compounds, Pu-Be source neutrons
9203[c]	Room 8, Assay Laboratory, Development Facility	Ra-Be, Po-Be neutron sources
9204-3[d]	D-D Project , Beta-3 Building	2 MeV neutrons from (d,d) reaction (1949–1950), Po-Be neutron sources
9205[e]	Assay Laboratory, Development Laboratories	Ra-Be, Po-Be neutron sources
9983[f]	HP Calibration Laboratory	Am-Be, Am-B neutron sources plus storage of other neutron sources
Minor sources for neutron exposures of Y-12 workers		
9201-2[g]	West Wing	86-inch cyclotron (1962–1983)
9201-2[h]	East Wing	5-MeV Van de Graff accelerator (1951–1952)
9201-2[i]	Fusion Energy Division	Fusion energy neutrons, Am-Be neutron sources
9204-3[j]	Beta-3 Building, Physics Division	63-inch cyclotron (1952–1961), Po-Be neutron sources
9207[k]	Biology Division	250-kV Cockcroft-Walton particle accelerator, PoBe neutron sources
9213[l]	Critical Experiments Facility	Fission energy neutrons (1950–1987), Po-Be, Pu-Be neutron sources, 150-kV Cockcroft-Walton particle accelerator
9983-17[m]	Trailer, Biology Division	1,000 µg Cf-252 fission-neutron source

a. Struxness (1951a, pp. 7-10), Struxness (1951b, pp. 17, 23-24), Livingston and Boch (1952), Livingston and Martin (1952), Ballenger (1952, pp. 36-42), Struxness (1953, pp. 22-25), Johnson and Schaffer (1994), Kerr (2007).
b. Roberts (1964, Attachment I), DOE (2004, Section 2, pp. 19-20), ORAUT (2005b).
c. Dahl (1946), Struxness (1949b, p. 6), Struxness (1951a, pp. 7-8).
d. Struxness (1949a, p. 6); Shipley and Livingston (1949a, pp. 7,11), Shipley and Livingston (1949b, pp. 5, 25), Shipley and Livingston (1950, pp. 5, 22), Livingston (1950, p. 6), Struxness (1951a, pp. 7-8).
e. Struxness (1949a, p. 6), Struxness (1951a, p. 7-8), Sanders (1956).
f. Struxness (1949a, p. 6), Struxness (1951a, p. 7-8), McRee (1960, 1961), UCNC (1963, p. 19), McLendon (1963, p. 85), Roberts (1964, Attachment I), McRee, West, and McLendon (1965, p. 77), Souleyrette (2003a, p. 2).
g. Livingston and Zucker (1962, p. 30), Livingston and Zucker (1963, p. 35), Butler (1963), Terry (1981), Auxier and Davis (1981, p. 84), Kerr et al. (1992, pp. 44-47), Johnson and Schaffer (1994), Tankersley (2009).
h. Ellis (1950, pp. 7, 44), Nielsen and Ellis (1950, pp. 233, 235), Ellis and Cottrell (1951, pp. 92-95), Struxness (1951b, pp. 23), Ballenger (1952, p. 43, 68), Good (1952, p. 1), Roberts (1952, pp. 2, 17-18), Shull (1952, pp. 1, 25), Snell and Wollan (1953, p.1), Copenhaver et al. (1986, p. 100), Johnson and Schaffer (1994), Kerr (2007).
i. Berry et al. (1975), Kim and Mihalczo (1979), Copenhaver et al. (1986, p. 113).
j. Ballenger (1952, p. 43), Livingston and Zucker (1962, p. 30), Livingston and Zucker (1963, p. 35), Johnson and Schaffer (1994, pp. 67-700), Kerr (2008a).
k. Slaughter (1953, p. 71), Struxness (1954, p. 16), Hollaender (1954, p. 72), Slaughter (1955, pp. 130-131), Carson (1956a, pp. 57-58), Carson (1956b, p. 61), Kerr (2008b).
l. Struxness (1951b, p. 17-22), Blizard et al. (1961, pp. 173-174), UCC (1962, pp. 3-11, 30-46), UCC (1967, pp. 56-70), Roberts (1964, Attachment I), ORAUT (2007c, pp. 41-42).
m. Adler and Carson (1972, p. 144), ORAUT (2007c, p. 39), Kerr (2008b).

3.2 Major Sources for Neutron Exposures to Y-12 Workers

The major sources for neutron exposures for Y-12 workers in Table 3-1 are characterized in this section using parameters of interest in the dose reconstructions for Y-12 workers (NIOSH 2007). These parameters include: (1) the neutron-to-gamma dose ratios for exposures to these various sources, (2) the missed neutron dose due to the angular response and assumed 0.7-MeV threshold energy of the NTA film dosimeters, and (3) the energy spectrum of the neutrons incident on a worker during exposure to one of these sources.

The neutron energy spectra used in dose reconstruction for workers is typically divided into the following five energy groups: <10 keV, 10-100 keV, 0.1-2 MeV, 2-20 MeV, and >20 MeV (NIOSH 2007, p. 19). The Radiation Effectiveness Factors used in NIOSH-IREP (NIOSH 2002) for calculating the POC are less for the lower two energy groups of <10 keV and 10-100 keV than for the 0.1-2 MeV energy group (NIOSH 2002; Kocher, Apostoaei, and Hoffman 2005). Thus, the two lower energy groups of <10 keV and 10-100 keV are combined with the 0.1-2 MeV group throughout this OTIB. The 0.1-2 MeV group is a substantial neutron component in each workplace, and it alone can be used (i.e., assigned 100%) as an analysis that is favorable to claimants when calculating their POC using NIOSH-IREP (NIOSH 2002, p. 31).

3.2.1 86-Inch Cyclotron

The Oak Ridge 86-Inch Cyclotron is treated here as a major source of neutron exposure to Y-12 workers from 1950 to 1961 because several Y-12 Departments were involved in the early operation of the cyclotron and the production of radioisotopes at the cyclotron (Bloch 1951). The need for a cyclotron in the Oak Ridge area was discussed as early as 1946 (Livingston and Boch 1952, pp. 7-8). The availability of large magnetic and vacuum components at the Y-12 Plant greatly simplified the planning of the 86-inch cyclotron and facilitated its fabrication (Johnson and Schaffer 1994, pp. 65-70). 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, p.10). The early operation of the 86-inch cyclotron was a cooperative Y-12 and ORNL effort (Johnson and Schaffer 1994, p. 67; Kerr 2007). Ground was broken for the magnet footings on September 21, 1949, and the machine was ready for test operations the following September (Livingston and Boch 1952, p. 7-8). The 86-inch cyclotron became operational in November 1950, and the first proton beam was observed on November 11, 1950 (Livingston and Boch 1952, p. 7-8). 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 1 milliampere at proton energies of 20 MeV were possible (Livingston and Boch 1952, pp. 7-8).

The first major use of the 86-Inch cyclotron was the production of ^{208}Po (Livingston and Martin 1952, p. 5; Butler 1963, p. 17; Kerr 2007). In 1952, internal revisions of the position and mounting of the ion source resulted in an increase in proton energy to 23 MeV (Livingston and Martin 1952, p. 50). At the higher energy, the ^{208}Po yield was more than doubled and a total of approximately 9 Ci of ^{208}Po was produced before the project was terminated in August 1952 (Livingston and Martin 1952, pp. 22-23; Butler 1963, p. 17). During the next few years, the groundwork was laid for the production of neutron-deficient radioisotopes (Butler 1963, p. 17). From 1952 to 1961, however, the 86-Inch cyclotron was used mainly in nuclear physics studies by the ORNL Electromagnetic Research Division (Howard 1954; Livingston 1958), and isotope production time was made available only when it did not interfere with the primary program (Butler 1963, 17). 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 December 1 from the ORNL Electronuclear Research Division to the ORNL Isotope Division (Livingston and Zucker 1962, p.35). The 86-inch cyclotron was used primarily by ORNL for production of medical radioisotopes until it was shut down permanently in 1983 (Kerr et al. 1992, pp. 44-47; Tankersley 2009).

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, Slaback, and Birky 1998, p. 11-71, Table 11.4.11). The shielding for the 86-Inch Cyclotron consisted of 5-ft-thick concrete walls supporting a 5-ft-thick concrete ceiling (Livingston and Boch 1952, pp. 88-89). Two mazes were the only openings into the cyclotron vault (Livingston and Boch 1952, p. 90). Measurements made in early 1950 indicated the presence of an excessive stray neutron flux outside the maze entrance and the emergency maze exit to the 86-inch cyclotron (Struxness 1951b, pp. 23-24; Ballenger 1952, pp. 37-38; Livingston and Boch 1952, p. 91). A completely enclosed cyclotron vault with a minimum of apertures and movable doors with overlapping side panels became the standard shielding design for other early cyclotrons producing high-energy proton beams (Patterson and Thomas 1973, p. 380). A maximum permissible flux of 250 n/cm^2-s was established to limit the neutron exposure of personnel at the Oak Ridge 86-Inch Cyclotron to less than 300 mrem per 40-hr workweek, which was the radiation protection guideline at that time (Wiley 2004; ORAUT 2007a, p. 14). The measured neutron flux in most occupied areas outside the shielding for the cyclotron was typically smaller than the maximum permissible flux of 250 n/cm^2-s by one to two orders of magnitude (Livingston and Boch 1952, p. 91; Howard 1952, p. 38; Ballenger 1952, p. 12).

The neutron energy spectra in work areas near the Oak Ridge 86-Inch Cyclotron, like the neutron energy spectra near other early proton accelerators, are not well known (IAEA 1988). To simulate the stray neutron fields near the Oak Ridge 86-Inch Cyclotron, 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 is the neutron energy. Table 3-2 lists the dose fractions in the neutron energy groups used in the dose reconstruction for Y-12 workers; the results 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 3-2 suggest that neutrons with energies less than 0.1 MeV and neutrons with energies from 14 to 20 MeV contribute only 12% and 8.7%, respectively, to the total neutron dose equivalent in the stray radiation fields at the 86-Inch Cyclotron. Therefore, combining the dose from these five neutron energy groups into only two neutron energy groups is reasonable and favorable to claimant simplification of the neutron dose reconstruction for Y-12 workers (Table 3-2).

Table 3-2. Estimated dose fractions for exposure to neutrons from the 86-inch cyclotron (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
Favorable to claimant dose fractions	
0.1–2 MeV	0.46
2–20 MeV	0.54

The fraction of the dose equivalent from neutrons below the effective threshold energy of 0.7 MeV for the NTA film was calculated to be approximately 30% (ORAUT 2006, p. 12, Fig. 4-3). Thus, an estimated correction factor to the recorded neutron dose for missed neutron dose due to the threshold energy of the NTA film should be approximately 1.4 (1 divided by 0.7) and the total correction factor for both the estimated missed neutron dose due to threshold energy and angular response of the NTA film should be approximately 1.8 (1.4 multiplied by 1.3) (ORAUT 2006, p. 18, Table 8-1).

3.2.2 Encapsulated Neutron Sources

Encapsulated sources that produced neutrons by alpha particle reactions with boron or beryllium provide a convenient source of neutrons for a variety of applications (Rees 1967, pp. 44 and 176). Table 3-3 provides some information on locations at the Y-12 Plant, where such sources were used (Buildings 9201-2, 9202, 9203, 9204-3, 9205, 9212, and 9983). Additional locations at the Y-12 Plant where encapsulated neutron sources were used include: Building 9737 (Struxness 1951a, pp. 7-8); Buildings 9204-1, 9734, and 9771 (Emerson 1952); and Buildings 9204-2 and 9987 (McRee 1960, 1961; Roberts 1964, Attachment I). These neutron sources were stored in accordance with accepted practices (Struxness 1951a, p. 7). They were surrounded by hydrogenous material, such as paraffin or water, which degraded the energetic fast neutron component by proton scattering, and the resulting slow (thermal) neutrons were then captured by various chemical elements in the scattering medium. For many of the larger sources, it was customary to enhance the probability of neutron capture in the scattering medium by addition of borax (Struxness 1951a, p. 7). Consequently, once the handing procedures for an encapsulated neutron source were established, the services provided by the Health Physics Department evolved into routine periodic checks. Instrumentation calibration with Po-Be, Am-Be, and Am-B sources was also a standardized operation in that the majority of calibrations were made at one location, and usually, by the same operator. Any unusual operations or transfers involving encapsulated neutron sources were done under the supervision of the Health Physics Department (Struxness 1951a, p. 7).

One unusual situation at the Y-12 Plant was the use of five large Ra-Be neutron sources in the Assay Laboratories of the Development Facility (Building 9203) and Development Laboratories (Building 9205) (Struxness 1949b, p. 6; Struxness 1951a, p. 8). These sources were contained in four so-called “Dog Houses” in Room 8 of Building 9203 (Dahl 1946; Struxness 1949b, p. 6; Struxness 1951a, p. 8; Emerson 1952) and the so-called “Birdbath Moderator” in Building 9205 (Struxness 1949b, pp. 6; Sanders 1956). In 1955, NTA films were included in the film badge dosimeters of all Department 2159 personnel (Alloy Maintenance), who were assigned to maintenance of assay monitors containing the Ra-Be sources (West 1955; Sanders 1956). These NTA film badges were exchanged every other week or biweekly (West 1955). Very little is known about the construction of the “Birdbath Moderator” in Building 2159, but there is detailed information available on the “Dog Houses” in Building 9203 (Daul 1949). The Ra-Be source was located at the center of a cylinder that provided about 12 in. of water shielding in the radial direction. The cylinder had a 17-in. outer radius, a 17-in. outer height , and an outer wall thickness of 0.125 in. of iron (Daul 1949). There were six ports in each cylinder so that the assay samples could be placed near the Ra-Be source at its center. The “Dog Houses” were placed near a wall in Room 6 of Building 9205 with a distance of about 80 in. between the centers of the water-filled metal cylinders (Daul 1949). Available records indicate that Ra-Be neutron sources from these Assay Laboratories were placed in permanent storage in the late 1950s (McRee 1960; 1961; Roberts 1964, Attachment I). The permanent storage area for excess neutron and photon sources was the Radioactive Source Storage Facility in Building 9987 (TAPP 2003, pp. 133-134).

Information on the neutron spectrum in work areas near the “Dog Houses” and “Birdbath Moderator” is not available. Thus, the neutron fields from these sources are simulated by the use of recent measurements made at a distance of 24 inches from the surface of a water filled drum containing both a ^{238}Pu-Be and ^{252}Cf encapsulated neutron source (Soldat et al. 1990, p. A.5; MMES 1992; ORAUT 2007b, pp. 27-28). The characterization of the neutron field consisted of measurements of the energy spectrum of the neutrons and the personal dose equivalent from both neutrons and gamma rays. The neutron-to-gamma dose ratio was approximately 3.7 (ORAUT 2007b, p. 27), and the neutron spectrum is provided in Table 3-3 using the following four neutron energy groups: <10 kev, 10-100 kev, 0.1-2 MeV, and 2-20 MeV (ORAUT 2007b, p. 28). The results in Table 3.3 suggest that neutrons with energies less than 0.1 MeV contribute only 2.1% to the total neutron dose equivalent. Therefore, combining the dose from these lower neutron energy groups with the nearby neutron energy group of 0.1-2.0 MeV provides a reasonable and favorable to claimant simplification of the dose reconstruction for Y-12 workers. The fraction of the dose equivalent from neutrons with energies less than the assumed effective threshold energy of 0.7 MeV for NTA film was also estimated to be approximately 20% based on the neutron spectrum data for the water-shielded ^{238}Pu-Be and ^{252}Cf sources (ORAUT 2007b, p. 28). Thus, the estimated correction to the recorded neutron dose for missed neutron dose due to the threshold energy of the NTA film should be approximately 1.3 (1 divided by 0.8) and the total correction factor for missed neutron dose due to both the threshold energy and angular response of the NTA film should be approximately 1.7 (1.3 multiplied by 1.3). It is important to note here that the ^{238}Pu-Be and ^{252}Cf sources were also shielded by 12 in. of water (Soldat et al. 1990, p. A.5). In addition, the neutron output of the Cf source was 2×10^7 n/sec, while that of the Pu-Be source was an order of magnitude larger or 2×10^8 n/sec (Soldat et al. 1990, p. A.5). Thus, these measurement results should provide a realistic simulation for use in the dose reconstruction for Y-12 workers who were exposed to neutrons from the Ra-Be sources in Buildings 9203 and 9205.

Table 3-3. Estimated dose fractions for exposure to water-shielded Ra-Be neutron sources (Buildings 9203 and 9205).

Neutron energy group	Dose fraction
<10 keV	0.013
10–100 keV	0.008
0.1–2 MeV	0.264
2–20 MeV	0.715
Favorable to claimant dose fractions	
0.1–2 MeV	0.29
2–20 MeV	0.71

Another storage facility for encapsulated neutron and photon sources at Y-12 was located at the HP Calibration Laboratory in Building 9983 (Soldat et al. 1990, p. 3.6; MMES 1992; ORAUT 2006, pp.8-9). The neutron field in this storage area was simulated by the use of recent measurements made at a distance of 18 inches of the storage safe located in one corner of the Calibration Laboratory. At the time of the measurements, the neutron sources were being stored in the room in shielded containers. The types of neutron sources in the room included twelve 2- to 4-Ci Am-B sources, several Am-Li sources, and several Am-Be sources. The safe also contained a ^{252}Cf source (Soldat el al. 1990, p. 3.22). The characterization of the neutron field near the safe included measurements of the energy spectrum of the neutrons and the personal dose equivalent from both neutrons and gamma rays (MMES 1992). The neutron-to-gamma dose ratio was approximately 8 and the neutron spectrum has been summarized in Table 3-4 using the following four energy groups: <10 keV, 10-100 keV, 0.1-2 MeV, and 2-20 MeV. The results in Table 3-4 suggest that neutrons with energies less than 0.1 MeV contribute only 6.2% to the total neutron dose equivalent. Therefore, combining the dose from these lower energy groups with the nearby neutron energy group of 0.1-2 MeV is a reasonable and favorable to claimant simplification of the dose reconstruction for Y-12 workers. The fraction of the dose equivalent from neutrons with energies less than the assumed effective threshold energy of 0.7 MeV for NTA film was also estimated to be approximately 40% (ORAUT 2006, p. 13). Thus, the estimated correction to the recorded neutron dose for missed neutron dose due to the threshold energy of the NTA film should be approximately 1.7 (1 divided by 0.65) and the total correction factor for missed neutron dose due to both the threshold energy and angular response of the NTA film should be approximately 2.2 (1.7 multiplied by 1.3).

Table 3-4. Estimated dose fractions for exposure to neutron sources stored at the HP Calibration Laboratory (Building 9983).

Neutron energy group	Dose fraction
<10 keV	0.055
10–100 keV	0.007
0.1–2 MeV	0.509
2–20 MeV	0.429
Favorable to claimant dose fractions	
0.1–2 MeV	0.57
2.0–20 MeV	0.43

3.2.3 Chemical Operation Areas

From about 1949 to 1964, the Y-12 Plant received cylinders of uranium hexafluoride (UF_6) containing highly enriched uranium as feed material for the manufacture of nuclear weapons components (ORAUT 2007d, p. 15). After 1964, the majority of enriched uranium processed at Y-12 was recycled uranium materials from nuclear weapons stockpiles (Owings 1995, pp. 22-23). These operations were confined primarily to Buildings 9202, 9206, and 9212 (ORAUT 2007d, p. 15). The recycled uranium contained transuranic material (e.g., plutonium and neptunium-237), fission products (e.g., technetium-99), and reactor-generated products (e.g., uranium-236) (BWXT Y-12 2000, Section 1, p. 1). Recycled uranium process streams involved the processing of other material forms including uranium metal, uranium alloys, and other uranium compounds such as UO_2, UO_3, and UF_4 (ORAUT 2007d, p. 15). The interaction of alpha particles from uranium with nuclei of fluorine, oxygen, and other low-atomic weight atoms generates neutrons with energies of approximately 2 MeV (DOE 2004, Section 6, pp. 4-10). The magnitude of the neutron flux varies based on total activity of the uranium (a function of enrichment) and chemical compound in question (mixing of uranium with fluorine or oxygen). In the case of UF_6, the typically measured neutron dose equivalent rates for storage containers are as follows (DOE 2004, Section 2, p. 19):

Natural to 5% enrichment:	0.01 to 0.2 mrem/hr,
Very high enrichment (97%+):	2 to 4 mrem/hr (contact) 1 to 2 mrem/hr (3 ft).

The potential for significant worker exposure 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 near storage or processing areas for large quantities of those materials (DOE 2004, Section 2, p. 19). At very high ^{235}U enrichments, the neutron-to-gamma dose ratio can be as much as 2:1 and neutrons can be the limiting radiation source for whole-body exposure (DOE 2004, Section 6, p. 8). The neutron doses from low enriched ^{235}U compounds or from uranium metals are considerably lower than the gamma-ray component and consequently are not limiting doses (DOE 2004, Section 6, p. 8).

The neutron fields in chemical processing areas of the Y-12 facility were simulated by the use of recent measurements made in Building 9212 at the Y-12 facility (Soldat et al. 1990, p. 3.6; MMES 1992). At the time of the measurements, this storage area in Building 9212 held storage containers of both enriched uranium fluoride (UF_4) and uranium trioxide (UO_3). Containers of these materials were placed on a rack of shelves and arranged in a matrix that was critically safe (Soldat et al. 1990, p. 3.6; MMES 1992). The measurements were made at a height of 39 in. (1 m) above the floor and 27 in. from the nearest container. The location of the measurements was also selected so that it was near only containers of UF_4 (Soldat et al. 1990, p. 3.6; MMES 1992). The characterization of the neutron field consisted of measurements of the energy spectrum of the neutrons and personal dose equivalent from both neutrons and gamma rays. The measured values for neutron dose equivalent and neutron-to-gamma dose ratio were 1.65 mrem/hr and 1, respectively, which are in good agreement with the above quoted values from the *Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities* (DOE 2004, Section 2, p. 19). The results of the neutron spectrum are summarized in Table 3-5 and suggest that the neutrons with energies less than 0.1 MeV and energies greater than 2 MeV contribute only 3% to the total neutron dose equivalent. Therefore, assigning all of the neutrons to the 0.1- to 2-MeV energy group is a reasonable and favorable to claimant simplification of the dose reconstruction for Y-12 workers. The fraction of the dose equivalent from neutrons with energies less than the assumed 0.7-MeV threshold energy of the NTA film is estimated to be about 40% (ORAUT 2006, p. 13). Thus, an estimated correction factor to the recorded dose for missed neutron dose due to the threshold energy of the NTA film should be approximately 1.7 (1 divided by 0.6) and the total correction factor for the missed neutron dose due to both the threshold energy and angular response of the NTA film should be approximately 2.2 (1.7 multiplied by 1.3).

Table 3-5. Dose fractions for exposure to neutrons from highly enriched uranium compounds (Buildings 9202, 9206, 9212).

Neutron energy group	Dose fraction
<10 keV	0.012
10–100 keV	0.003
0.1–2 MeV	0.970
2–20 MeV	0.015
Favorable to claimant dose fractions	
0.1–2 MeV	1.00

The monitoring of workers in the UF_4 (fluid-bed) processing areas of the Y-12 Plant has been cited as an example of a group of workers who were involved in hands-on operations of neutron-producing materials and should have been monitored for fast- and thermal-neutron exposures during the film badge era (SCA 2005, p. 75). It was speculated that their exposures may have been due mainly to thermal and epithermal neutrons, and therefore, their neutron doses would not have been measured using NTA films (SCA 2005, p. 75). In the 1990s, however, workers in UF_4 (fluid-bed) processing areas were monitored for neutron exposure using thermoluminescent neutron dosimeters (TLNDs) (SCA 2006, p. 8). The TLNDs were extremely sensitive to thermal and epithermal neutrons (MMES 1992, Volume 1, Executive Summary, pp 1-6; Oxley 2001, p. 17) and have a MDL of the order of 10-20 mrem for exposures involving neutrons of all energies (Oxley 2001, pp. 17, 44-46; Souleyrette 2003a, p. 6). No positive doses were observed for these individuals, so the neutron monitoring for this group of workers was discontinued in the mid- to late-1990s (SCA 2006, p. 8). Data on all Y-12 employees monitored for neutrons over the 12-year period following the introduction of the so-called four-element TLND in January 1990 is provided in Table 3-6 (Souleyrette 2003b). It should be noted from the data in Table 3-6 that the cumulative annual neutron doses and average annual neutron doses were quite small for the Y-12 workers who were monitored using the four-element TLNDs during the 12-year period from 1990 to 2001.

3.2.4 D-D Project

In 1949 and 1950, the Beta calutrons in Building 9204-3 were investigated for use as a source of monoenergetic neutrons (Struxness 1949a, p. 3). The high positive ion current produced by a calutron made it particularly attractive when used to produce neutrons via the low-energy deuteron-

Table 3-6. Number of neutron monitored Y-12 workers, cumulative annual neutron dose, and average annual neutron dose for 12-year period following the introduction of the four-element TLND in 1989 (Souleyrette 2003b).

Year	Neutron monitored workers	Cumulative neutron dose (mrem)	Average neutron dose (mrem)
1990	82	1085	13.2
1991	64	463	7.2
1992	86	200	2.3
1993	215	343	1.6
1994	301	1,289	4.3
1995	165	116	0.7
1996	203	470	2.3
1997	38	10	0.3
1998	47	57	1.2
1999	141	121	0.9
2000	49	35	0.7
2001	73	55	0.8

deuteron (D-D) reaction (Shipley and Livingston 1949a, p. 7). Because the neutrons from this reaction are monoenergetic with energies of approximately 2.5 MeV and free of gamma rays, a D-D neutron source appeared to be useful for the determination of shielding attenuation data and measurement of the cross sections for inelastic scattering (Shipley and Livingston 1949a, p. 7). The maximum neutron output obtained using 40-keV deuteron ions incident on several different kinds of targets was approximately 1×10^9 neutrons/sec (Shipley and Livingston 1949b, p. 25; Livingston 1950, p. 45).

The total neutron output from all experiments was kept at a safe level by deliberately limiting the beam current (Shipley and Livingston 1949a, p. 9). No personnel were allowed within 20 ft of the neutron target source during experiments and no shielding was required (Shipley and Livingston 1949a, p. 9). The neutron counter used in the measurement of neutron output from a target consisted of a boron-lined proportional counter encased in a cylinder of paraffin (Shipley and Livingston 1949a, p. 11) and provided a nearly uniform sensitivity to neutrons with energies from 10 keV to 3 MeV (Hanson and McKibben 1947). The neutron counter was calibrated by placing a Po-Be neutron source at the position of the neutron producing target in the calutron (Shipley and Livingston 1949a, p. 11). The electronic pulses from the neutron counter were sent to a preamplifier that was connected to a metal cabinet containing the high voltage supplies, discriminator, scaler, and mechanical counter to provide a continuous readout of the neutron output from a target (Shipley and Livingston 1950, p. 24).

Neutron sensitive films were first added to the film badges of workers in 1949 with the inauguration of the D-D Project (Struxness 1949a). The monitoring of individual neutron exposures used special alpha emulsion films provided by the ORNL Health Physics Division, who also calibrated the film and estimated the neutron dose by counting the density of the neutron-produced recoil tracks in the exposed film. The neutron monitoring for this group of workers was highly developmental and the available results from the last calendar-year quarter of 1949 and first calendar-year quarter of 1950 appear to be inadequate for dose reconstruction purposes (Wiley 2005). The neutron monitoring results for the D-D workers are also not included in the external dose database discussed in the following section of this report (Section 4.0). A listing is available for the small group of individuals who participated in the D-D Project (Parsons 1949).

4.0 NEUTRON DOSES IN THE EXTERNAL DOSE DATABASE

Quarterly neutron doses in mrem were among the variables contained in the electronic files that the Y-12 site delivered to the Center for Epidemiologic Research 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 (ORAUT 2005a, pp. 14-15). Neutron doses in the files were summations of biweekly or monthly doses (or blanks) that are no longer available.

5.0 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 nondetect) 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 ensure that the calculated neutron-to-gamma dose ratios would be favorable to claimants. 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 $r_i^+ = n_i / g_i, I = m+1,...,N$, when the gamma dose is a nondetect and N is the number of quarters with data. If the gamma dose is a nondetect (i.e., left censored) then the ratio $r_i^+ = n_i / g_i^*$ is right censored (i.e., r^+ 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 $\{r_i \; I = 1,...,m; \; r_i^+ \; I = m+1,...,N\}$ is:

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

where $g(r;\mu,\sigma) = \exp[-½\left(\log 1 - \mu\right)^2 / \sigma^2]\left(\sqrt{2\pi}\ \sigma r\right)^{-1}$ is the probability density function for the lognormal distribution and G(r^+, μ,σ) 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 RDCT (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:

$$\hat{\mu} = \sum y_i / N, \hat{\sigma} = \left[\sum\left(y_i - \hat{\mu}_i\right)^2 / N\right]^{½}, where\ y_i = \log(r_i) \quad (3)$$

6.0 EVALUATION OF FILM BADGE DATA

6.1 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 could have arisen for two different reasons: (1) the worker was monitored with NTA film but all measured neutron doses during the quarter were less than the MDL; or (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. Table 6-1 summarizes the distribution of positive neutron quarterly doses and cumulative neutron doses by year, and Table 6-2 further summarizes the cumulative neutron doses by year and department of exposure.

Table 6-1. Quarterly neutron doses and cumulative neutron dose by year from 1952 to 1962.

Year	Number of employees	Number of positive neutron doses	Cumulative neutron dose (mrem)
1952	3	3	338
1953	3	3	434
1954	42	48	5,927
1955	57	99	17,631
1956	32	66	2,458
1957	34	76	1,650
1958	19	22	530
1959	19	54	3,009
1960	2	2	81
1961	0	0	0
1962	2	2	210
Total	143	375	32,268

Table 6-2. Cumulative neutron dose (mrem) by department and year from 1952 to 1962.[a]

	Year										
Dept.	**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				1,083
2091			50								50
2108			262	1,923	257	142	41	259			2,884
2158					288	168	12				468
2159				6,424	759						7,001
2160				2,556	33						2,589
2231			200			334					534
2260			50								50
2301				1,128	703	743	283	2,750			5,607
2303				1,016							1,016
2345										210	210
2616	18		2,552								2,570
2617			2,235	3,231							5,466
2618	320	340	50						66		776
2685				50							50
2687						60					60
2701							131				131
2703									15		15
2791					90						90
Total	338	434	5,927	17,631	2,458	1,650	530	3,009	81	210	32,268

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

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 A-1 and A-2 of Attachment 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 period, and only 7 departments had 10 or more workers with at least 1 positive quarterly neutron dose. Figure 6-5 is a lognormal quantile-quantile (Q-Q) plot of the (total) 375 positive quarterly neutron doses from all departments, including ML estimates of the lognormal parameters and additional summary statistics. The median quarterly neutron dose was 46 mrem, and only 41.6% of the quarterly neutron doses were greater than 50 mrem, with 191 quarterly neutron doses (50.9%) less than 50 mrem and 28 (7.5%) equal to 50 mrem.

Our study found that only a small fraction of the Y-12 workers had a significant potential for exposure to neutrons and that these exposures were confined to the period from 1950 to 1962 (see Table 6-1). This has been confirmed in another recent study by Markowitz et al. (2004). In their study, they found one additional positive neutron dose for the film badge period from 1950 to 1980 (Markowitz et al. 2004, Appendix B1, p. 7). By comparing their data in Table B-1 of Attachment B to our data in Table A-1 of Attachment A to this report, the one additional recorded positive neutron dose is found to be in so-called Department 2000. This department was a “catch-all department” to which individuals were assigned on a temporary basis for various reasons. The number of positive neutron doses in all other departments is in exact agreement (see both Table A-2 of Attachment A and Table B-1 of Attachment B).

6.2 NEUTRON-TO-GAMMA DOSE RATIOS

One problem in calculating 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 A-1 and A-2 of Attachment A). Whenever the corresponding quarterly gamma dose was greater than zero, Table A-1 presents the neutron-to-gamma dose ratios for the individual worker and quarter grouped by worker. Table A-2, under the same circumstances, shows these ratios grouped by department and reveals that there can be substantial variation in the neutron-to-gamma dose ratios 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 to calculate 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 6-1 to 6-5 present 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 nondetect), the neutron- to-gamma dose ratio is obtained by dividing the neutron dose by an MDL of 30 mrem for the quarterly gamma-ray doses and treating the ratio as right censored (see Section 5 for details). This procedure ensures that ratios derived from the available data in Tables A-1 and A-2 of Attachment A are favorable to claimant values. The percentage of nondetects or gamma doses equal to zero varied from a low of zero for Departments 2159 and 2160 (Figures 6-3 and 6-4) to a high of 41% for Department 2301 (Figure 6-5).

Figure 6-6 shows the neutron-to-gamma ratio based on the combined data for all 25 departments. The neutron-to-gamma ratio for all departments combined appears to be unreasonably large in comparison with the ratios for the four specific departments in Figures 6-2 to 6-5. It was determined that the unacceptably large value was due primarily to two departments, the Product Chemical Department (2616) and the 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

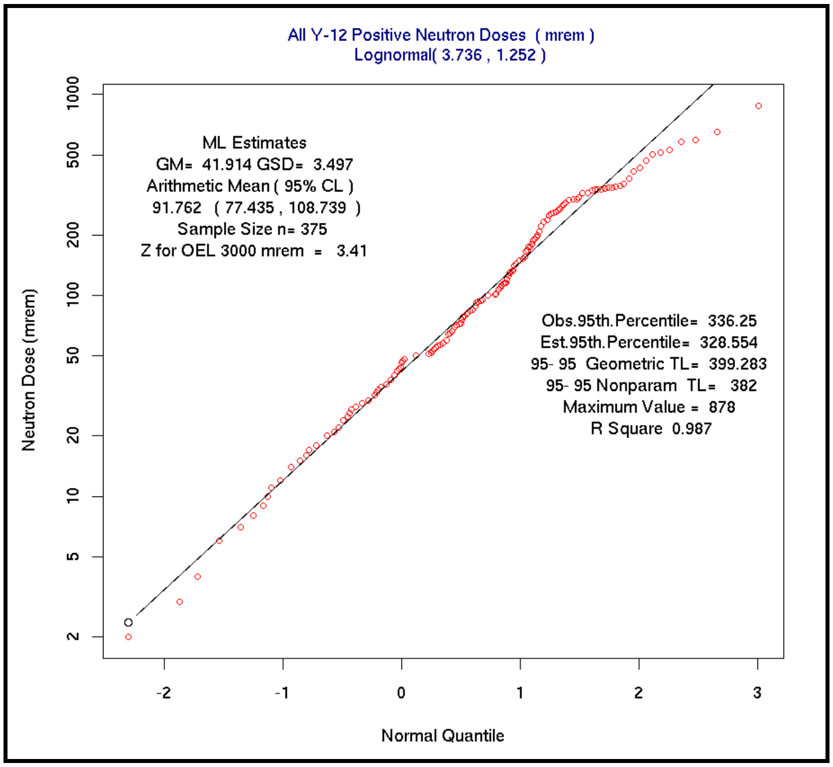

Figure 6-1. Lognormal Q-Q plot of neutron doses from all Y-12 departments.

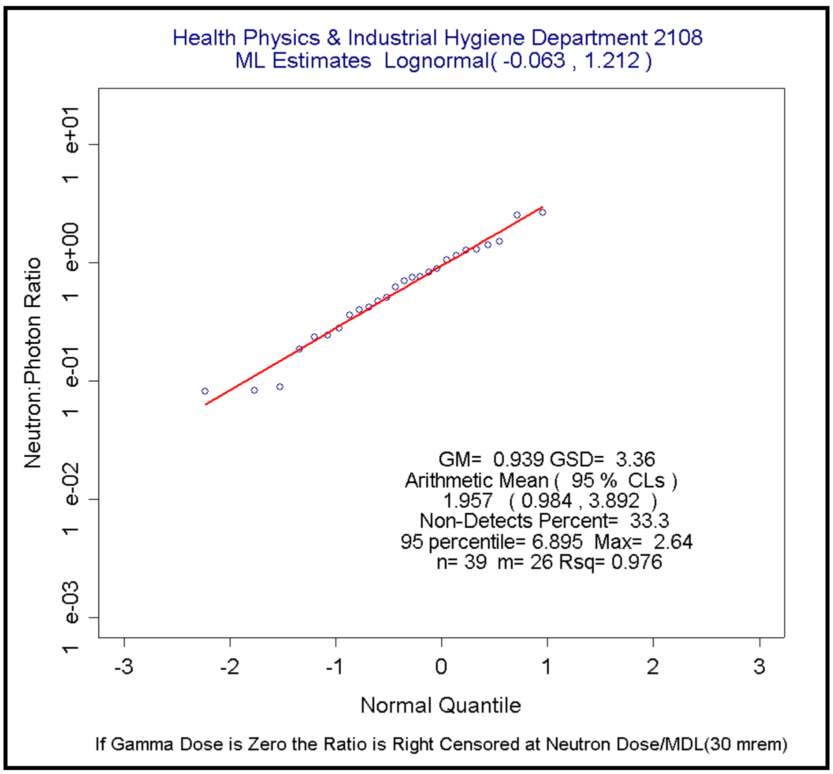

Figure 6-2. Lognormal Q-Q plot of neutron-to-gamma dose ratios for the Health Physics Department (2108).

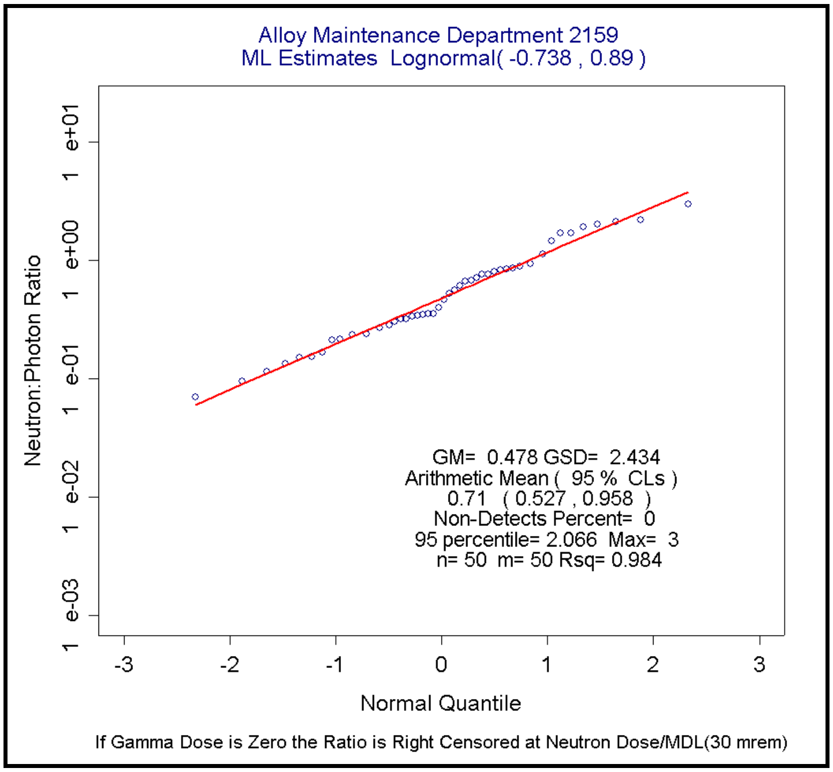

Figure 6-3. Lognormal Q-Q plot of neutron-to-gamma dose ratios for the Alloy Maintenance Department (2159).

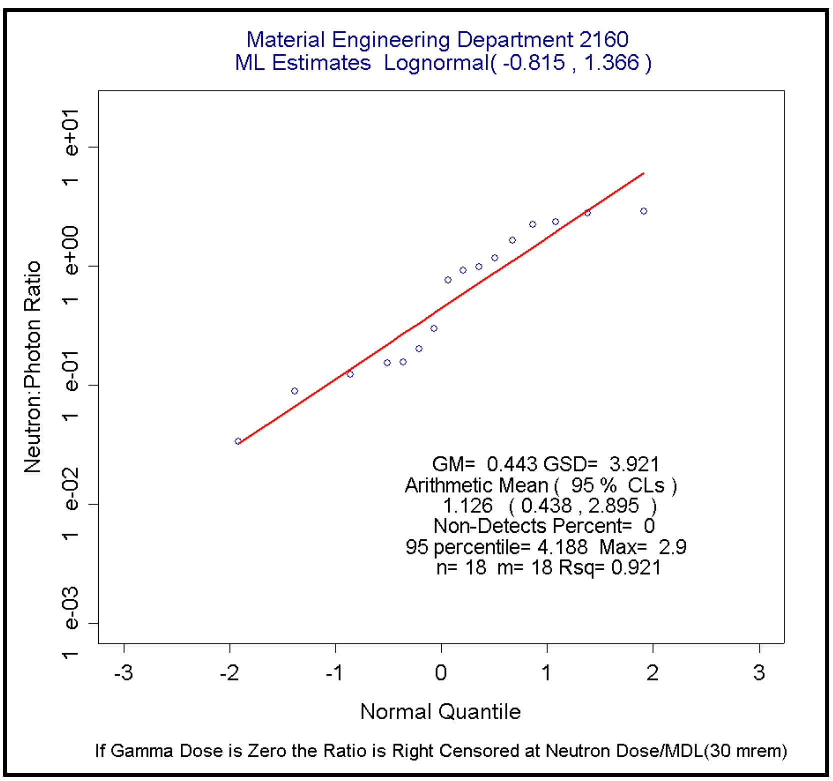

Figure 6-4. Lognormal Q-Q plot of neutron-to-gamma dose ratios for the Material Engineering Department (2160).

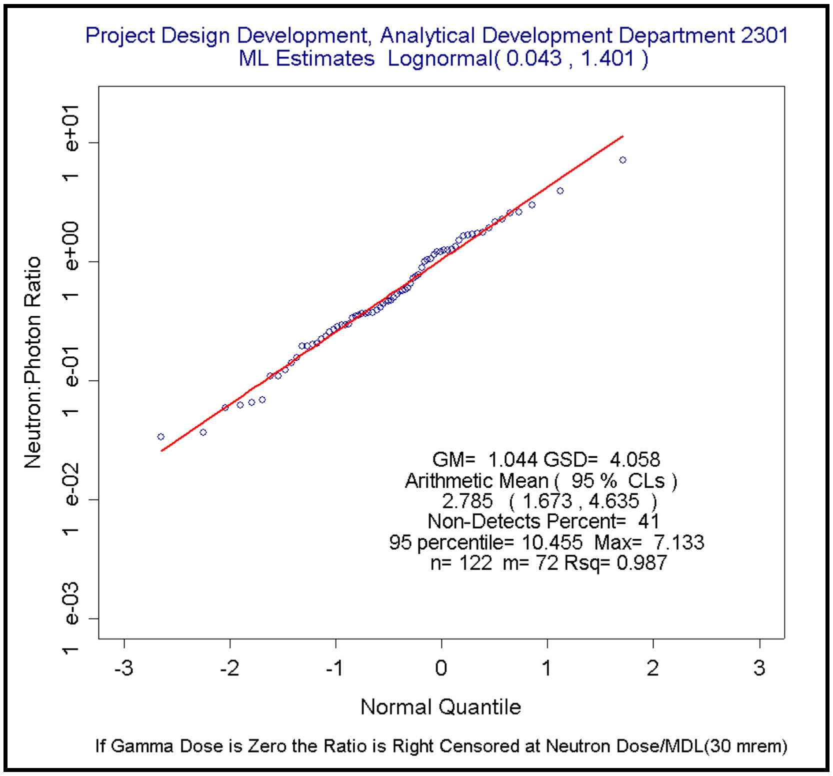

Figure 6-5. Lognormal Q-Q plot of neutron-to-gamma dose ratios for Developmental Operations Department (2301).

include 25 quarterly neutron doses that are multiples of 50 mrem. These positive neutron doses are likely to have consisted of assigned biweekly doses of 50 mrem substituted for below-MDL readings.

Figure 6-7 shows the neutron-to-gamma dose ratio obtained using combined data on all workers with positive neutron doses, with the exception of 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 7-1. The expected values (means) of the ratios in Table 7-1 of the lognormal prediction densities appear to be reasonable in comparison 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 3.2).

7.0 ESTIMATING DOSE FOR QUARTERS WITH NO RECORDED POSITIVE NEUTRON DOSE

Neutron doses should be estimated using the methods developed in this TIB only during the film badge period before 1980. To estimate the neutron dose for a quarter when the only available data is the gamma dose for a worker in Departments 2108, 2159, 2160, or 2301, dose reconstructors should use the appropriate lognormal parameters for the neutron-to-gamma dose ratio distribution listed in Table 7-1. For workers in other departments, dose reconstructors should use the recommended default parameters of the lognormal distribution on the last line of Table 7-1.

Assigning neutron doses from monitored individuals to other workers in the same departments, but who have no record of neutron exposure, is not recommended unless clearly indicated by the unmonitored individuals' work history (see Section 6.1). If an individual has no positive neutron doses

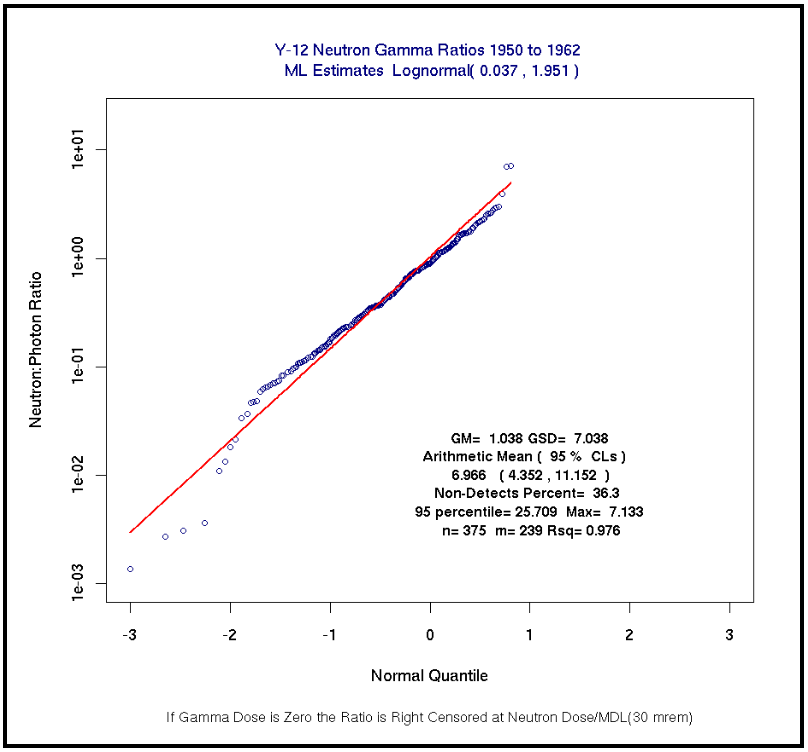

Figure 6-6. Lognormal Q-Q plot of neutron-to-gamma dose ratios for all Y-12 departments.

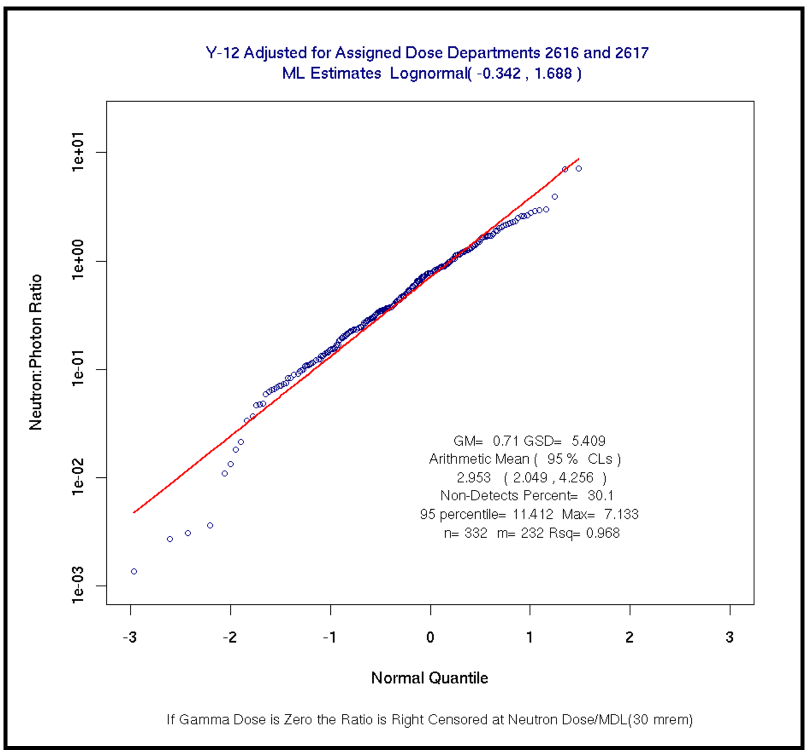

Figure 6-7. Lognormal Q-Q plot of neutron-to-gamma dose ratios for all Y-12 departments other than the Product Chemical Department (2616) and the Product Processing Department (2617).

before 1962, it is unlikely that the individual experienced neutron exposure; therefore the best estimated neutron dose would be zero. This recommendation is consistent with the recommendations for the assignment of missed neutron doses based on dosimeter records in ORAUT-OTIB-0023 (ORAUT 2008, p. 6).

Table 7-1. Parameter estimates for a lognormal prediction density of neutron-to-gamma dose ratios.[a]

Department[b]	μ	σ	GM	GSD	ER
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. GM = geometric mean; GSD = geometric standard deviation; ER = expected neutron-to-gamma dose ratio (mean) of the distribution.
b. See Figures 6-6 to 6-9 and 7-11.

8.0 DISCUSSION

The purpose for this series of TIB reports is to provide background information on the film badge dosimetry program from 1950 to 1980 at the Y-12 site as a resource for dose reconstruction. This report focused on neutron exposures and developed neutron-to-gamma dose 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 7-1). 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 dose ratios of these various prediction densities appear to be reasonable in comparison 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 occupational exposure to neutron dose was largely confined to research activities at the Oak Ridge 86-Inch Cyclotron and to workers in certain departments during 1952 to 1962. During this period, however, our study found only 375 positive quarterly neutron doses among 143 workers. Therefore, 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 had no positive neutron doses before 1962, it is unlikely that the worker experienced neutron exposure; therefore, the best estimated neutron dose would be zero.

While the potential for neutron exposure 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. There are, however, large variations in neutron doses and neutron-to-gamma dose ratios for individual workers from one quarter to the next. Therefore, dose reconstructors should be wary of assigning neutron doses to other individuals in the same departments if they have no record of neutron exposure, unless such exposure is clearly indicated by an individual’s work records.

9.0 ATTRIBUTIONS AND ANNOTATIONS

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

REFERENCES

Adler, H. I., and S. F. Carson, 1972, *Biology Division Annual Progress Report for Period Ending June 30, 1972*, ORNL-4817, Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October. [SRDB Ref ID: 42095]

Auerbach, S. I., 1993, *A History of the Environmental Sciences Division of Oak Ridge National Laboratory*, ORNL/M-2732, Martin Marietta Energy Systems, Oak Ridge National Laboratory, Oak Ridge, Tennessee. [SRDB Ref ID: 32219]

Auxier, J. A., and D. M. Davis, 1981, *Industrial Safety and Applied Heath Physics Annual Report for 1980*, ORNL-5821, Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee. [SRBD Ref ID: 22552]

Ballenger, H. F., 1952, *Health Physics Progress Report, July 1, 1951 to December 31, 1951*, Y-858, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, March 15. [SRBD Ref ID: 8602, pp. 110-178]

Berry, L. A., A. C. England, J. F. Lyon, and G. L. Morgan, 1975, *Neutron Emission from ORMAK*, ORNL-TM-5054, Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September. [SRDB Ref ID: 42088]

Blizard, E. P., A. D. Callihan, F. C. Maienschein, and A. Simon, 1961, *Neutron Physics Division Annual Progress Report for Period Ending September 1, 1961*, ORNL-3193, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 31. [SRDB Ref ID: 64171]

Bloch, A. L., 1951, "Regulations Established for Protection of Personnel in Bldg. 9201-2," May 29 (see attached list of persons with keys to locks in 86-inch cyclotron hazard area). [SRDB Ref ID: 31220]

Butler, T. A., 1963, *Isotopes Development Center Progress Report, Reactor- and Cyclotron-Produced Isotopes, July – October 1962*, ORNL/TM-463, Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 1. [SRDB Ref ID: 11934]

BWXT Y-12, 2000, *Recycled Uranium Mass Balance Project Y-12 National Security Complex Site Report*, Y/LB-16,036, Rev. 1, Y-12 National Security Complex, Oak Ridge, Tennessee, December. [SRDB Ref ID: 16500]

Callihan, D., and J. T. Thomas, 1959, "Accidental Radiation Excursion at the Oak Ridge Y-12 Plant – I. Description and Physics of the Accident," *Health Physics*, volume 1, number 4, pp. 363–372. [SRDB Ref ID: 8606]

Carson, S. F., 1956a, *Biology Division Semiannual Progress Report for Period Ending February 15, 1956*, ORNL-2060, Union Carbide Nuclear Company, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 4. [SRBD Ref ID: 42101]

Carson, S. F., 1956b, *Biology Division Semiannual Progress Report for Period Ending August 15, 1956*, ORNL-2155, Union Carbide Nuclear Company, Oak Ridge National Laboratory, Oak Ridge, Tennessee, November 7. [SRDB Ref ID: 42092]

CCCC (Carbide and Carbon Chemicals Corporation), 1950, “9213 Health Physics Program,” memorandum to A. D. Callihan, K-25 Plant, Oak Ridge, Tennessee, July 12. [SRDB Ref ID: 4690]

Cheka, J. S., 1954, “A Neutron Film Dosimeter,” *Nucleonics*, volume 12, number 6, pp. 40–43.

Cohen, A. C., 1991, *Truncated and Censored Samples: Theory and Applications*, Taylor & Francis, New York, New York.

Copenhaver, E. D., B. S. Houser, H. M. Butler, Jr., J. S. Bogard, M. F. Fair, C. E. Hayes, and D. C. Parzyck, 1986, *Technical Qualification Requirements and Training Programs for Radiation Protection Personnel at Oak Ridge National Laboratory*, ORNL/TM-10119, Martin Marietta Energy Systems, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April. [SRDB Ref ID: 40906]

Dahl, A. H., 1946, “Radiation Hazard Around Doghouses in Building 9203,” Report No. G-2.300.5, memorandum to C. Leggo, Y-12 Plant, Oak Ridge, Tennessee, April 4. [SRDB Ref ID: 694]

DOE (U.S. Department of Energy), 2004, *Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities*, DOE-STD-1136-2004, Washington, D.C., December. [SRDB Ref ID: 18881]

Ellis, C. B., and W. B. Cottrell, editors, 1951, *Aircraft Nuclear Propulsion Project, Quarterly Progress Report for Period Ending December 10, 1950*, ORNL-919, Union Carbide and Carbon Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, February 26. [SRDB Ref ID: 52808]

Ellis, C. B., editor, 1950, *Aircraft Nuclear Propulsion Project, Quarterly Progress Report for Period Ending February 28, 1950*, ORNL-629, Union Carbide and Carbon Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 19. [SRDB Ref ID: 52801]

Emerson, L. C., 1952, “Radioactive Materials within the Y-12 Area,” memorandum to E. B. Pflasterer, Y-12 Plant, Carbide and Carbon Chemicals Company, Oak Ridge, Tennessee, July 2. [SRBD Ref ID: 21589]

Emlet, L. B., 1952, “Contamination Control: Appendix A – Health Physics Aspects,” letter to R. C. Armstrong (Oak Ridge Operations, U.S. Atomic Energy Commission), Carbide and Carbon Chemicals Company, Oak Ridge, Tennessee, July 21. [SRBD Ref ID: 20122]

Emlet, L. B., 1956, “Radiation Protection at UCNC Production Facilities,” letter to S. R. Sharpie (U.S. Atomic Energy Commission, Oak Ridge Operations Office), Union Carbide Nuclear Company, Oak Ridge, Tennessee, August 29. [SRBD Ref ID: 23616]

Good, W. M., editor, 1952, *Physics Division Quarterly Progress Report for Period Ending December 20, 1951*, ORNL-1278, Carbide and Carbon Chemicals Company, Oak Ridge National Laboratory, Oak Ridge, Tennessee, July 11. [SRDB Ref ID: 52802]

Handloser, J. S., 1959, *Health Physics Instrumentation*, Pergamon Press, Oxford, England.

Hanson, A. O., and J. L. McKibben, 1947, “A Neutron Detector Having a Uniform Sensitivity from 10 keV to 3 MeV,” *Physical Review*, volume 72, pp. 251–256.

Hollaender, A., 1954, *Biology Division Semiannual Progress Report for Period Ending February 15, 1954*, ORNL-1693, Carbide and Carbon Chemicals Company, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May 14. [SRDB Ref ID: 42099]

Howard, F. T., 1954, *Electronuclear Research Division Semiannual Progress Report for Period Ending September 20, 1954*, ORNL-1795, Carbide and Carbon Chemicals Company, Oak Ridge National Laboratory, Oak Ridge, Tennessee, November 4. [SRDB Ref ID: 16637]

Howard, F. T., editor, 1952, *Electromagnetic Research Division, Quarterly Progress Report, Part I for Period Ending December 31, 1951*, ORNL-1269, Carbide and Carbon Chemicals Company, Oak Ridge National Laboratory, Oak Ridge, Tennessee, January 15. [SRDB Ref ID: 11914]

Howell, R. L., and Z. Batte, 1982, *Thermoluminescent Dosimetry for Union Carbide Corporation Nuclear Division Personnel*, Y/DK-291, Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee, April. [SRDB Ref ID: 8603]

Hurst, G. S., R. H. Ritchie, and L. C. Emerson, 1959, "Accidental Radiation Excursion at the Oak Ridge Y-12 Plant–III. Determination of Radiation Doses," *Health Physics,* volume 1, number 2, pp. 121–133. [SRDB Ref ID: 10132]

IAEA (International Atomic Energy Agency), 1985, *Neutron Monitoring for Radiological Protection*, Technical Report Series No. 252, Vienna, Austria, September.

IAEA (International Atomic Energy Agency), 1988, *Radiological Safety Aspects of the Operation of Proton Accelerators*, Technical Report Series No. 283, Vienna, Austria.

IAEA (International Atomic Energy Agency), 1990, *Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes*, Technical Report Series No. 318, Vienna, Austria, June.

Johnson, L., and D. Schaffer, 1994, *Oak Ridge National Laboratory, The First Fifty Years*, The University of Tennessee Press, Knoxville, Tennessee.

Jones, V. C., 1985, *United States Army in World War II, Special Studies – Manhattan: The Army and the Atomic Bomb*, U.S. Army, Center of Military History, Washington, D.C. [SRDB Ref ID: 6603]

Kathren, R. L., C. T. Prevo, and S. Block, 1965, "Angular Dependence of Eastman Type A (NTA) Personnel Monitoring Film," *Health Physics*, volume 11, pp. 1067–1068.

Kerr, G. D., 2007, "Early 1950s Work as a Health Physicist at the Y-12 Plant, documented communication with L. C. Emerson, Oak Ridge Associated Universities Team, Oak Ridge, Tennessee, April 9. [SRDB Ref ID: 31372]

Kerr, G. D., 2008a, "The Oak Ridge 63-Inch Cyclotron," documented communication with W. G. Tankersley and A. Zucker, Oak Ridge Associated Universities Team, Oak Ridge, Tennessee, October 21. [SRDB Ref ID: 52404]

Kerr, G. D., 2008b, "Early Work in the ORNL Biology Division at Y-12 Site," documented communication with E. B. Darden, Jr., Oak Ridge Associated Universities Team, Oak Ridge, Tennessee, February 21. [SRDB Ref ID: 42104]

Kerr, G. D., R. H. Ritchie, S. V. Kaye, and J. S. Wassom, 1992, *A Brief History of the Health and Safety Research Division*, ORNL/M-2108, Martin Marietta Energy Systems, Oak Ridge National Laboratory, Oak Ridge, Tennessee, July. [SRBD Ref ID: 42109]

Kim, J., and J. T. Mihalczo, 1979, *D-D Neutron Measurements on a 40-kV, 60-A Neutral Beam Test Facility*, ORNL/TM-7016, Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October. [SRBD Ref ID: 42103]

Kocher, D. C., A. I. Apostoaei, and F. O. Hoffman, 2005, “Radiation Effectiveness Factors for Use in Calculating Probability of Causation of Radiogenic Cancers,” *Health Physics*, volume 89, pp. 3-32.

Livingston, R. S., 1950, excerpt from *Progress Report – Electromagnetic Research Division, January 1, 1950 to March 31, 1950*, Y-584, Y-12 Plant, Oak Ridge, Tennessee, May 3. [SRDB Ref ID: 46772, p. 7]

Livingston, R. S., 1958, *Electronuclear Research Division, Annual Progress Report for Period Ending October 1, 1957*, ORNL-2434, Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 15. [SRDB Ref ID: 11945]

Livingston, R. S, and A. L. Boch, 1952, *The Oak Ridge 86-Inch Cyclotron*, ORNL-1196, Carbide and Carbon Chemicals Company, Oak Ridge National Laboratory, Oak Ridge, Tennessee, June 12. [SRDB Ref ID: 11942]

Livingston, R. S., and J. A. Martin, 1952, *Production of Polonium 208, Final Report on Termination of Project*, ORNL-1392, Carbide and Carbon Chemicals Company, Oak Ridge National Laboratory, Oak Ridge, Tennessee, August. [SRDB Ref ID: 11936]

Livingston, R. S., and A. Zucker, 1962, *Electronuclear Division Annual Progress Report for Period Ending December 31, 1961*, ORNL-3257, Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, August 17. [SRDB Ref ID: 11949]

Livingston, R. S., and A. Zucker, 1963, *Electronuclear Division Annual Progress Report for Period Ending December 31, 1962*, ORNL-3432, Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May 17. [SRBD Ref ID: 11948]

Markowitz, S., C. Scarbough, S. Kieding, and M. Griffin, 2004, *Y-12 and Oak Ridge National Laboratory Medical Surveillance Program – Phase I; Needs Assessment*, Queens College, City University of New York, New York, New York, February 12. [SRBD Ref ID: 12516]

Marsden, E. H., 1945, “Clinton—a Monument to Teamwork,” *Engineering News-Record, Special Number Featuring Construction for Atomic Bomb Production Facilities*, December 13, pp. 115–117. [SRDB Ref ID: 44454]

McLendon, J. D., 1963, *Y-12 Radiation Safety Manual*, Y/KB-29, Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee, July 23. [SRBD Ref ID: 8541]

McLendon, J. D., R. G. Affell, A. G. Bailey, K. A. Davis, and E. D. Gupton, 1980, *External Radiation Monitoring of Union Carbide Nuclear Division Personnel*, Y/DD-268, Union Carbide Corporation, Y-12 Plant, Oak Ridge, Tennessee, March 26. [SRBD Ref ID: 20126]

McRee, P. C., 1960, “Radioactive Source Storage Inventory – Building 9987,” internal correspondence to C. M. West, Union Carbide Nuclear Company, Oak Ridge, Tennessee, May 16. [SRDB Ref ID: 28139]

McRee, P. C., 1961, “Inventory of Radioactive Sources,” memorandum to C. M. West, Y-12 Plant, Union Carbide Nuclear Company, Oak Ridge, Tennessee, November 6. [SRDB Ref ID: 28135]

McRee, P. C., C. M. West, and J. D. McLendon, 1965, *Y-12 Radiation Safety Manual*, Y-1401 Revised, Y-12 Plant, Oak Ridge, Tennessee, May 11. [SRDB Ref ID: 8577]

MMES (Martin Marietta Energy Systems), 1992, *Dosimeter Response Characterization for Personnel Neutron Dosimetry (Volumes 1-4)*, Oak Ridge National Laboratory, Oak Ridge, Tennessee. [SRBD Ref ID: 11927, 11939, 11973, and 11976]

Morgan, K. Z., and D. M. Davis, 1965, *Applied Health Physics Annual Report for 1964*, ORNL-3820, Oak Ridge National Laboratory, Oak Ridge, Tennessee, June. [SRBD Ref ID: 12093]

Morgan, K. Z, D. M. Davis, and J. C. Hart, 1963, *Applied Health Physics Annual Report for 1962*, ORNL-3490, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September. [SRDB Ref ID: 1293]

Murray, J. P., 1958, *Administrative and Service Responsibilities for ORNL Employees Located in the Y-12 Area*, Y-12 Plant Bulletin AR – No. 213, Union Carbide Nuclear Corporation, Oak Ridge, Tennessee, September. [SRDB Ref ID: 48616]

Murray, R., 1948, *Health Physics Progress Report, December 1 - 31, 1947*, Y-94/1R, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, January 12. [SRDB Ref ID: 8602, pp. 483-502]

NCRP (National Council on Radiation Protection and Measurements), 1971, *Protection Against Neutron Radiation*, NCRP Report 38, Washington, D.C.

Nielsen, M. J., and C. B. Ellis, 1950, *The Aircraft Nuclear Propulsion Project, Quarterly Progress Report for Period Ending May 31, 1950*, ORNL-768, Oak Ridge National Laboratory, Oak Ridge, Tennessee, August 14. [SRBD Ref ID: 52807]

NIOSH (National Institute for Occupational Safety and Health), 2002, *NIOSH-Interactive RadioEpidemiological Program (NIOSH-IREP) Technical Documentation*, Office of Compensation Analysis and Support, Cincinnati, Ohio, June 18. [SRDB Ref ID: 22398]

NIOSH (National Institute for Occupational Safety and Health), 2007, *External Dose Reconstruction Implementation Guideline*, OCAS-IG-001, Rev. 3, Office of Compensation Analysis and Support, Cincinnati, Ohio, November 21.

ORAUT (Oak Ridge Associated Universities Team), 2005a, *Historical Evaluation of the Film Badge Program at the Y-12 Facility in Oak Ridge, Tennessee, Part 1 – Gamma Radiation*, ORAUT-RPRT-0032, Oak Ridge, Tennessee, April 13.

ORAUT (Oak Ridge Associated Universities Team), 2005b, *Estimation of Neutron Dose Rates from Alpha-Neutron Reactions in Uranium and Thorium Compounds*, ORAUT-OTIB-0024, Rev. 00, Oak Ridge, Tennessee, April 7.

ORAUT (Oak Ridge Associated Universities Team), 2006, *Effect of Threshold Energy and Angular Response of NTA Film on Missed Dose at the Oak Ridge Y-12 Facility*, ORAUT-OTIB-0051, Rev. 00, Oak Ridge, Tennessee, May 5.

ORAUT (Oak Ridge Associated Universities Team), 2007a, *Historical Evaluation of the Film Badge Dosimetry Program at the Y-12 Plant in Oak Ridge, Tennessee, Part 3 – Beta Radiation*, ORAUT-OTIB-0046, Rev. 00, Oak Ridge, Tennessee, June 22.

ORAUT (Oak Ridge Associated Universities Team), 2007b, *Oak Ridge National Laboratory – Occupational External Radiation Dose*, ORAUT-TKBS-0012-6, Rev. 01, Oak Ridge, Tennessee, September 10.

ORAUT (Oak Ridge Associated Universities), 2007c, Oak Ridge National Laboratory – Site Description, ORAUT-TKBS-0012-2, Rev. 02, Oak Ridge, Tennessee, August 17.

ORAUT (Oak Ridge Associated Universities Team), 2007d, *Y-12 National Security Complex – Site Description*, ORAUT-TKBS-0014-2, Rev. 02, Oak Ridge, Tennessee, November 8.

ORAUT (Oak Ridge Associated Universities Team), 2008, *Assignment of Missed Neutron Dose Based on Dosimeter Records*, ORAUT-OTIB-0023, Rev. 01, Oak Ridge, Tennessee, May 14.

Owings, E., 1995, *Historical Review of Accountable Nuclear Materials at the Y-12 Plant*, Y/EXT-00153/DEL REV, Y-12 Plant, Oak Ridge, Tennessee, July 28. [SRDB Ref ID: 691]

Oxley, L. S., 2001, Technical Basis for the External Dosimetry Program at the Y-12 National Security Complex, RCO/TBD-007, Rev. 3, BWXT Y-12, Y-12 National Security Complex, Oak Ridge, Tennessee, August 2. [SRBD Ref ID: 8467]

Parsons, L. E., 1949, "Listing of Personnel Participating in D-D Work in Building 9204-3," memorandum to E. G. Struxness, Y-12 Plant, Oak Ridge, Tennessee, May 6. [SRDB Ref ID: 20083]

Patterson, H. W., and R. H. Thomas, 1973, *Accelerator Health Physics*, Academic Press, New York, New York. [SRDB Ref ID: 22527]

Patterson, G. R. Jr., C. M. West, and J. D. McLendon, 1957, *The Y-12 Health Physics Program*, Y-1186-Deleted Version, Y-12 Plant, Oak Ridge, Tennessee, November 1. [SRBD Ref ID: 14022]

Quist, A. S., 2000, *A History of Classified Activities at Oak Ridge National Laboratory*, ORCA-7, Oak Ridge Classification Associates, Oak Ridge, Tennessee, September 29. [SRBD Ref ID: 32028]

RDCT (R Development Core Team), 2008, R: *A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, ISBN-3-900051-07-0, Vienna, Austria. [SRDB Ref ID: 44452]

Reese, D. J., 1967, *Health Physics: Principles of Radiation Protection*, MIT Press, Cambridge, Massachusetts.

Roberts, E. Jr., 1964, *Radioactive Source and X-Ray Survey*, Y-KB-48, Y-12 Plant, Oak Ridge, Tennessee, January 9. [SRDB Ref ID: 19819]

Roberts, L. D., 1952, *Physics Division Quarterly Progress Report for Period Ending June 20, 1951*, ORNL-1092, Oak Ridge National Laboratory, Oak Ridge, Tennessee, January 11. [SRDB Ref ID: 45332]

Sanders, M., 1956, "Radiation Survey in Building 9205", memorandum to W. R. Carver, Y-12 Plant, Carbide and Carbon Chemicals Corporation, Oak Ridge, Tennessee, August 1. [SRDB Ref ID: 31162]

SCA (S. Cohen & Associates), 2005, *Y-12 National Security Complex Site Profile Review*, SCA-TR-TASK1-0007, Rev. 0, McLean, Virginia, September 19.

SCA (S. Cohen & Associates), 2006, *Y-12 National Security Complex Site Profile Review – Site Expert Review Summary*, Attachment 6 to SCA-TR-TASK1-0007, Rev. 0, McLean, Virginia, May 3.

Shipley, E. D., and R. S. Livingston, 1949a, *Progress Report – Research and Development Division, Part III. Electromagnetic Research Laboratory, January 1, 1949 to June 30, 1949*, Y-445, Y-12 Plant, Oak Ridge, Tennessee, July 18. [SRDB Ref ID: 46772, pp. 4-5]

Shipley, E. D., and R. S. Livingston, 1949b, *Progress Report – Research and Development Division, Part III. Electromagnetic Research Laboratory, July 1, 1949 to September 30, 1949*, Y-495, Y-12 Plant, Oak Ridge, Tennessee, October 15. [SRDB Ref ID: 46772, p. 5]

Shipley, E. D., and R. S. Livingston, 1950, *Progress Report – Research and Development Division, Part III. Electromagnetic Research Laboratory, October 1, 1949 to December 31, 1949*, Y-548, Y-12 Plant, Oak Ridge, Tennessee, January 3. [SRDB Ref ID: 46772, pp. 6-7]

Shleien, B., L. A. Slaback, Jr., and B. K. Birky, editors, 1998, *Handbook of Health Physics and Radiological Health, Third Edition,* Williams & Wilkins, Philadelphia, Pennsylvania, January.

Shull, C. G., 1952, *Physics Division Quarterly Progress Report for Period Ending September 20, 1951*, ORNL-1164, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 14. [SRDB Ref ID: 45333]

Slaughter, E. J., 1953, *Biology Division Semiannual Progress Report for Period Ending August 15, 1953*, ORNL-1614, Oak Ridge National Laboratory, Oak Ridge, Tennessee, November 16. [SRDB Ref ID: 42098]

Slaughter, E. J., 1955, *Biology Division Semiannual Progress Report for Period Ending August 15, 1955*, ORNL-1953, Oak Ridge National Laboratory, Oak Ridge, Tennessee, November 28. [SRDB Ref ID: 41102]

Snell, A. H., and E. O. Wollan, 1953, *Physics Division Quarterly Progress Report for Period Ending December 20, 1952, ORNL-1496*, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 12. [SRDB Ref ID: 52804]

Soldat, K. L., L. W. Brackenbush, M. P. Moeller, R. I. Scherpelz, and J. E. Tanner, 1990, *Neutron Dose Equivalent and Energy Spectra Measurements at the Oak Ridge National Laboratory and Y-12 Plant*, PNL-7528, Pacific Northwest Laboratory, Richland, Washington, May. [SRDB Ref ID: 11093 and 8525]

Souleyrette, M. L., 2003a, *Summary of Historical Monitoring Techniques Provided to NIOSH for EEOICPA Requests*, Y-12 National Security Complex, Oak Ridge, Tennessee, February 18. [SRDB Ref ID: 8586]

Souleyrette, M. L., 2003b, "External Dose Data for Y-12 Employees from 1950 to 2003," correspondence with G. D. Kerr, Kerr Consulting, Knoxville, Tennessee, September 3. [SRDB Ref ID: 63468]

Stapleton, D. R., 1992, *A Brief History of the Research Reactors Division of Oak Ridge National Laboratory*, ORNL/M-2342, Oak Ridge National Laboratory, Oak Ridge, Tennessee. [SRDB Ref ID: 16542]

Struxness, E. G., 1948, *Health Physics – Industrial Hygiene Progress Report, May 1 - 31, 1948,* Y-181/1R, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, June 16. [SRBD Ref ID: 8602, pp. 456-467]

Struxness, E. G., 1949a, *Health Physics – Hygiene Progress Report, May 1 - 31, 1949*, Y-429/1R, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, June 27. [SRDB Ref ID: 8602, pp. 296-305]

Struxness, E. G., 1949b, *Health Physics – Hygiene Progress Report, February 1 - 28, 1949*, Y-365/1R, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, March 15. [SRDB Ref ID: 8602, pp. 333-339]

Struxness, E. G., 1951a, *Health Physics Progress Report, November 1, 1950 to December 31, 1950*, Y-780, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, June 14. [SRBD Ref ID: 8602, pp. 215-216]

Struxness, E. G., 1951b, *Health Physics Progress Report, January 1, 1951 – June 30, 1951*, Y-836, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, December 15. [SRDB Ref ID: 8602, pp. 257-294]

Struxness, E. G., 1953, *Health Physics Progress Report – January 1, 1952 to July 1, 1952*, Y-940, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, February 19. [SRDB Ref ID: 8602, pp. 180-215]

Struxness, E. G., 1954, *Health Physics Progress Report, January 1, 1953 Through June 30, 1953*, Y-1070, Carbide and Carbon Chemicals Company, Y-12 Plant, Oak Ridge, Tennessee, April 4. [SRDB Ref ID: 8602, pp. 53-84]

Tankersley, W. G., 2009, "Oak Ridge 86-Inch Cyclotron," documented communication with J. Beck, G. D. Kerr, and J. W. Terry, Oak Ridge Associated Universities Team, Oak Ridge, Tennessee. [SRDB Ref ID: 66365]

TAPP (Thomas and Associates Preservation Planners), 2003, *Y-12 National Security Complex, National Historic Preservation Act, Historic Preservation Plan*, Y/TS 1893, Oak Ridge, Tennessee, September. [SRDB Ref ID: 19331]

Terry, J. W., 1981, "Production of Radioisotopes in the ORNL 86-Inch Cyclotron," *IEEE Transactions on Nuclear Science*, volume NS-28, pp. 1597–1598. [SRBD Ref ID: 42105]

Thomas, D. J., D. T. Bartlett, M. Burke, N. Horwood, R. Tanner, and G. C. Taylor, 1997, *Response Characteristics of PADC Track Etch and NTA Film Neutron Personal Dosimeters for Backscatter from Standard Calibration Phantoms*, CIRM 7, Centre for Ionising Radiation Metrology, National Physical Laboratory, Teddington, Middlesex, United Kingdom, October. [SRDB Ref ID: 64169]

Thomas, D. J., N. Horwood, and G. C. Taylor, 1999, *Neutron Dosemeter Responses in Workplace Fields and the Implications of Using Realistic Neutron Calibration Fields*, CIRM 27, Centre for Ionising Radiation Metrology, National Physical Laboratory, Teddington, Middlesex, United Kingdom, March. [SRDB Ref ID: 64170]

Thornton, W. T., D. M. Davis, and E. D. Gupton, 1961, *The ORNL Badge Dosimeter and Its Personnel Monitoring Applications*, ORNL-3126, Oak Ridge National Laboratory, Oak Ridge, Tennessee, December. [SRDB Ref ID: 8573]

UCC (Union Carbide Corporation), 1962, *A Safety Review of the Oak Ridge Critical Experiments Facility*, ORNL/TM-349, Oak Ridge National Laboratory, Oak Ridge, Tennessee, December. [SRDB Ref ID: 15646]

UCC (Union Carbide Corporation), 1967, *A Safety Analysis of the Oak Ridge Critical Experiments Facility*, ORNL/TM-349, Rev. 1, Oak Ridge National Laboratory, Oak Ridge, Tennessee, February. [SRDB Ref ID: 15655]

UCNC (Union Carbide Nuclear Corporation), 1958, *Accidental Radiation Excursion at the Y-12 Plant, June 16, 1958, Final Report*, Y-1234, Y-12 Plant, Oak Ridge, Tennessee, July 28. [SRDB Ref ID: 4439]

UCNC (Union Carbide Nuclear Corporation), 1963, *Y-12 Plant Quarterly Health Physics Report, Fourth Quarter CY 1962*, Y-KB-26, Y-12 Plant, Oak Ridge, Tennessee, March 5. [SRDB Ref ID: 23618]

Watkins, J. P., J. L. Regan, D. L. Cragle, E. L. Frome, C. W. West, D. J. Crawford-Brown, and W. G. Tankersley, 1993, *Data Collection, Validation, and Description for the Oak Ridge Nuclear Facilities Mortality Study*, ORISE 93/J-42, Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee, January. [SRBD Ref ID: 10133]

Watkins, J. P., J. L. Regan, D. L. Cragle, E. L. Frome, C. W. West, D. J. Crawford-Brown, and W. G. Tankersley, 1997, "Collection, Validation, and Treatment of Data for a Mortality Study of Nuclear Workers," *Applied Occupational and Environmental Hygiene*, volume 12, number 3, pp. 195–205.

West, C. M., 1955, "Establishment of a Film Program," memorandum to W. R. Carver, Y-12 Plant, Carbide and Carbon Chemicals Corporation, Oak Ridge, Tennessee, April 26. [SRDB Ref ID: 19805]

West, C. M., 1956, "Listing of External Exposures on IBM Sheets," memorandum to P. Johnson, Union Carbide Nuclear Company, Oak Ridge, Tennessee, October 21. [SRDB Ref ID: 19803]

Wilcox, W. J. Jr., 2001, *An Overview of the History of Y-12 (1942-1992): A Chronology of Some Noteworthy Events and Memoirs*, American Museum of Science and Energy, Oak Ridge, Tennessee, August. [SRDB Ref ID: 9609]

ATTACHMENT A
Page 1 of 19

Wiley, S. W., 2004, “Y-12 Historical Radiation Standards,” letter to G. D. Kerr, Kerr Consulting, Knoxville, Tennessee, June 3. [SRDB Ref ID: 28131]

Wiley, S. W., 2005, "Contract DE-AC05-000R-22800, Informational Requests by Oak Ridge Associated Universities on behalf of National Institute for Occupational Safety and Health (NIOSH)," letter with attachments to W. G. Tankersley (Oak Ridge Associated Universities) with attachment, BWXT Y-12, Y-12 Plant, Oak Ridge, Tennessee, October 3. [SRDB Ref ID: 30939]

Williams, W. J., 1948, “Fabrication of Weapon Components,” memorandum to J. C. Franklin, U.S. Atomic Energy Commission, Oak Ridge Directed Operations, Washington, D.C., January 15. [SRDB Ref ID: 46691]

Table A-1. 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	1,925	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	
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	

ATTACHMENT A
Page 2 of 19

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	

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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
	55	3	2159	120	60	2.00
030	54	1	2018	2	1,485	<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

ATTACHMENT A
Page 3 of 19

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
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	

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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	1,042	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
	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

ATTACHMENT A
Page 4 of 19

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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
	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
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

ATTACHMENT A
Page 5 of 19

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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
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	
	59	3	2301	21	36	0.58
	59	4	2301	56	34	1.65

ATTACHMENT A
Page 6 of 19

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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
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

ATTACHMENT A
Page 7 of 19

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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	
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	
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

ATTACHMENT A
Page 8 of 19

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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
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	2,760	0.02
132	54	3	2231	50	708	0.07
133	53	2	2618	85	0	
134	54	4	2616	150	0	

ATTACHMENT A
Page 9 of 19

Worker	Year	Quarter	Department	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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
	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

ATTACHMENT A
Page 10 of 19

Table A-2. 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[a]	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[a]	55	2	300	253	1.19
108	58	4	15	0	
121	58	4	15	0	
Department 2070: Mechanical Engineering Department, Tool Engineering					
046[a]	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[a]	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	

ATTACHMENT A

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
006[a]	56	1	12	135	0.09
	56	4	34	0	
137[a]	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	
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
078[a]	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	

ATTACHMENT A
Page 12 of 19

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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[a]	56	1	56	195	0.29
080[a]	56	1	48	195	0.25
087[a]	56	1	84	195	0.43
116[a]	56	1	72	195	0.37
117[a]	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[a]	57	2	6	0	
	57	4	60	44	1.36
	58	1	12	0	
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[a]	55	2	878	400	2.20
	55	3	334	390	0.86
	55	4	84	360	0.23
	56	2	70	75	0.93

ATTACHMENT A
Page 13 of 19

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
087[a]	55	2	268	400	0.67
	55	3	180	60	3.00
	56	2	24	75	0.32
137[a]	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[a]	55	3	52	150	0.35
	55	4	54	474	0.11
	56	2	60	75	0.80
127[a]	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[a]	56	1	29	135	0.21
	56	2	20	60	0.33
054[a]	56	2	42	75	0.56
	56	3	4	30	0.13
060	56	2	32	15	2.13
074[a]	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[a]	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[a]	55	2	654	400	1.64
	55	3	166	60	2.77
054[a]	55	2	322	350	0.92
	55	3	134	60	2.23
	55	4	11	90	0.12
117[a]	55	2	232	200	1.16
	55	3	140	60	2.33
	55	4	3	90	0.03
127[a]	55	2	343	350	0.98
006[a]	55	4	11	90	0.12
055[a]	55	4	14	90	0.16
074[a]	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[a]	55	4	27	90	0.30

ATTACHMENT A
Page 14 of 19

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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
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[a]	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	
062[a]	55	3	302	390	0.77
	55	4	56	400	0.14
	56	1	81	195	0.42
	56	2	40	75	0.53

ATTACHMENT A
Page 15 of 19

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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[a]	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
074[a]	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

ATTACHMENT A
Page 16 of 19

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
020	57	1	6	88	0.07
	57	2	35	0	
	57	3	9	0	
	57	4	6	0	
	58	1	6	0	
022[a]	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[a]	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
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

ATTACHMENT A

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

ATTACHMENT A
Page 18 of 19

Worker	Year	Quarter	Neutron dose (mrem)	Gamma dose (mrem)	Neutron-to-gamma dose ratio
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[a]	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[a]	55	1	336	0	
109[a]	55	1	150	140	1.07
110	55	1	100	0	
115[a]	55	1	50	0	
118[a]	55	1	150	0	
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

a. This worker had doses from more than one department.

ATTACHMENT B

Table B-1. Rounded quarterly neutron doses for Y-12 workers versus Y-12 Department for the film badge period from 1950 to 1980 (Markowitz et al. 2004, Appendix B1, p. 7).

	Rounded quarterly neutron dose (mrem)																		
Department	**<5**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**900**	**Total**
2000	1	1				4						1							7
2001			1		1														2
2003											1			1					2
2018	3	2	1	1	1	1													9
2044			2										1						3
2070						1				2									3
2077	4	5	3	2		1		1	1	1		1		1					20
2091						1													1
2108		7	6	4	5	2	2	3	1		4	2	2	1					39
2158		4	1	1		1	3	1	1										12
2159	1	3	5	8	2	5	3	1	2	1	5	2	8		2	1		1	50
2160	2	5		2							2	3	3				1		18
2231	2	2	8	5		4													21
2260						1													1
2301	3	21	20	12	18	14	8	7	6	4	6	1	2						122
2303										1									4
2345									1		1			2					2
2616			1			1		1		1		4	4			1			11
2617						6					11	7	6		2				32
2618				1		1							2						6
2685						1													1
2687	1	2	2																5
2701											1								1
2703			1																1
2791				3															3
Total	17	52	51	39	27	44	16	14	12	10	31	22	28	5	4	2	1	1	376