DOE Review Release 05/03/2013

Document Title:	Document Number:	ORAUT-OTIB-0044
Historical Evaluation of the Film Badge Dosimetry Program at the Y-12 Facility in Oak Ridge, Tennessee: Part 1 – Gamma Radiation	Revision:	01
	Effective Date:	04/29/2013
	Type of Document:	OTIB
	Supersedes:	ORAUT-RPRT-0032 Rev 00

Subject Expert(s): George D. Kerr and Janice P. Watkins

Approval:	Signature on File George D. Kerr, Document Owner	Approval Date:	04/23/2013
Concurrence:	Signature on File John M. Byrne, Objective 1 Manager	Concurrence Date:	04/22/2013
Concurrence:	Signature on File Edward F. Maher, Objective 3 Manager	Concurrence Date:	04/22/2013
Concurrence:	Vickie S. Short Signature on File for Kate Kimpan, Project Director	Concurrence Date:	04/22/2013
Approval:	Signature on File James W. Neton, Associate Director for Science	Approval Date:	04/29/2013

☐ 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
04/14/2005	00	This report was previously published as an Oak Ridge Associated Universities document and has been incorporated as an ORAU Team controlled document. Future revisions will be reviewed and approved by NIOSH. Initiated by George D. Kerr.
04/29/2013	01	Revision initiated to update Figure 6-1. Sections 7.4 and 7.6 were deleted and replaced by Sections 5.6 and 7.5. Section 5.6 in the current document is essentially Section 7.4 from OTIB-0044 Rev. 01-B. Section 7.5 is new and provides examples of the application of techniques developed in this work for the estimation of whole-body doses from gamma rays to Y-12 workers not monitored in years prior to 1961. 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 and Janice P. Watkins.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AM	arithmetic mean
CDF	cumulative distribution function
CER	Center for Epidemiologic Research
cm	centimeter
COC	Cincinnati Operations Office
DOE	U.S. Department of Energy
gal	gallon
GM	geometric mean
GSD	geometric standard deviation
HP	health physics
ID	identification number
K-M	Kaplan-Meier
MDL	minimum detection level (same as the LOD)
MeV	megaelectron-volt, 1 million electron-volts
mg	milligram (1/1000 of a gram)
ML	maximum likelihood
MLPD	maximum likelihood prediction density
mm	millimeter
mrem	millirem
NIOSH	National Institute for Occupational Safety and Health
NTA	nuclear track emulsion, Type A
ORAU	Oak Ridge Associated Universities
PIC	pocket ionization chamber (same as a “pencil dosimeter’)
PLE	product limit estimator
Q	calendar quarter
q-q	quantile-quantile
RPG	radiation protection guideline
TIB	technical information bulletin
TLD	thermoluminescent dosimeter
UCCND	Union Carbide Corporation-Nuclear Division
U.S.C.	United States Code
UTL	upper tolerance limit
wk	week

Y-12	Y-12 plant
§	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 historical background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). TIBs may be used to assist 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

To use data appropriately it is essential to understand the context in which they were collected. An awareness of the developing dosimetry program is particularly important for proper evaluation of the external dose records of individuals employed at the nuclear facilities operated by DOE or its predecessors over half a century ago. The startup period for the nuclear industry was of critical importance in the development of occupational safety standards and practices designed to protect the health of nuclear workers (Struxness 1949a; Inkret, Meinhold, and Taschner 1995; Strom et al. 1996).

Monitoring policies, recording practices, and personnel dosimeters were repeatedly modified and updated over time as knowledge increased and technology advanced (ORAUT 2009a). The purpose of this TIB is to provide definitive documentation of these changes over time at the Oak Ridge Y-12 Plant and to furnish information that allows recorded gamma doses measured with film badge dosimeters to be used appropriately in dose reconstruction. Other TIBs have been prepared that deal with film badge dosimetry for beta radiation (ORAUT 2007) and neutron radiation (ORAUT 2009b).

Maximum likelihood (ML) methods used to estimate parameters for randomly left-censored lognormal data are described by Frome and Watkins (2004). A summary of these methods is provided in this report. These parameters can be used to determine quarterly lognormal prediction densities for gamma radiation doses to Y-12 worker populations. Tables of geometric means (GMs) and geometric standard deviations (GSDs) defining the prediction densities are supplied for 1947 to 1979 and can be used for sampling individual worker doses.

Graphical methods were used to evaluate the lognormal assumption for the quarterly dose data. Modified boxplots and quantile-quantile (q-q) plots with accompanying summary statistics supplied detailed information on quarterly doses and supported lognormal distributions for quarters after 1956. Quarterly data before 1956 were not found to fit a lognormal or other statistical distribution, and details of the monitoring policies and recording practices for this period confirmed that these data might not be suitable for use in estimating quarterly missed doses.

As an alternative, parameters for quarterly lognormal prediction densities before 1956 were obtained from ML regression based on data from a subgroup of 147 workers monitored regularly before and after 1961 and who worked in departments with potential for exposure to gamma radiation. Although all employees were to be monitored with film badges from 1961 to 1979, before 1961 only workers with the largest exposure potential were routinely monitored. As a consequence, it is to be expected that estimated doses based on the regression analysis of these subgroup data are favorable to the claimant.

All statistical analyses were carried out using the R system (RDCT 2008). The R system is an integrated suite of free software for data manipulation, calculation, and graphical display. Detailed documentation of the R system can be found on the internet at http://www.r-project.org.

3.0 Y-12 FILM BADGE PROGRAM

3.1 OVERVIEW

Ground was broken for the first building at the Y-12 Plant in February 1943, and the first production unit was in use by January 1944 (Marsden 1945; Jones 1985). The Y-12 Plant was managed by Tennessee Eastman Corporation for the Manhattan Engineer District of the U.S. Army Corps of Engineers and produced enriched uranium by the electromagnetic separation process (Marsden 1945; Jones 1985). The primary hazard from this process was internal radiation exposure from alpha radiation from dust of natural and enriched uranium (Dupree et al. 1994). In May 1947, the U.S. Atomic Energy Commission (AEC) transferred management of Y-12 to the Union Carbide Corporation Nuclear Division (UCCND), and the mission of the facility changed to nuclear material processing and fabrication (Watkins et al. 1993, 1997). Internal radiation exposure from alpha radiation from dust of uranium was still the largest concern at Y-12, but there were increased concerns over the external radiation dose from gamma rays and beta particles in the uranium metal fabrication departments (Emlet 1952).

The Y-12 film badge dosimetry program evolved as improved technology was developed and as the complex radiation fields encountered in the workplace were better understood (ORAUT 2009a). The routine film badge exchange frequency was gradually decreased and corresponded to sequential reductions in the radiation protection standards (Morgan 1961). An excellent discussion of the sequential reductions in radiation protection limits over time is in Inkret, Meinhold, and Taschner (1995). Table 3-1 summarizes the radiation protection guidelines used at Y-12, Table 3-2 summarizes the exchange frequencies for film badge dosimeters, and Table 3-3 provides information on minimum detection levels (MDLs) of the film badges and the gamma or beta doses that were to be assigned to workers when their film badge readings were less than the MDL. The film badge period ended in 1979 when film dosimeters at Y-12 were largely replaced by thermoluminescent dosimeters (TLDs) (McLendon et al. 1980; Howell and Batte 1982; BWXT Y-12 2001).

The first film badge dosimeter used at Y-12 in 1948 (West 1993a) was identical to the badge that was used at the Oak Ridge National Laboratory in 1949 and described by Thornton, Davis, and Gupton (1961). This badge was an AEC Catalog Number PF-1B film badge manufactured by the A. M. Samples Machine Company in Knoxville, Tennessee (Patterson, West, and McLendon 1957; West 1993b). The radiation-sensitive medium (photographic film) in the PF-1 badge was encased in a protective packet with a clip for attachment to clothing or a lanyard (Handloser 1959, Figure 8-1). The film badge was normally worn on the front of the torso between the neck and the waist. A portion of the film was covered by a 1-mm-thick cadmium filter to determine the dose from gamma rays and high-energy X-rays, and the remaining uncovered portion of the film (open window) was used to determine the dose from beta particles and low-energy X-rays (Handloser 1959; Morgan 1961).

This film badge was used until 1961 when a newer film badge dosimeter was adopted for use at all UCCND facilities (Thornton, Davis, and Gupton 1961; McLendon 1963; McRee, West, and McLendon 1965). It served as a security badge and provided for monitoring of both routine and accident-related radiation exposures. As in the PF-1B, a cadmium filter with a thickness of approximately 1 mm or mass density of 1,000 mg/cm^2 was to measure the penetrating whole-body dose from gamma rays. In addition, Y-12 film badges continued to include an open window to measure beta radiation and to distinguish film exposures due to beta and gamma radiation. Plastic and aluminum filters were also incorporated into the UCCND film badge. The areas behind

Table 3-1. Historical radiation protection guidelines for the Y-12 Plant (rem) (Wiley 2004).

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

a. The extremities are defined typically as the hands and arms below the elbow and the feet and legs below the knee.
b. DOE has used the total effective dose equivalent to limit the sum of the internal and external whole-body (effective) doses since 1989.
c. Accumulated dose not to exceed 10(N-18) rem, where N is the age in years.
d. Accumulated dose not to exceed 5(N-18) rem, where N is the age in years.
e. Accumulated dose not to exceed N rem, where N is the age in years.

Table 3-2. Exchange frequencies for film badges used to measure gamma and beta doses.[a]

Period[b]	Exchange frequency
May 1948–September 1958	Weekly
October 1958–December 1960	Monthly
January 1961–December 1979	Quarterly

a. McLendon (1958a,b), Reavis (1958), West (1993a), Watkins et al. (1993, 1997), Souleyrette (2003), and ORAUT (2009a).
b. Dates are approximate because changes did not occur for all employees at the same time.

the plastic and aluminum filters were read, but results were not used routinely in the evaluation of a worker's dose from beta and gamma radiation at the Y-12 Plant (Sherrill and Tucker 1973).

Film badges were calibrated (1) for beta particles by placing the badges face down on a slab of natural uranium (ORAUT 2007) and (2) for gamma rays by exposing the badges in air at known distances from a calibrated gamma-ray source (Struxness 1951a, McRee et al. 1965). The gamma dose to the film badges was determined by exposing a Victoreen R-chamber at the same distance from the gamma ray source as the badges (Struxness 1951a; McRee et al. 1965). A radium source encased in 0.5 mm of platinum was used initially as the gamma-ray source (Struxness 1951a), and a ^{60}Co source was used starting in the early 1960s (UCNC 1963). The average energy of the gamma rays from the ^{60}Co source was approximately 1.25 MeV (Shleien, Slaback, and Birky 1998) and the average energy of the gamma rays from the radium source encased in 0.5 mm of platinum was approximately 1.15 MeV (Handloser 1959, Table 7-1). The film badge dosimeters typically exhibited about the same sensitivity to gamma and beta radiation (i.e., a 1-rem dose of beta particles yielded about the same response in the film as 1 rem of gamma rays) (Auxier 1967). Thus, the MDLs of the film badges were essentially the same for beta and gamma radiation (Table 3-3).

An MDL of 10 to 30 mrem is usually reported for the types of films used to measure the gamma dose at the Y-12 Plant (Morgan 1961; Wilson 1987). An MDL of 10 mrem was possible if an experienced film-badge technician read the exposed films in small batches (Morgan 1961). During film badge

Table 3-3. MDLs and assigned MDL doses in mrem for film badges used to measure gamma and beta doses.[a]

Period[b]	MDL	Assigned dose
May 1948–December 1949	30	30[c]
January 1950–December 1951	30	0
January 1952–September 1952	50	50[d]
October 1952–December 1952	43	43[d]
January 1953–June 1954	50	50[d]
July 1954–December 1954	30	30[d]
January 1955–December 1957	30	15[e]
January 1958–October 1979	30	Not applicable[f]

a. ORAUT(2009a), Souleyrette (2003), Watkins et al. (1993, 1997), West (1993a), McLendon (1958a,b), and Reavis (1958).
b. Dates are approximate because the changes did not occur for all employees at the same time.
c. Assigned to both the gamma dose and beta dose if shielded and open-window film readings were less than the MDL.
d. Assigned to gamma dose for workers with a high potential for exposure to gamma rays or to beta dose for workers with a high potential for exposure to beta particles (or soft X-rays) if shielded and open-window film readings were less than the MDL.
e. Assigned to beta dose if shielded and open-window film readings were less than the MDL.
f. The actual shielded and open-window film readings were used to calculate the gamma and beta doses even when the film readings were less than the MDL.

exchange, when thousands of films were read in large batches by film badge technicians with widely varying experience, an MDL of about 30 mrem was about as good as could be expected (Morgan 1961). Assigned doses to monitored workers at the Y-12 Plant were particularly significant in the 1950s when film badge dosimeters were exchanged on a weekly basis (Tables 3-2 and 3-3). For example, a monitored worker could have a quarterly assigned gamma dose during 1953 of as much as 650 mrem (i.e., 13 weeks times 50 mrem/wk). The large amount of assigned dose to workers in the early 1950s resulted in quarterly dose data that were found not to fit lognormal or other commonly used statistical distributions (Attachment B, pages 1-4).

Neutron-sensitive films were added to the film badge dosimeters in 1949 for the assessment of neutron exposures to workers (Struxness 1949b; Long 1950; ORAUT 2009b), and were exchanged initially on a biweekly schedule (Souleyrette 2003). These neutron-sensitive films were nuclear track emulsions, Type A (or NTA films) that had been calibrated using neutrons from a polonium-beryllium (^{210}Po-Be) source starting in 1949 (Souleyrette 2003; Struxness 1953) and an americium-beryllium (^{241}Am-Be) source starting in the early 1960s (Souleyrette 2003; UCNC 1963). Neutron doses were recorded as zero if (1) the worker was not exposed to neutrons and the neutron film in the worker's film badge was not processed or read and (2) the neutron film in a worker's badge was processed but the reading was less than the MDL of the neutron film. The MDL of the neutron film is believed to be 50 mrem for all years of use at Y-12 (ORAUT 2009b).[1] There were only a few locations at the Y-12 Plant where neutron exposures were routinely possible, and in these cases personnel monitoring was provided by the use of NTA films in the film badge dosimeters (Emlet 1956).

During the last quarter of 1962, the NTA films were desiccated and sealed in a moisture-proof "pouch" of paper (Morgan, Davis, and Hart 1963). It had been shown by Cheka (1954) that fading of the latent

1 An MDL of 50 mrem for NTA film applies to neutron energy spectra similar to those from a ^{210}Po-Be or ^{241}Am-Be neutron calibration sources. The MDL of the NTA film can be greater than 50 mrem for a workplace spectrum of neutrons that is severely degraded in energy compared to that from a ^{210}Po-Be or ^{241}Am-Be neutron calibration source. The neutron spectra from all radionuclide sources using the (α,n) reaction in beryllium are similar, and the average energy of the neutrons is about 4 MeV (Nachtigall 1967; Kerr, Jones and Hwang 1978).

image of neutron-produced recoil ions was reduced by an appreciable factor when the film was packaged in a moisture-proof container. Thornton, Davis, and Gupton (1961) experimented with moisture-proof pouch paper and found that the latent image of neutron-produced recoil ions could be controlled while the film remained in the film badge dosimeter (Morgan, Davis, and Hart 1963, Figure 23). Before this time, it was necessary to process and read NTA films on a two to four-week period for workers who were routinely exposed to neutron radiation. Starting in late 1962, however, it was possible to achieve complete film badge dosimetry for gamma, beta, and neutron radiation on a regular quarterly exchange cycle (Morgan, Davis, and Hart 1963).

External monitoring records for 1950 to 1988 were provided by the Y-12 Plant from 1978 through the early 1990s for use in epidemiologic studies by the Oak Ridge Associated Universities (ORAU) Center for Epidemiologic Research (CER) (see Section 4.1). These records were quarterly data with each record containing a two-digit year and single-digit quarter. The study of the Y-12 monitoring program over many years has confirmed the use of weekly and monthly exchange schedules during the earlier years of Plant operation, rather than a quarterly schedule as implied by the records themselves. In addition, many of the nominal quarterly results in earlier years are equal to the product of the existing MDL times 13 weeks, which lends further evidence for a weekly exchange frequency (Table 3-2). For some time, it was assumed that no external monitoring records were available before 1950. Following considerable investigation by the ORAU Team, including interviews with knowledgeable Y-12 staff members, it was discovered that a limited set of external monitoring data did exist for 1948 and 1949 (West 1980). Further investigation resulted in the retrieval of a single electronic external monitoring data file with 11,492 records (ORAUT 2013).

Recorded doses throughout the film badge period reflect not only individual radiation exposures but also changing recording practices and other administrative procedures and policies. In addition, calibration equations and other technical aspects had an effect on the quarterly doses recorded for an individual worker. The recorded dose from penetrating radiation was the sum of the doses from gamma rays and neutrons during the exposure period, and the recorded dose to the skin was the sum of the dose from beta particles and the penetrating dose from gamma rays plus neutrons. The recorded quarterly dose to the skin (or shallow dose) to a Y-12 worker should always be equal to or greater than the worker’s quarterly penetrating (or deep) dose.

3.2 1948 TO 1949

The first experience with the machining of uranium metal at the Y-12 Plant occurred in December 1947 in a shop in Building 9766 (Murray 1948a; Emlet 1952). In the spring of 1948, steps were taken for the transfer of certain weapon fabrication functions from Los Alamos National Laboratory to Building 9212 of the Y-12 Plant, where the chemical processing of uranium had long been in existence. 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 (Struxness 1948; Emlet 1952).

The HP Department started an external dosimetry 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 (Murray 1948b,c; Struxness 1948, 1949b). Radiation doses to the hands were measured using finger film pads exchanged on a daily basis (Larson 1949) or rubber finger rings containing film (Struxness 1949c) that were exchanged on a daily basis. The radiation doses to the whole body were recorded using both pocket ionization chambers (PICs) exchanged on a daily basis and PF-1B film badge dosimeters exchanged on a weekly basis (Souleyrette 2003). The MDLs for these dose measurements during the 1948-1949 period were approximately 5 mrem for the PICs and 30 mrem for the film in the finger film pads, film in the rubber finger rings, and sensitive film in the badge dosimeters.

The single Y-12 external monitoring file for 1948 and 1949 contained weekly records with dose fields based on PIC and film badge doses (ORAUT 2013). Although 69% of the 11,492 records in this monitoring file were blank for all dose fields, analysis of the 3,616 records that contain dose values was carried out with results published in a report (ORAUT 2013). The external monitoring data for 1948 and 1949 are not readily available by social security number and are not being supplied by Y-12 in response to Energy Employees Occupational Illness Compensation Act requests (Souleyrette 2003). The data from the Y-12 external monitoring file for 1948 and 1949 have been posted on an internal server at the ORAU Team Cincinnati Operations Office (COC) and linked to other worker information for dose reconstruction purposes for Y-12 workers. The film badge period for Y-12 is considered to range from 1950 through 1979 because nearly all film badge doses for 1948 and 1949 had the value of the MDL, and the PIC reading was the dose of record for this period (ORAUT 2013).

3.3 1950 TO 1951

An extensive documentation of the worker radiological protection programs beginning in the 1950s is in *Recycled Uranium Mass Balance Project for the Y-12 National Security Complex Site Report* (BWXT Y-12 2000). The external dosimetry program in place in 1950 was expanded to include all Y-12 personnel working with (1) depleted uranium metal, (2) discrete sources of gamma rays or beta particles, (3) X-rays, and (4) materials contaminated with fission products (McLendon 1960). The film pads and rubber film rings were replaced with plastic film rings to assess beta dose to the hands of depleted uranium metal workers (Struxness 1951b, 1952, 1953). The film badge and plastic film rings were normally exchanged on a weekly basis (Souleyrette 2003).

It was the policy at Y-12 in the 1950s to monitor all workers whose potential radiation exposure might exceed 10% of the radiation protection guidelines (RPGs) in affect at that time (Souleyrette 2003). The RPG for the deep or penetrating dose from gamma rays in 1950 and 1951 (Table 3-1) was 0.3 rem/wk (3.9 rem/quarter) and the 10% value for this RPG was 30 mrem/wk (390 mrem/quarter). Other workers at Y-12 were monitored because they had the potential to exceed the 10% value of the RPGs for the shallow or nonpenetrating dose from beta particles (ORAUT 2007).

Dosimetry practice was to record weekly open-window dose or nonpenetrating dose from beta particles (and low-energy X-rays) or the penetrating doses from gamma rays behind the 1-mm cadmium filter as zero if they were less than 30 mrem (West 1993a). As a result, there was only one positive penetrating gamma-ray dose of 65 mrem to the whole body among the 268 quarterly doses for the 148 workers monitored in 1950, and none of the 406 gamma-ray whole-body doses were positive for the 184 workers monitored in 1951. There were, however, a number of positive skin doses (or nonpenetrating doses) from beta particles among monitored workers in 1950 and 1951 (ORAUT 2007).

3.4 1952 TO MID-1956

The documented dosimetry policy at the Y-12 Plant during this period was to assign the MDL dose for weeks with results less than the MDL for either gamma or beta radiation (Table 3-3). The MDL was estimated to be 50 mrem during weeks 1 to 38 of 1952, 43 mrem during weeks 39 to 52 of 1952, and 50 mrem during all of 1953 and weeks 1 to 30 of 1954. For the remainder of 1954, all of 1955, and the first half of 1956, the MDL was 30 mrem. The assigned MDL dose (Table 3-3) was recorded as gamma or beta radiation according to a worker's potential type of exposure as judged by the HP staff (West 1981). That is, the MDL was assigned to gamma rays and to penetrating radiation for persons with potential for that kind of exposure. For persons working with natural or depleted uranium, which involves exposure to nonpenetrating radiation such as beta particles and low-energy X-rays, the MDL was assigned to beta radiation. In practice, however, weekly doses less than the MDL were often left blank in the computer records for the Y-12 film badge program (ORAUT 2009a).

In 1981 a discrepancy was noted in the penetrating radiation doses recorded for Y-12 workers in 1954 (Beck 1981; West 1981). The average yearly value for a Y-12 worker in 1954 was only about 10 mrem, whereas it was several hundred mrem for 1952, 1953, and 1955. A review of the 1952–1955 data by Plant personnel indicated that many workers assigned to departments with a penetrating dose potential showed elevated nonpenetrating (or skin) doses in 1954 (Beck 1981). However, these same workers showed elevated penetrating radiation doses and low nonpenetrating radiation doses in 1953 and 1955. For 61 workers, it was decided to exchange the penetrating and nonpenetrating radiation doses in the computer records for the Y-12 film badge program in 1954 (West 1981).

From 1952 to mid-1956, the differences between the doses summed to get the skin and penetrating doses now appear to be random, with some being greater than the skin or penetrating doses and others being smaller. In general, comparisons between the skin and penetrating doses and the sums of the beta, gamma, and neutron doses used to determine these doses are highly consistent during the film badge program at the Y-12 Plant from 1952 to 1979.

3.5 MID-1956 TO 1960

The radiation dosimetry policy to monitor only selected workers (approximately 10-20%) was continued (Watkins et al. 1993, Figure 6). Line supervision at the Y-12 Plant, with the assistance of the HP Department, decided which groups and which persons in a group would be assigned to the film badge monitoring program, and kept the list of assigned workers up to date (Patterson, West, and McLendon 1957; West 1993b). The workers typically selected for the program were those whose potential radiation exposure might exceed 10% of the RPGs in effect at that time (Souleyrette 2003). For example, the 10% value for penetrating dose was 30 mrem/wk (390 mrem/quarter) from 1956 through 1958 and 300 mrem/quarter from 1959 through 1960 (Table 3-1). The line supervisor initiated requests for the HP Department to either add or remove workers from the film badge program. HP forwarded the request to the monitoring laboratory, with all necessary data on a formal request card. The film badge dosimeters were exchanged on a monthly basis (Table 3-2). Monthly doses for film badge dosimeters reading less than the MDL were recorded as 15 mrem, half the MDL (Table 3-3), and entered as beta doses.

In 1958, the external monitoring of 704 workers was reviewed during the switch from a weekly to a monthly badge exchange frequency (McLendon 1958a,b; Reavis 1958). Some of the factors considered in the review were (1) type of exposure expected, (2) exposure potential involved, (3) typical experience over the last year with respect to average and high exposures, (4) expected changes in this typical experience in the near future, and (5) statistical limit of errors and detectability. As a result, it was decided to make a number of changes in the external monitoring program during April 1958 (McLendon 1958a). The reasons for and the nature of the changes were discussed with, and agreed upon, by supervision for the various departments (McLendon 1958a). Of the 704 workers involved in the initial review, 89 were dropped from the external monitoring program and 615 were selected to remain in the program (McLendon 1958a). The workers in the program were distributed among departments as follows (department number in parentheses): 207 in A Wing, H2, and F Area (2703), 58 in Z-Area (2701), 53 in Product Control (2665), 45 in Production and Inspection (2233), 38 in H-2 Foundry (2702), 34 in Product Processing (2617), 31 in the 9215 Rolling Area (2793), 25 in the Fire Department (2093), 24 in Uranium Chip Recovery (2618), 23 in Mechanical Inspection (2044), and 77 in 10 other departments [Electrical Maintenance (2077), Medical Department (2090), Guard Department (2091), Health Physics (2108), Plant Superintendent and Directors (2200), Shift Superintendents (2205), Special Testing (2231), Development Operations (2301), Product Chemical (2616), and Chemical (2619)]. During October 1958, the switch from a weekly to a monthly badge exchange frequency was extended to all departments at the Y-12 Plant (McLendon 1958b, Reavis 1958).

On June 16, 1958, an unexpected nuclear excursion occurred in the C Wing of Building 9212 at the Y-12 Plant (UCNC 1958). An enriched uranium nitrate solution, sufficient to become critical, was drained from a bank of “always safe geometry” cylinders with small diameters into a 55-gal drum during an operation in which only water was expected to be in the cylinders. Workers who were not expected to be exposed to radiation during this operation and were not wearing film badge dosimeters received penetrating doses from gamma rays and neutrons ranging from about 23 to 365 rem (Hurst, Ritchie, and Emerson 1959).[2] These workers were identified by neutron activation of an indium strip in their security badge and neutron activation of sodium in their blood. Their radiation doses were estimated using each worker’s blood sodium activation data and other data obtained from a controlled physical mockup of the accident (Callihan and Thomas 1959). More information on these workers and 23 other workers who were in the area of the excursion but exposed to much smaller radiation doses based on neutron activation of the indium foil in their security badges are available on an internal drive of a data server at ORAU-COC (ORAUT 2006).

3.6 1961 TO 1979

As a result of the 1958 criticality accident at the Y-12 Plant, a program was instituted in 1961 to monitor all Y-12 workers for external radiation exposure using a newer dosimeter system that was an integral part of the worker’s security badge and contained components for routine and accident-related dosimetry (Thornton, Davis, and Gupton 1961; McLendon 1963; McRee, West, and McLendon 1965; ORAUT 2009a). The film badges were read quarterly (Table 3-3), and the quarterly readings of the film badge dosimeters were recorded as determined, even if the readings were less than the MDL, and thus essentially not different from zero (West 1993a).

In 1962 a semiautomatic film reader was developed and installed during the third quarter (Q3) to measure simultaneously the transmission of light through four film areas: the open window and three areas with plastic, aluminum, and cadmium filters. Light transmission measurements through each filter area were recorded in volts on punch cards (UCNC 1963). Factors for converting the volts to radiation doses were calculated from sets of calibrated films. The radiation doses were tabulated by computer using the volts on the punch cards, and the computer-tabulated doses were used as the dose of record for each quarter. The film control program was reviewed at that time and was changed to focus on dose levels of chief interest (i.e., at ranges from 120 to 2,500 mrem) (UCNC 1963; McLendon 1963). As a result, the calibration films were exposed to gamma doses ranging from 0 to 5,000 mrem (i.e., 0, 30, 120, 240, 480, 720, 960, 1440, 1920, 2880, 3840, and 5000 mrem). In 1972, additional gamma doses of 1400, 1750, and 3250 mrem were added to the films to better define the calibration curve for the film badge dosimeters at higher gamma doses (Sherrill and Tucker 1973).

The external doses to Y-12 workers were always determined from the film readings behind the cadmium filters and open windows of the film badges (Sherrill and Tucker 1973). The film areas behind the plastic and aluminum filters in the newer dosimeters were read and recorded, but they were not used in the normal evaluation of worker doses. The film badge period ended in 1979 as film dosimeters at the Y-12 plant were largely replaced by TLDs (McLendon et al. 1980; Howell and Batte 1982; BWXT Y-12 2001).

4.0 <u>Y-12 EXTERNAL DOSE DATABASE</u>

4.1 DATA DELIVERED TO ORAU/CER

From 1978 through the early 1990s, the Y-12 Plant delivered electronic files of worker data to CER as a resource for the Health and Mortality Studies conducted for DOE and its predecessor agencies.

---

[2] The accident doses for the eight most highly exposed Y-12 workers were summed with data on the film-badge doses from gamma rays for other Y-12 workers to obtain the very large entry for the collective penetrating dose in 1958 to all workers at the Y-12 Plant in Strom et al. (1996, Table 4).

Data in these files had been obtained from hard-copy records and manually transcribed by UCCND beginning in 1965 at the request of the AEC (Denton and Fore 1979). Files containing records for more than 17,000 Y-12 workers were received on magnetic tapes that included beta, gamma, and neutron radiation measurements, penetrating dose and skin dose, and additional relevant information. Due to changes over time in recordkeeping practices and procedures at Y-12, the files were in several similar but not identical formats. Most data elements were represented in all format types but differed by label, measurement units, and other properties. CER transferred all the data from tape to disk and constructed a carefully linked relational database with a standardized file format (Watkins et al. 1993, 1997).

The data set underlying this analysis consists of more than 512,000 records for 1950 to 1988 with more than 425,000 records pertaining to 1979 or earlier. Records contain all data elements received from the original Y-12 files, including first, middle, and last name, plant badge number, social security number, year of record, quarter of record, quarterly summations of dose readings for the monitoring period (weekly, monthly, or quarterly), and other work history, processing, and demographic data. The quarterly summations are of beta, gamma, and neutron measurements in mrem. Although each record has a flag to note an error condition, this flag had all null values before 1980 and was not relevant for the film badge period of interest. The database records from the film badge period (through 1979) were converted to a text file used for developing methods to provide individual doses for unmonitored quarterly periods of employment. To maintain confidentiality of worker data, personal identifying information was not included.

4.2 SUBGROUP DATA FOR REGRESSION ANALYSIS OF GAMMA DOSES

Data for a subgroup of 147 Y-12 workers provide the basis for the regression analysis to evaluate the time trend in the dose potential from gamma radiation during the period from 1956 to 1965. The 147 workers in this subgroup were employed in departments where most job tasks involved a potential to gamma radiation and were monitored before and after 1961. The regression model can be used to describe the temporal pattern of the gamma dose, and the results can be used to estimate quarterly distributions of gamma dose for unmonitored quarters before 1956.

Job titles with corresponding dates were obtained for each of the 147 long-term Y-12 workers from data acquired by ORAU/CER from the Y-12 Plant. Frequently, multiple job titles for individuals showed a progression of promotions as they gained skills and seniority. A recurring example was the progression from machine operator to specialty machinist to machinist and, occasionally, to supervisor of machining. For each individual in each group, the job held during the majority of the period from 1956 to 1960 was selected, and the job was classified by type of activity (e.g., machining) and duties (worker, foreman, supervisor, or manager).

Table 4-1 lists the results of the job analysis for the gamma dose regression group. Among the 147 employees, 129 or about 88% were involved in performing tasks that involved no management or supervisory duties. Most of these 129 were machinists, chemical or production operators, or fire and security workers. Another 14 members or about 10% of this group were laboratory, inspection, or production supervisors, fire captains, or foremen, and carried out some supervisory tasks. The foremen probably had similar exposure potential as their workers since they performed similar tasks. The supervisors probably had similar or somewhat lower exposure potential as the workers they supervised since they may have had less direct contact with radioactive materials. Only four members or about 3% of the 147 individuals were managers, including one superintendent of utilities, one shift superintendent, and two assistant shift superintendents.

Table 4-1. Job activities and duties for 147 long-term Y-12 workers selected for regression analysis of gamma doses.

Activity	Duties	Number of workers
Fire and security	Supervisor	5
Fire and security	Worker	14
Inspection	Supervisor	1
Inspection	Worker	6
Laboratory work	Supervisor	3
Laboratory work	Worker	6
Machining	Worker	71
Management	Manager	4
Medical	Worker	1
Production	Foreman	4
Production	Supervisor	1
Production	Worker	28
Production support	Worker	2
Research and development	Worker	1

5.0 STATISTICAL METHODS

5.1 MAXIMUM LIKELIHOOD ESTIMATION FOR LOGNORMAL DATA WITH NONDETECTS

For notational convenience, let the m detected radiation doses d_i be listed first followed by the d_i^* indicating nondetects, so that the data are $\mathbf{d} = \{d_i,\ i = 1,...,m,\ d_i^*,\ i = m+1,...,n\}$, and let $\mathbf{x}_i$ be the row vector of explanatory variables for each value of i. If the value of d_i^* is the MDL, then d_i is in the interval $(0,d_i^*)$ and this is an example of a left singly censored sample (Type I). The situation where the d_i^* are different is known as randomly (or progressively) left-censored data (Cohen 1991; Schmoyer et al. 1996). If a value of zero is recorded for d_i if the measured dose is less than the MDL, this is sometimes referred to as a "missed dose" and should not be confused with an unmonitored "missed dose."

Assuming the data are a random sample from a lognormal distribution, the log of the likelihood function for the unknown parameters β, σ, given the data, is:

$$L(\boldsymbol{\beta},\sigma) = \sum_{i=1}^{m} \log[g(d_i;\mu_i,\sigma)] + \sum_{i=m+1}^{n} \log[G(d_i^*;\mu_i,\sigma)], \qquad (5\text{-}1)$$

where $\mu_i = \mu(\mathbf{x}_i, \boldsymbol{\beta})$, $g(d;\mu,\sigma)$ is the probability density function for lognormal distribution, and $G(d^*;\mu,\sigma)$ is the lognormal cumulative distribution function (CDF) [i.e., $G(d^*;\mu,\sigma)$ is the probability that d is less than or equal to d*]. The ML equations are obtained by differentiating the log-likelihood function (1) with respect to the β_j, j = 1,…, p and σ. The resultant equations cannot be solved directly, so a Newton-Raphson iterative algorithm is used to find a root of this system of equations. The numerical approach to obtain a unique global maximum of (1) can be implemented based on the R function "optim()," a general-purpose optimization. The large sample variance-covariance matrix of the ML estimate $\hat{\boldsymbol{\beta}}, \hat{\sigma}$ can be obtained by inverting the information matrix evaluated at $\hat{\boldsymbol{\beta}}, \hat{\sigma}$. Further details and instructions on how to obtain and use R can be found in Frome and Watkins (2004).

5.2 UPPER CONFIDENCE LIMIT FOR PTH PERCENTILE WITH NONDETECTS

Let d_p denote the 100pth percentile of the lognormal distribution. For complete samples the point estimate is $d_p = \exp(\bar{y} + z_p s_y)$ where z_p is the pth quantile of the standard normal distribution. $U(p,\gamma)$

is the value such that we are γ% confident that at least p% of the values is below this tolerance limit. In small samples without nondetects, exact 100γ% for d_p can be obtained using the method of Johnson and Welsh (1940).

For censored data, the large sample ML approach can be used to obtain a point estimate of

$y_p = \log(d_p)$, *which is* $\hat{y}_p = \hat{\mu} + z_p\hat{\sigma}$ *with variance:*

$$\begin{aligned}\mathrm{var}(\hat{y}_p) &= \mathrm{var}(\hat{\mu} + z_p\hat{\sigma}) \\ &= \mathrm{var}(\hat{\mu}) + z_p^2\,\mathrm{var}(\hat{\sigma}) + 2z_p\,\mathrm{cov}(\hat{\mu}, \hat{\sigma}).\end{aligned}$$

The 100γ% upper confidence limit for d_p (i.e., the estimated 100p-100γ geometric tolerance limit) is:

$$\hat{U}(p,\gamma) = \exp[\hat{y}_p + t(\gamma, m-1)\mathrm{var}(\hat{y}_p)^{1/2}]. \tag{5-2}$$

All of the above quantities can be obtained from the R function "lnmlnd()" (Frome and Watkins 2004).

5.3 PREDICTION DENSITY WITH NONDETECTS

To estimate the prediction density for an unmonitored quarterly dose z = log(d) at known values of the explanatory variables x_f, we use the "large sample" maximum likelihood prediction density (MLPD) proposed by Lejeune and Faulkenberry (1982):

$$q(z; \mathbf{x}_f, \mathbf{y}, \mathbf{X}) = n[\mu(\mathbf{x}_f, \hat{\boldsymbol{\beta}}), \hat{\sigma}^2 + \mathrm{var}[\mu(\mathbf{x}_f, \hat{\boldsymbol{\beta}})]], \tag{5-3}$$

along with the ML estimate $\hat{\boldsymbol{\theta}}$, and the estimated variance-covariance $V(\hat{\boldsymbol{\theta}})$. If the mean is linear in **X** then $\mu(\mathbf{x}_f, \hat{\boldsymbol{\beta}}) = \mathbf{x}_f\hat{\boldsymbol{\beta}}$, and $\mathrm{var}(\mathbf{x}_f\hat{\boldsymbol{\beta}}) = \mathbf{x}_f V(\hat{\boldsymbol{\beta}})\mathbf{x}'_f$, where $V(\hat{\boldsymbol{\beta}})$ corresponds to the p × p submatrix of $V(\hat{\boldsymbol{\theta}})$ obtained by deleting the last row and column. It then follows from large-sample results for ML estimators (Frome and Watkins 2004, Section 3.4) that the prediction density for z is approximately:

$$q(z|x_f) = n(\mathbf{x}_f\hat{\boldsymbol{\beta}}, \hat{\sigma}^2 + \mathbf{x}_f V(\hat{\boldsymbol{\beta}})\mathbf{x}'_f), \tag{5-4}$$

(i.e., the prediction density for d is lognormal). In particular, if p=2, $\boldsymbol{\beta} = (\alpha,\beta)$, and $\mathbf{x} = (1, x_f)$, then $\hat{\mu}(\mathbf{x}\hat{\boldsymbol{\beta}}) = \hat{\alpha} + x_f\hat{\beta}$ and $\mathrm{var}[\hat{\mu}(x_f\, \hat{\boldsymbol{\beta}})] = \mathrm{var}[\hat{\alpha} + x_f\hat{\beta}]$. The MLPD is

$$q(z|x_f) = n(\hat{\alpha} + \hat{\beta}x_f, \hat{\sigma}^2 + \mathrm{var}[\hat{\alpha} + x_f\hat{\beta}]), \tag{5-5}$$

where $\mathrm{var}[\hat{\alpha} + x_f\hat{\beta}] = \mathrm{var}(\hat{\alpha}) + 2x_f\,\mathrm{cov}(\hat{\alpha}, \hat{\beta}) + x_f^2\,\mathrm{var}(\hat{\beta})$.

5.4 NONPARAMETRIC METHODS FOR SAMPLES WITH NONDETECTS

The product limit estimator (PLE) of the CDF was first proposed by Kaplan and Meier (1958) for right-censored data. For randomly left-censored data, Schmoyer et al. (1996) defined the PLE as follows: Let $a_1 < \ldots < a_L$ be the L distinct values at which detects occur, r_j be the number of detects at a_j, and n_j be the sum of nondetects or detects that are less than or equal to a_j. Then the PLE is 0 for $0 \le x \le a_1'$ where a_1' is a_1 or the value of the detection limit for the smallest nondetect if this limit is less than a_1. For $a_1' \le x < a_L$, the PLE is $\hat{F}_j = \prod_j (n_j - r_j)/n_j$, where the product is over all $a_j > x$, and the PLE is 1 for $x \ge a_L$. If there are only detects, this reduces to the usual definition of the CDF. The R function "plend()" can be used to compute the PLE (Frome and Watkins 2004).

The PLE is used to determine the plotting positions on the horizontal axis for the censored-data version of a theoretical lognormal q-q plot (Chambers et al. 1983; Waller and Turnbull 1992). The q-q plot is obtained by plotting a_j (on log scale) versus $H_j = G^{-1}((\hat{F}_j + \hat{F}_{j-1})/2)$, where G^{-1} is the inverse of the CDF of the standard normal distribution. If the empirical distribution approximates log normal, the points on the plot will fall near a straight line. The square of the correlation coefficient $R^2 = \text{cor}(\log(a_j), H_j)^2$ is an objective evaluation of the lognormal fit. In the complete data case, this will closely approximate the Shapiro-Wilk W statistic used as a test for normality (Royster 1982). A formal test for normality of randomly left-censored data has not been developed.

5.5 NONPARAMETRIC UPPER TOLERANCE LIMIT

A nonparametric upper tolerance limit can be obtained using the method described by Somerville (1958). Given a random sample of size n from a continuous distribution, with a confidence level of at least γ, 100p% of the population will be below the kth-largest value in the sample. The value of k for specific values of n, p, and γ can be obtained from the R function "nptl()" (Frome and Watkins 2004). The 100γ% upper tolerance bound is equivalent to an upper 100γ% confidence interval for the 100pth percentile of the population.

5.6 SCALING PROCEDURE BASED ON MAXIMUM LIKELIHOOD METHODS

Let d_t be the worker's recorded dose during quarter t and μ_t and σ_t be known lognormal parameter values for that same quarter. Then $y_t = \log(d_t)$ follows the normal distribution with mean $\mu_t + \varphi$, and standard deviation σ_t, where the scaling factor φ represents the average relative difference (on the log scale) of the individual's doses from the population values. The ML estimate of φ is $\hat{\varphi} = \Sigma_t w_t v_t / \Sigma_t w_t$, where $w_t = 1/\sigma_t^2$, and $v_t = y_t - \mu_t$. The variance of $\varphi = [\Sigma_t w_t]^{-1}$. If for any quarter $d_t = 0$ (indicating a nondetectable dose), replace y_t with y_t^o, the conditional expectation of y given that it is less than the log (MDL). To obtain y_t^o, first calculate $z_t = [\log(\text{MDL}) - \mu_t] / \sigma_t$. Then $y_t^o = \mu_t - [n(z_t)/N(z_t)]\, \sigma_t$, where n(z) is the standard normal density and N(z) is the standard normal cumulative distribution function (Johnson, Kota, and Balakrishnan 1994, Section 10.1).

6.0 EVALUATION OF FILM BADGE DOSES OVER TIME

6.1 ANNUAL DOSES

Figure 6-1 shows the annual employment figures for Y-12 during the film badge period along with the total number of workers monitored at least one quarter during the year and the number whose dose was recorded as zero for every time the employee was monitored during the year. Figure 6-1 confirms that nearly all Y-12 workers were monitored for gamma radiation beginning in 1961 (Watkins et al. 1993, 1997).

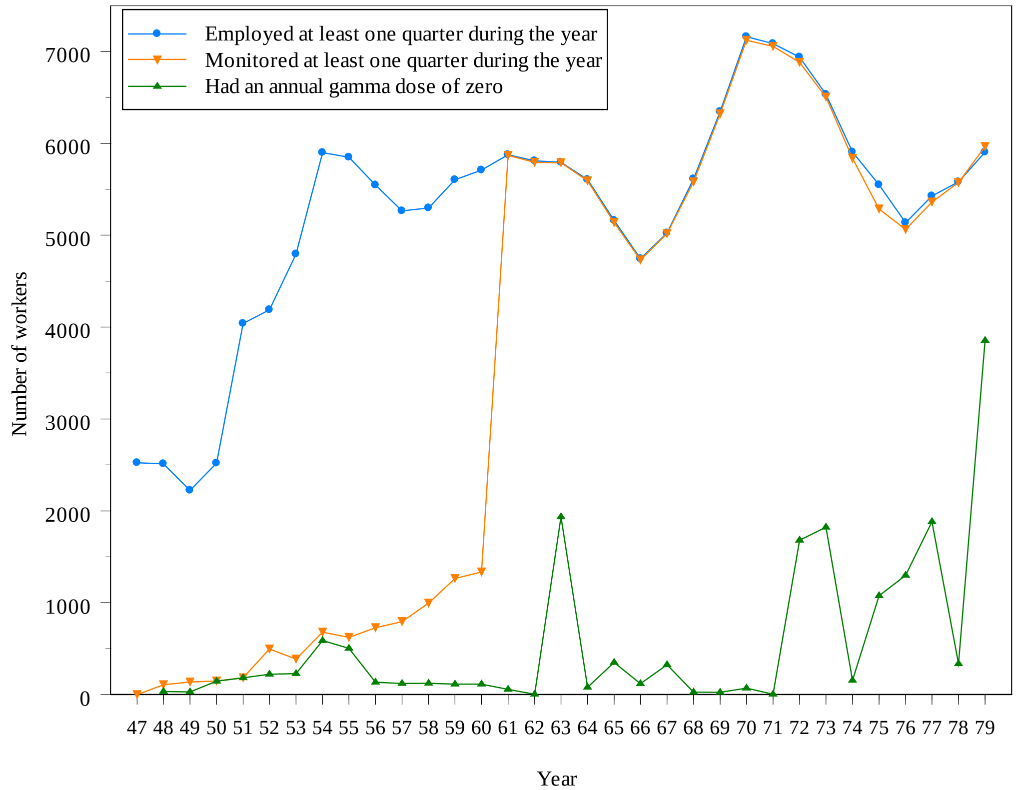

Figure 6-1. Annual employment and film badge monitoring of Y-12 workers for gamma exposure.

6.2 QUARTERLY DOSES

As seen in Table 3-2, film badges were routinely exchanged on a quarterly basis from 1961 to 1979. Although film badges were read more frequently (generally weekly) in earlier years, only quarterly summations were available. The general Y-12 policies for this period (Table 3-3) suggest that there would be no quarterly doses less than 30 mrem with the exception of the period from 1956 to 1961 when the lowest recorded dose could be half the MDL (15 mrem). There were no doses recorded between 0 and 30 mrem before 1956. However, from 1956 to 1961 there were doses between 0 and 15 mrem every year (1956, 1; 1957, 96; 1958, 19; 1959, 70; 1960, 339; 1961, 2,601). From 1962 to 1979 the number of recorded quarterly doses less than 30 mrem ranged from 2,555 in 1979 to 18,090 in 1971, and the number less than 15 mrem ranged from 1,749 in 1964 to 8,708 in 1971.

Histograms were constructed for exploring the distributions of gamma doses for each quarter beginning with 1952, because all quarterly doses in 1951 and all but one dose in 1950 were zero (Watkins et al. 1993, 1997). Attachment A includes annual graphs for 1952 to 1979 with a separate plot for each quarter. In addition to the quarterly histograms, the graphs contain the number of doses, number of zeros, percent of zeros, and maximum dose for each quarter. An examination of the shapes of the quarterly histograms before 1957 revealed little resemblance to a normal, lognormal, or any other statistical distribution. In general, the histograms in this period showed a large number of zeros and a cluster of values around 400 or 600 mrem (Attachment A, pp. 1–4). Film badges were read weekly before 1960, and there were 13 weeks in a quarter. If the MDL was assigned to doses below the MDL as was general policy (Table 3-3), the clustering of quarterly doses around 400 and

600 mrem could be influenced by these dosimetry practices (Section 3.1). After 1956 the histograms showed distributions that typically resembled lognormal with a cluster of values at low doses near zero and skewing to the right.

To further investigate the suitability of fitting lognormal models to the quarterly gamma dose data after 1956, q-q plots and R-square statistics were produced for each quarter (Section 5.4). Attachment B contains these graphs. With few exceptions, R-square was well above 0.9 for quarters in 1956 and later but was much lower in earlier years.

6.3 QUARTERLY GAMMA DOSES FROM 1956 TO 1979

Figure 6-2 shows quarterly gamma doses from 1956 to 1979 in a modified boxplot. The modified boxplot was obtained by calculating the first and third quartiles (i.e., the 25th percentile, xq25, and 75th percentile, xq75,) using inverse interpolation from the PLE to take nondetects into account. The modified boxplots in this TIB show xq25 as an inverted triangle, the median as an open circle, and xq75 as an upright triangle; the box connecting these quartiles is not drawn. The maximum dose is represented by a red bull's eye, and the minimum dose is a diamond if no left-censored data were present. Each dose in a quarter that exceeded (on log scale) log(xq75) + 1.5 × [log(xq75) - log(xq25)] appears as a black plus sign (+). All data points in a quarter that are less than (on log scale) log(xq25) - 1.5 × [log(xq75) - log(xq25)] are also shown as plus signs, although these might be incomplete if there were a large number of zero doses.

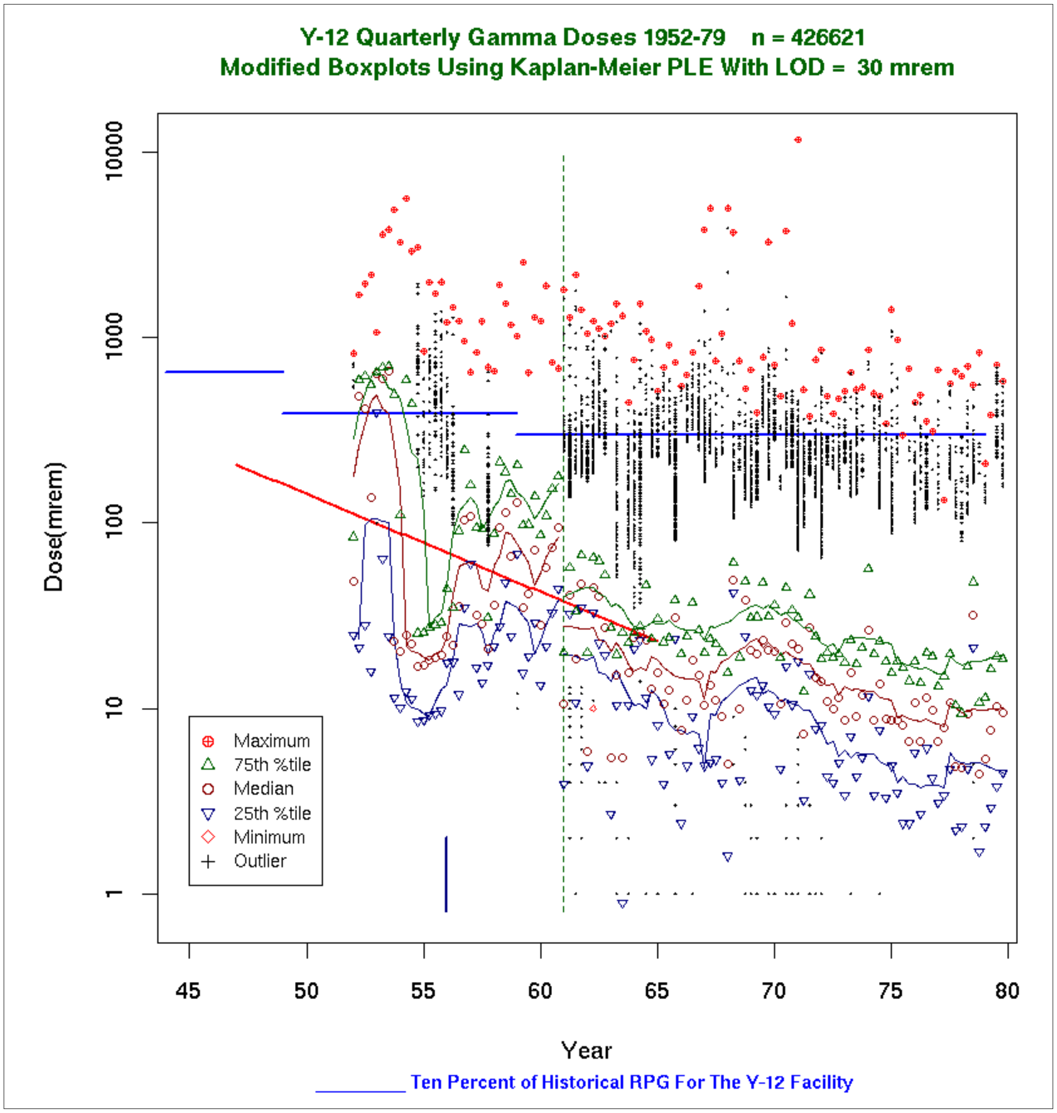

Figure 6-2. Quarterly gamma doses, 1952 to 1979.

In addition to the modified boxplot, Figure 6-2 includes a green vertical dashed line to indicate where complete monitoring began for the Y-12 workforce and a short blue vertical line to mark the year when lognormal distributions generally began to fit the quarterly data. The horizontal blue lines indicate the dose that was 10% of the RPG for the various time periods. The solid red line is the regression line derived from the doses for the subgroup of 147 workers described in Section 4.2. Details of the regression are in Section 7.1. The distributions before 1961 are for workers who were selected for monitoring based on their potential for exposure (i.e., individuals with low exposure potential were not included). The abrupt drop in these distributions in 1961 demonstrates clearly that individuals with low exposure potential were being excluded before 1960. If large groups of individuals with high exposure potential were not excluded before 1961, the distributions and related statistics should increase in 1961. This is clearly not the situation shown in Figure 6-2.

6.4 COMPARING 1961 GAMMA DOSE DISTRIBUTIONS OF WORKERS MONITORED VERSUS NOT MONITORED IN 1960

A further assessment of the 1961 gamma doses to appraise whether workers with higher exposure potential had been selected to be monitored before 1961 is presented below. Because reportedly workers monitored before 1961 were selected because of higher dose potential, the distribution of the doses in 1961 for previously monitored individuals should be higher than the distribution of doses for workers who were first monitored in 1961. To verify this selection criterion, the 1961 doses were separated into two groups partitioned by each worker's monitoring status in 1960. "Group 1" consisted of doses for workers monitored in both 1961 and 1960, and "Group 2" included workers monitored in 1961 but not in 1960.

Figure 6-3 provides an initial look at the 1961 Q3 and Q4 gamma doses of the two groups of workers. Because Group 2 was approximately four times the size of Group 1, histograms were based on percents rather than counts. The top two graphs for Group 1 show relatively fewer doses in the lower dose range and distinctly more doses above 100 mrem than the corresponding Group 2 doses.

The statistics above each plot were based on a lognormal model with EX indicating the expected value of the doses, SDX the standard deviation, GM the geometric mean, and GSD the geometric standard deviation. The indicated parameters derived from each of the lognormal models are the natural logarithms of the GM and GSD. These statistics verify that the average doses were higher for workers who had been selected for monitoring in 1960.

Statistics for 1961 quarterly gamma doses are listed in Table 6-1 for the two groups of Y-12 workers. For each group and each quarter the percentiles, Kaplan-Meier (K-M) means, and adjusted cumulative doses were calculated taking into account doses recorded as zero, which indicated film badge readings below the MDL. These statistics were derived using nonparametric left-censored methods with the nondetectable doses designated to have an upper limit of 30 mrem, as described in Frome and Watkins (2004, Section 4.4). In Q1 of 1961 the percents of nondetectable doses were 53 and 86 for the previously monitored and newly monitored groups, respectively, which substantially increased the adjusted cumulative doses, percentiles, and K-M means, particularly for Group 2.

Because there were very few zero doses in Q2, Q3, and Q4 of 1961, the left-censored methods had little impact on the calculated statistics, as can be seen by comparing the directly calculated cumulative doses to the adjusted cumulative doses in Table 6-1. In every quarter of 1961 the 25th, 50th (median), and 75th percentiles for Group 1 workers were higher than those for Group 2. Further, with the exception of Q1, medians for previously monitored individuals were higher than the 75th percentiles for the newly monitored, verifying that workers who were selected to be monitored in 1960 had higher exposure potential.

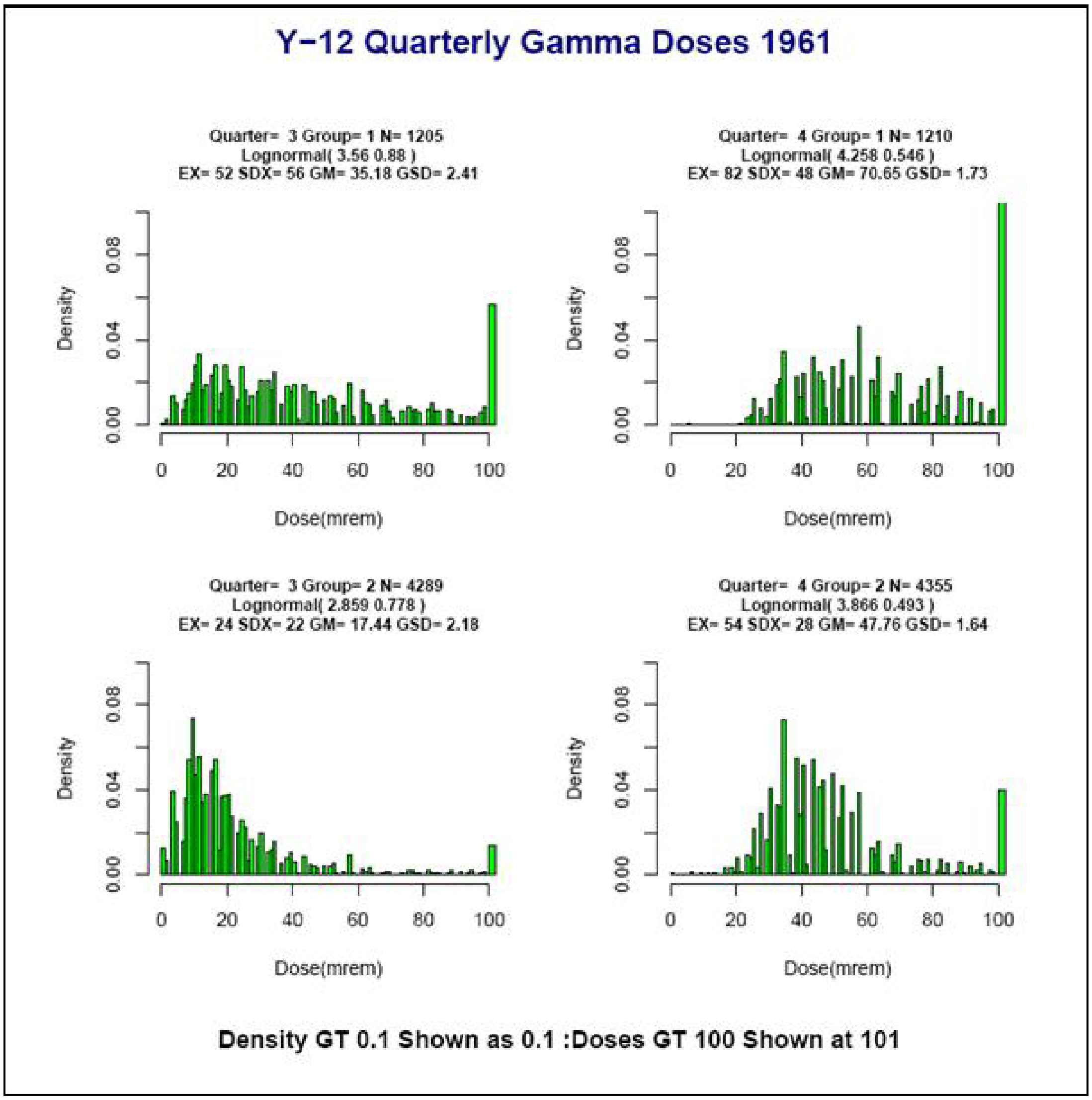

Figure 6-3. Y-12 quarterly gamma doses in 1961 for two groups of workers partitioned by monitoring status in 1960 (Group 1 monitored in 1960; Group 2 not monitored in 1960).

Table 6-1. Descriptive statistics for 1961 Y-12 quarterly gamma doses in mrem for two groups of workers partitioned by monitoring status in 1960.

	Quarter							
	Q1		Q2		Q3		Q4	
Group	**1**[a]	**2**[b]	**1**	**2**	**1**	**2**	**1**	**2**
25th %tile	5.4	3.7	43.8	30.4	18.9	9.9	46.2	34.4
median	12.8	10.2	63.4	38.5	35.8	16.3	67.2	45.1
75th %tile	27.8	16.8	98.2	51.3	67.1	25.5	103.7	56.4
max dose	1,810	1,621	710	1,276	1,791	2,173	483	1,413
K-M mean[c]	38.4	15.8	84.5	47.3	52.4	25.4	82.6	55.4
cum dose[d]	39,350	25,943	103,323	202,773	63,123	108,285	99,946	241,033
cum dose adj[e]	47,078	64,385	103,428	203,437	63,142	108,941	99,962	241,267
% below MDL[f]	53.1	85.9	0.5	0.7	0.1	1.2	0.0	0.1
N[g]	1,226	4,075	1,224	4,301	1,205	4,289	1,210	4,355

a. Y-12 workers in 1961 who were monitored in 1960.
b. Y-12 workers in 1961 who were not monitored in 1960.
c. K-M mean; product-limit estimate of mean using censored data methods with upper limit of 30 mrem for doses recorded as 0.
d. Dose accumulative by adding all recorded quarterly doses for the group.

e. Cumulative dose adjusted upward by using left-censored methods with upper limit of 30 mrem for doses recorded as 0.
f. Percent of records recorded as 0 to indicate below MDL.
g. Number of quarterly doses for the group.

A modified boxplot, as described in Section 6.2, was used to summarize the quarterly gamma dose data for the two groups. The statistics in Table 6-1 are shown in the modified boxplot of Figure 6-4. There are four pairs of boxplots in Figure 6-4, one for each quarter in 1961. The left-hand plot in each pair is for Group 1 and the right-hand plot is for Group 2. A horizontal line is shown at 300 mrem, corresponding to 10% of the quarterly RPG dose in 1961, and it is clear that fewer than a dozen workers from either group had doses above this level in any quarter. Because Group 1 contained approximately 1,200 workers each quarter and Group 2 more than 4,000, at most one-half of one percent of the doses for either group in any quarter were above 10% of the RPG.

Altogether 65 workers, including 35 in Group 1 and 30 in Group 2, had at least one quarterly dose greater than 300 mrem. Group 1 workers were known to have higher exposure potential because they had been selected for monitoring in 1960. Group 2 workers were not expected to have potential for higher exposure, although these 30 individuals received a quarterly dose above 300 mrem in 1961 when all workers began being monitored. Information was gathered to investigate why these 30 workers had not been selected for monitoring in 1960. Collected data included hire dates, dates of change for job titles and departments, monitoring data for earlier years, and all quarterly gamma doses for 1961 through 1965. The 30 Group 2 workers who were not monitored at Y-12 in 1960 and had a quarterly doses greater than 300 mrem in 1961 will be referred to as the “why not monitored?” group. Results of this investigation are listed in Table 6-2. For individuals whose annual gamma dose was above 1,200 mrem, which was 10% of the yearly RPG, each quarterly dose for 1961 and the highest quarterly dose for 1962 are also listed.

The total number of workers in Group 2 was approximately 300 greater during the latter part of 1961 than in Q1, indicating that new employees were probably hired during Q1. Hire dates revealed that four of the “why not monitored?” group were not employed at Y-12 in 1960, and two additional members worked only part of 1960. Among the remaining 24 individuals, 18 had only one quarter with dose above 300 mrem. Dates of change for job titles and departments uncovered five more members of the “why not monitored?” group who changed departments in the second half of 1960 or early in 1961, which might have resulted in increasing their exposure potential. Seven group members had been monitored during the late 1950s and were found to have low gamma doses at that time, with the exception of one quarterly dose of 337 mrem. For the remaining 12 members of the “why not monitored?” group, the explanation of why they were not selected for monitoring in 1960 is less obvious. In 1961 eight of these 12 workers had only one quarterly dose above 300 mrem and an annual dose below 10% of the yearly RPG. The highest quarterly dose in 1962 for six of these eight workers was below 300 mrem; two individuals had a quarterly dose in 1962 above this limit. Among the workers with annual doses in 1961 above 1,200 mrem, one had three quarterly doses each below 80 mrem and a Q3 dose of 1,413 mrem. The final individuals had quarterly doses consistently above 300 mrem.

The dose assignment methodology for unmonitored quarters before 1961 includes an upward scaling factor based on an individual’s doses after 1961 (ORAUT 2004a,b). Details of the scaling factor are in Section 7.4. This scaling factor would be implemented to adjust doses derived for each unmonitored quarter before 1961 for all of the approximately 4,000 Y-12 workers (including members of the “why not monitored?” group) who met the two criteria. In particular, the few individuals for whom there is no clear explanation of why they were not monitored before 1961 would have received doses that were favorable to claimants due to the scaling factor adjustment. Out of more than 5,000 Y-12 workers only six (approximately one-tenth of one percent) might have been overlooked when selecting the workers to be monitored in 1960.

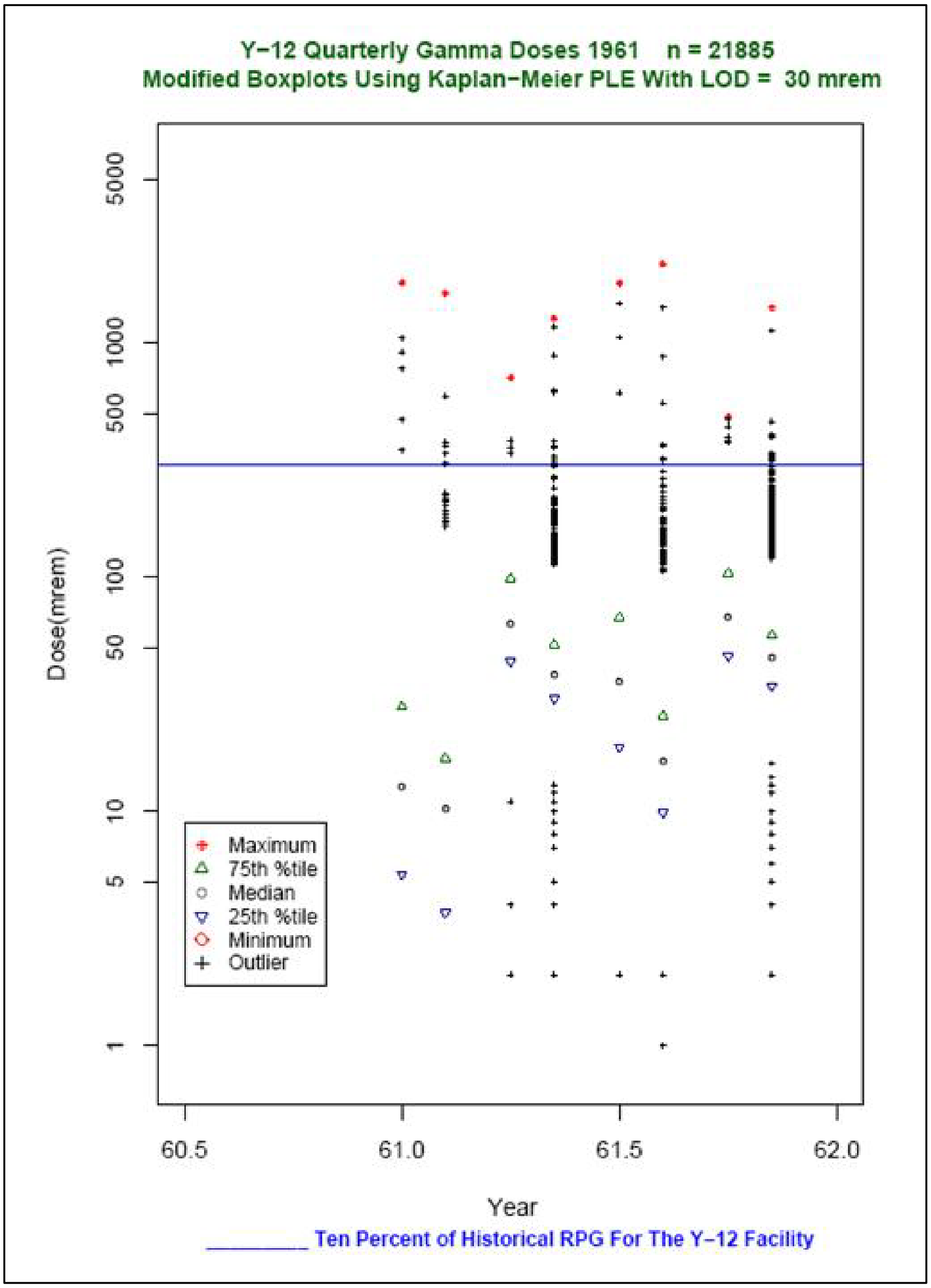

Figure 6-4. Modified boxplot for Y-12 quarterly gamma doses in 1961 for two groups of workers partitioned by monitoring status in 1960.

6.5 LIMITATIONS OF DOSES FOR DOSE RECONSTRUCTION

After reviewing the quarterly histograms, q-q plots, and R-square statistics, as well as studying the monitoring and recording practices during the film badge period, it was decided that a lognormal model could be used with quarterly dose data after 1956 for estimating the prediction density for the dose reconstruction procedure described in ORAUT (2004a). However, quarterly data before 1956 could not be used justifiably for such estimation.

Certain summary statistics were investigated and confirmed the suitability of using the lognormal model and data from the quarter where the unmonitored dose occurred in the process of

Table 6-2. Job and 1961 gamma dose information (mrem) for Y-12 workers not selected for monitoring in 1960 but with a quarterly dose above 300 mrem in 1961.

Annual 1961 dose	Highest 1961 dose	Dept	Comments	Monit. qrtrs 61-65[a]
Not a Y-12 employee during all of 1960				
1518	1413	2703	Hired 4/10/61. 1961 doses – Q2 = 41, Q3 = 64, Q4 = 1413. All 4 doses for 1962 below 80. Had Group 2 max Q4 dose.	16
1198	1170	2619	Hired 1/9/61.	11
1163	871	2722	Hired 1/31/61.	20
614	362	2003	Hired on 10/3/60.	20
516	460	2077	Hired 1/16/61.	17
501	322	2259	Hired 3/1/60. Changed from Dept. 2230 on 8/7/6; high dose in Q4.	13
Previously monitored in late 1950s with same job tasks				
1493	2173	2703	Monitored in 1956 and 1957; low doses. 1961 doses – Q1 = 8, Q2 = 220, Q3 = 2173, Q4 = 92. Highest 1962 dose 98. Had Group 2 max Q3 dose.	19
1745	883	2018	Monitored in 1958 and 1959; low doses. 1961 doses – Q1 = 305, Q2 = 883, Q3 = 230, Q4 = 327. Highest 1962 dose 429.	19
1298	552	2018	Monitored in 1958 and 1959; low doses. 1961 doses – Q1 = 212, Q2 = 129, Q3 = 552, Q4 = 405. Highest 1962 dose 215.	5
792	323	2701	Monitored in 1958 and 1959; three low doses and one dose of 337. Changed from Dept. 2128 on 10/3/60.	20
756	337	2776	Monitored in 1957; dose 0.	19
368	318	2003	Monitored in 1958 and 1959; low doses.	20
362	316	2659	Monitored in 1958 and 1959; low doses.	20
Change in department or job tasks between 1960 and 1961				
1686	1621	2057	Changed from Dept. 2058 on 8/1/60. 1961 doses – Q1 = 1621, Q2 = 23, Q3 = 16, Q4 = 26. Highest 1962 dose 6. Had Group 2 max Q1 dose.	5
1202	401	2018	Switched from machinist on 9/19/60. 1961 doses – Q1 = 337, Q2 = 309, Q3 = 157, Q4 = 401. Highest 1962 dose 557.	20
775	395	2638	Changed from Dept. 2638 on 6/27/60.	20
516	356	2722	Changed from Dept. 2687 on 1/16/61.	20
Unclear why not monitored in 1960				
2443	1127	2018	1961 doses – Q1 = 590, Q2 = 360, Q3 = 366, Q4 = 1127. Highest 1962 dose 1018.	19
2210	1276	2018	1961 doses – Q1 = 378, Q2 = 1276, Q3 = 316, Q4 = 240. Highest 1962 dose 277. Had Group 2 max Q2 dose.	20

Annual 1961 dose	Highest 1961 dose	Dept	Comments	Monit. qrtrs 61-65[a]
1582	617	2018	1961 doses – Q1 = 362, Q2 = 617, Q3 = 323, Q4 = 280. Highest 1962 dose 956.	19
1557	1413	2158	1961 doses – Q1 = 14, Q2 = 77, Q3 = 1413, Q4 = 53. Highest 1962 dose 178.	19
1106	624	2820	Highest 1962 dose 200.	20
905	624	2018	Highest 1962 dose 71.	20
798	381	2018	Highest 1962 dose 296.	20
751	309	2617	Highest 1962 dose 59.	20
683	310	2619	Highest 1962 dose 264.	19
649	333	2617	Highest 1962 dose 569.	19
504	327	2018	Highest 1962 dose 861.	19
370	318	2158	Highest 1962 dose 65.	18
357	300	2018	Highest 1962 dose 19.	20

a. Number of quarters of monitoring data from 1961-65. Any worker with at least 5 monitored quarters in 1961-65 (with similar job duties and location before and after 1961) has a scaling factor applied to the assigned dose for each unmonitored quarter before 1960. Scaling factors less than one are changed to one so that scaling cannot lower dose.

estimating the dose for years after 1956. Table 6-3 lists the summary statistics based on application of a lognormal model to each set of quarterly film badge data beginning with 1956. The five-fold jump between 1960 and 1961 in the number of dose measurements per quarter corroborates the policy change from monitoring selected workers with higher exposure potential to monitoring all workers. Including workers with lower exposure potential led to a generally higher percentage of nondetectable quarterly doses, although this percentage varied substantially from quarter to quarter. The log-scale mean, standard deviation, and standard error of the mean can be used to determine a lognormal prediction density for sampling a dose for an unmonitored quarter.

Table 6-3. Summary statistics for Y-12 quarterly gamma doses, 1956 to 1979.

Year	Qtr.[a]	N[b]	%nd[c]	μ[d]	σ[e]	se(μ)[f]	GM[g]	AM[h]	KM[i]	d_{99}[j]	UTL[k]	npUTL[l]
1956	1	448	71	2.296	2.086	0.178	10	87	67	1272	1957	1207
	2	492	58	3.042	1.220	0.075	21	44	54	358	443	1282
	3	617	40	3.648	1.264	0.058	38	85	83	726	875	977
	4	620	20	4.480	1.184	0.049	88	178	155	1387	1631	935
1957	1	565	10	4.550	0.747	0.032	95	125	119	538	598	612
	2	595	29	3.646	1.191	0.052	38	78	78	613	725	756
	3	668	32	3.563	1.286	0.054	35	81	83	702	835	955
	4	678	57	3.038	1.002	0.052	21	34	41	215	248	586
1958	1	704	25	3.726	0.965	0.038	42	66	67	392	444	484
	2	694	15	4.385	1.187	0.046	80	162	145	1269	1474	875
	3	689	13	4.549	1.020	0.039	95	159	149	1015	1155	1056
	4	788	24	4.116	1.065	0.040	61	108	104	731	833	600
1959	1	844	5	4.727	0.870	0.030	113	165	155	854	941	710
	2	854	44	3.612	1.244	0.049	37	80	70	669	785	595
	3	909	23	3.793	1.025	0.036	44	75	74	481	540	530
	4	1,053	20	4.174	1.004	0.032	65	107	103	671	745	564
1960	1	1,148	28	3.569	1.114	0.035	35	66	66	474	530	502

Year	Qtr.[a]	N[b]	%nd[c]	μ[d]	σ[e]	se(μ)[f]	GM[g]	AM[h]	KM[i]	d_{99}[j]	UTL[k]	npUTL[l]
	2	1,104	11	3.961	1.055	0.032	53	92	88	611	678	517
	3	1,055	4	4.216	1.015	0.031	68	113	104	719	794	452
	4	985	7	4.459	0.937	0.030	86	134	127	764	842	521
1961	1	5,301	78	2.060	1.238	0.035	8	17	21	140	150	222
	2	5,525	1	3.815	0.598	0.008	45	54	56	183	187	269
	3	5,494	1	3.013	0.853	0.012	20	29	31	148	153	178
	4	5,565	0	3.951	0.530	0.007	52	60	61	178	183	244
1962	1	5,583	0	2.460	0.940	0.013	12	18	22	104	108	178
	2	5,352	0	3.910	0.584	0.008	50	59	62	194	199	329
	3	5,394	0	3.630	0.795	0.011	38	52	52	240	248	355
	4	5,327	0	3.346	1.079	0.015	28	51	47	350	366	257
1963	1	5,456	58	2.419	1.217	0.023	11	24	25	190	202	227
	2	5,536	57	2.757	0.882	0.016	16	23	27	123	128	208
	3	5,549	66	1.996	1.581	0.033	7	26	26	291	315	300
	4	5,461	78	2.432	0.903	0.025	11	17	22	93	98	165
1964	1	5,477	83	2.186	1.300	0.047	9	21	34	183	199	255
	2	5,314	83	2.181	1.266	0.046	9	20	35	168	182	230
	3	5,360	14	3.090	1.207	0.017	22	46	41	364	384	288
	4	5,122	73	2.182	1.336	0.033	9	22	25	198	213	276
1965	1	5,037	35	2.735	1.044	0.017	15	27	27	175	183	206
	2	4,474	42	2.433	1.158	0.021	11	22	24	168	179	252
	3	4,345	0	2.713	0.935	0.014	15	23	26	133	139	230
	4	4,336	0	3.505	0.529	0.008	33	38	40	114	117	252
1966	1	4,333	61	1.977	1.436	0.032	7	20	21	204	221	242
	2	4,339	41	2.471	1.284	0.023	12	27	28	235	251	285
	3	4,400	0	2.889	1.416	0.021	18	49	39	484	518	340
	4	4,485	37	2.767	1.074	0.018	16	28	32	194	204	374
1967	1	4,515	76	2.112	1.333	0.039	8	20	26	184	199	326
	2	4,613	45	2.457	1.221	0.022	12	25	27	200	213	280
	3	4,753	9	2.532	0.991	0.015	13	21	22	126	132	176
	4	4,797	47	2.307	1.048	0.019	10	17	19	115	121	189
1968	1	4,884	23	2.027	1.179	0.019	8	15	19	118	125	167
	2	4,974	1	3.971	0.336	0.005	53	56	57	116	118	169
	3	5,212	91	1.612	1.161	0.062	5	10	15	75	80	136
	4	5,293	1	3.468	0.744	0.010	32	42	40	181	187	211
1969	1	5,398	8	2.993	0.742	0.010	20	26	26	112	116	169
	2	5,466	6	2.947	0.883	0.012	19	28	28	149	154	194
	3	5,935	7	3.191	1.022	0.013	24	41	40	262	274	311
	4	5,882	10	2.839	1.044	0.014	17	29	30	194	203	279
1970	1	6,024	6	2.938	1.045	0.014	19	33	32	215	224	242
	2	6,002	5	2.333	0.932	0.012	10	16	16	90	94	95
	3	6,509	6	3.268	0.914	0.011	26	40	39	220	228	225
	4	6,672	19	2.983	0.990	0.013	20	32	32	197	205	243
1971	1	6,759	0	3.230	0.632	0.008	25	31	34	110	113	201
	2	6,757	26	2.012	1.019	0.014	7	13	13	80	83	131
	3	6,629	1	3.225	0.778	0.010	25	34	34	154	158	196
	4	6,556	10	2.651	0.924	0.012	14	22	22	122	126	164
1972	1	6,525	23	2.561	0.970	0.013	13	21	22	124	129	187
	2	6,400	75	2.069	1.115	0.026	8	15	17	106	112	177
	3	6,403	92	1.566	1.106	0.056	5	9	14	63	67	113
	4	6,194	90	1.723	1.123	0.048	6	11	16	76	81	141
1973	1	6,311	58	2.059	1.143	0.020	8	15	16	112	118	162
	2	6,062	89	1.762	1.237	0.055	6	13	19	104	111	144
	3	5,880	35	2.225	1.080	0.016	9	17	18	114	120	190
	4	5,398	96	1.005	1.280	0.133	3	6	15	54	59	79
1974	1	5,298	5	3.277	1.058	0.015	26	46	45	311	325	346
	2	5,359	40	2.203	1.222	0.020	9	19	19	155	164	198
	3	5,364	13	2.630	0.964	0.014	14	22	23	131	136	188
	4	5,214	71	1.997	1.131	0.027	7	14	15	102	109	127
1975	1	5,168	21	2.209	0.988	0.015	9	15	17	91	95	151
	2	4,917	88	1.678	1.170	0.050	5	11	15	81	87	142

Year	Qtr.[a]	N[b]	%nd[c]	μ[d]	σ[e]	se(μ)[f]	GM[g]	AM[h]	KM[i]	d_{99}[j]	UTL[k]	npUTL[l]
	3	4,483	91	1.537	1.112	0.059	5	9	13	62	66	94
	4	4,540	89	1.610	1.075	0.049	5	9	12	61	65	86
1976	1	4,618	45	2.390	0.847	0.016	11	16	17	78	82	131
	2	4,605	83	1.869	1.065	0.036	6	11	13	77	82	126
	3	4,572	46	2.445	0.954	0.018	12	18	19	106	111	143
	4	4,694	95	1.669	0.928	0.072	5	8	13	46	49	70
1977	1	4,933	74	1.825	1.025	0.026	6	10	12	67	71	92
	2	5,021	81	1.869	0.924	0.028	6	10	11	56	59	59
	3	5,058	54	2.325	0.984	0.019	10	17	18	101	106	177
	4	4,902	72	1.646	1.013	0.025	5	9	9	55	58	81
1978	1	5,007	61	1.684	1.038	0.022	5	9	10	60	64	75
	2	5,073	50	2.214	0.972	0.018	9	15	16	88	92	114
	3	5,202	8	3.460	0.724	0.010	32	41	41	171	177	189
	4	5,255	77	1.616	1.108	0.030	5	9	10	66	70	83
1979	1	5,169	77	1.672	1.021	0.027	5	9	10	57	61	87
	2	5,512	83	1.939	0.924	0.029	7	11	12	60	63	80
	3	5,196	86	1.801	1.185	0.044	6	12	18	95	102	236
	4	5,489	88	1.840	1.091	0.043	6	11	16	80	85	142

a. Qtr. = quarter (1, 2, 3, or 4).
b. N = number of quarterly doses.
c. %nd = percent of nondetectable quarterly doses (< MDL).
d. μ = mean of the doses on log scale.
e. σ = standard deviation of doses on log scale.
f. se(μ) = standard error of μ.
g. GM = exp(μ); geometric mean; median of doses on original scale.
h. AM = $\exp(\mu + \sigma^2/2)$; estimate of arithmetic mean of doses on original scale; expected value of dose based on lognormal model.
i. KM = nonparametric K-M (product-limit) estimate of mean of doses on original scale, adjusted for censoring.
j. d_{99} = 99th percentile of doses on the original scale.
k. UTL = 99-95 geometric upper tolerance limit based on lognormal model.
l. npUTL = nonparametric 99-95 geometric upper tolerance limit.

As expected, beginning in 1961 the estimates of mean, median, 99th-percentile, and upper tolerance limits dropped substantially from earlier years because the population of monitored workers was no longer restricted to individuals with higher exposure potential. During the period before 1961, which had numerous unmonitored quarters, the expected dose derived from the quarterly lognormal model [the arithmetic mean (AM)] was generally higher than the mean dose estimated nonparametrically (the PLE). In addition, beginning with Q4 of 1956 through 1960, the upper tolerance limit (UTL) based on the lognormal model generally exceeded the nonparametric estimate (npUTL). These findings support the use of the model-based approach because it would be likely to result in estimated doses that were somewhat higher and therefore favorable to the claimant. In addition, the UTLs demonstrate compliance with the radiation protection guidelines in force during the film badge period (Section 3.1).

7.0 ESTIMATES FOR UNMONITORED QUARTERLY DOSES

7.1 PROCEDURE USED THROUGH THIRD QUARTER OF 1956

As discussed in Section 6.2, information gathered from the histograms and q-q plots led to the determination that quarterly dose datasets before 1956 might not be suitable for estimating doses for unmonitored quarters. An alternative approach was developed in which unmonitored doses were estimated from a regression analysis based on data from the subgroup of 147 workers from 1956 to 1965 described in Section 4.2. Because workers selected to be monitored before 1961 had higher exposure potential, it was likely that the subgroup had higher recorded doses in those quarters than doses received by workers who were not monitored. Figure 7-1 shows all quarterly doses for the subgroup, which is the set of data used for the alternative approach based on regression modeling. Because the vertical axis is on a logarithmic scale, for graphing purposes each subgroup member's zero doses during a quarter were replaced by half the worker's minimum nonzero quarterly dose. The smoothing function "supsmu()" in the computer program R (RDCT 2008) produced the green curve that begins with a slight rise then dips steeply and ends with another small rise. The red line from upper left to lower right shows the expected dose for each quarter determined by the ML estimates based on the 5,686 data points by fitting a lognormal model for left-censored data with zero doses replaced by the MDL of 30 mrem. These plots show a general trend of decreasing dose with increasing time.

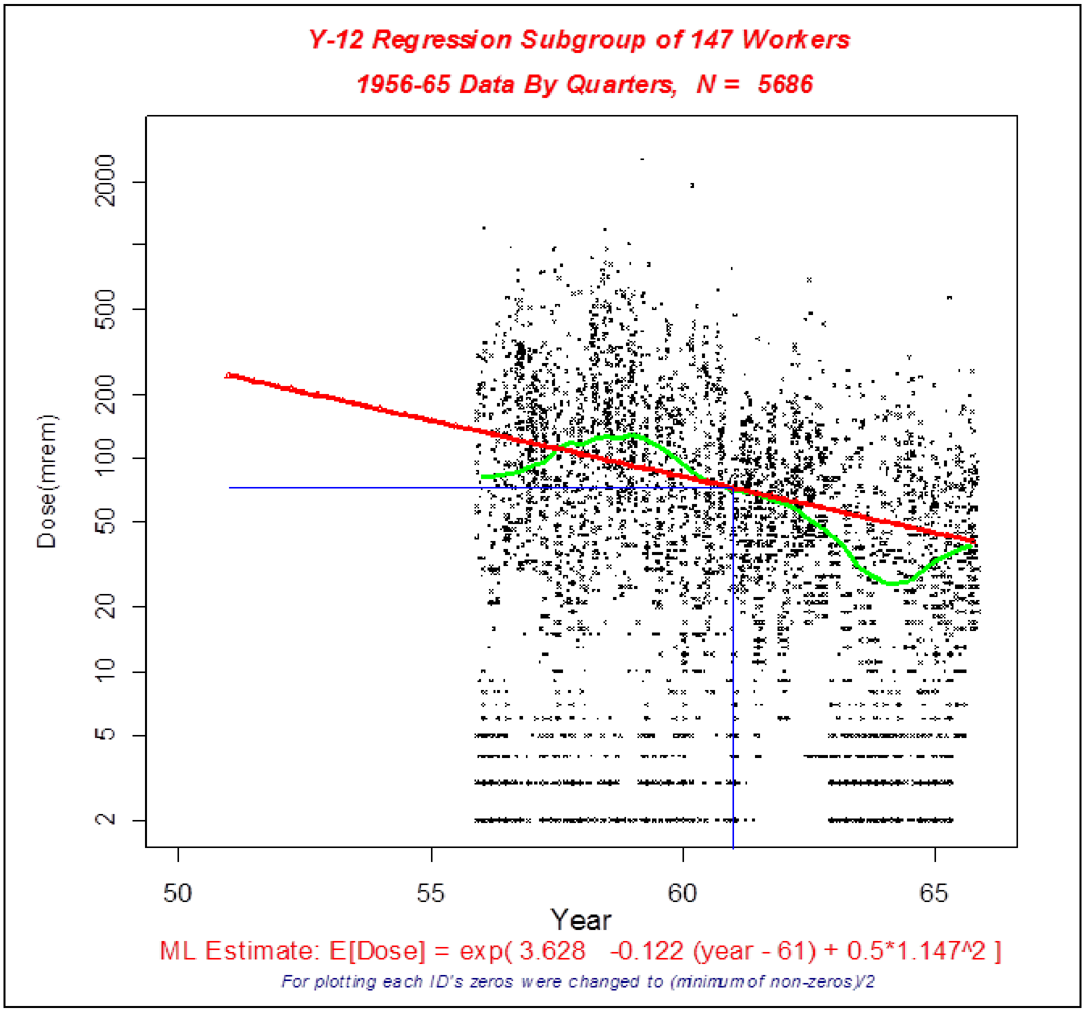

Figure 7-1. Regression of quarterly gamma dose data from 1956 through 1965 for a subgroup of 147 workers monitored before and after 1961.

ML estimates were used to obtain the GMs and GSDs for the prediction densities before 1957. The ML parameter values were determined using data for the subgroup of 147 workers and a lognormal model where the expected dose E(log(dose)) = $\mu_i = \alpha + \beta x_i$, where $x_i = t_i - 61$ for t_i the time in years (i.e., the last two digits of the year) and quarters (i.e., 0.25 for Q1, 0.50 for Q2, 0.75 for Q3) for the ith observation. The following estimates were obtained: $\hat{\alpha} = 3.628126$, $\hat{\beta} = -0.121503$, $\hat{\sigma} = 1.147311$, var($\hat{\alpha}$) = 0.000263, var($\hat{\beta}$) = 0.000030, and cov($\hat{\alpha}, \hat{\beta}$) = 0.000005. These quantities were used in equation 5-5 to determine the prediction density for each quarter of this period. As an extra assurance of favorability to the claimant, $\hat{\sigma}$ was replaced by its upper 95th% confidence limit when regression model parameters were used to calculate the GM and GSD for prediction densities.

The intersecting horizontal and vertical blue lines in Figure 7-1 indicate that the expected dose from the regression for the first quarter of 1961 (year = 61.25) was about 70 mrem. These ML estimates are equivalent to parameter values obtained from a least-squares regression using the logarithms of the doses with a normal model.

7.2 PROCEDURE USED AFTER THIRD QUARTER OF 1956

Exploratory data analysis showed that it was reasonable to fit lognormal models to the actual quarterly dose data beginning with Q4 of 1956 (Sections 6.2 and 6.3). The period before 1961 was of particular interest because unmonitored quarters after 1960 were rare. Lognormal parameters were calculated from each quarterly dose dataset using ML methods for left-censored data as described in Section 5.1. These parameters were used to determine separate lognormal prediction densities that could be sampled to estimate dose for a worker's unmonitored quarter. The ML prediction density in any quarter for z = log(d) is normal with mean $\hat{\mu}$ and $\sigma_{pd} = (\hat{\sigma}^2 + \text{var}(\hat{\mu}))^{1/2}$. This equation is equivalent to equation 4 if there are no predictor variables so that $\hat{\mu} = \hat{\alpha}$ and $\text{var}(\hat{\mu}) = \text{var}(\hat{\alpha})$.

Values of $\hat{\mu}$, $\hat{\sigma}$, and $\text{var}(\hat{\mu})$ can be determined from columns 5 to 7 [μ, σ, and se(μ)] in Table 6-3.

For easier implementation in dose reconstruction, the quantity $(\hat{\sigma}^2 + \text{var}(\hat{\mu}))^{1/2}$ was calculated for each quarter and appears in column 4 [σ] of Table 7-1. The GSD in Table 7-1 was calculated using the variance of the prediction density.

Table 7-1. Parameters for lognormal prediction density, 1947 to 1965.

Yr	Qtr	μ	σ	GM (reg)	GSD (reg)	E(dose)
1947	3	5.2684	1.1710	194.1093	3.2254	385.3264
	4	5.2380	1.1710	188.3017	3.2251	373.7602
1948	1	5.2077	1.1709	182.6679	3.2248	362.5419
	2	5.1773	1.1708	177.2026	3.2245	351.6610
	3	5.1469	1.1707	171.9009	3.2243	341.1072
	4	5.1165	1.1706	166.7578	3.2240	330.8709
1949	1	5.0862	1.1706	161.7685	3.2238	320.9423
	2	5.0558	1.1705	156.9285	3.2235	311.3123
	3	5.0254	1.1704	152.2334	3.2233	301.9717
	4	4.9950	1.1703	147.6787	3.2230	292.9120
1950	1	4.9647	1.1703	143.2603	3.2228	284.1247
	2	4.9343	1.1702	138.9740	3.2226	275.6015
	3	4.9039	1.1701	134.8161	3.2224	267.3344
	4	4.8735	1.1701	130.7825	3.2222	259.3159
1951	1	4.8432	1.1700	126.8696	3.2220	251.5383
	2	4.8128	1.1699	123.0738	3.2217	243.9945
	3	4.7824	1.1699	119.3915	3.2216	236.6773
	4	4.7520	1.1698	115.8194	3.2214	229.5801
1952	1	4.7217	1.1697	112.3542	3.2212	222.6961
	2	4.6913	1.1697	108.9927	3.2210	216.0189
	3	4.6609	1.1696	105.7317	3.2208	209.5423
	4	4.6305	1.1696	102.5683	3.2206	203.2603
1953	1	4.6002	1.1695	99.4995	3.2205	197.1670
	2	4.5698	1.1695	96.5226	3.2203	191.2567
	3	4.5394	1.1694	93.6347	3.2202	185.5239
	4	4.5090	1.1694	90.8333	3.2200	179.9633
1954	1	4.4786	1.1693	88.1156	3.2199	174.5698
	2	4.4483	1.1693	85.4793	3.2197	169.3381
	3	4.4179	1.1693	82.9218	3.2196	164.2636
	4	4.3875	1.1692	80.4409	3.2195	159.3415
1955	1	4.3571	1.1692	78.0341	3.2193	154.5671
	2	4.3268	1.1691	75.6994	3.2192	149.9361

Yr	Qtr	μ	σ	GM (reg)	GSD (reg)	E(dose)
	3	4.2964	1.1691	73.4346	3.2191	145.4441
	4	4.2660	1.1691	71.2375	3.2190	141.0869
1956	1	4.2356	1.1690	69.1061	3.2189	136.8606
	2	4.2053	1.1690	67.0385	3.2188	132.7611
	3	4.1749	1.1690	65.0328	3.2187	128.7846
	4	4.4804	1.1849	88.2670	3.2705	178.1117
1957	1	4.5501	0.7481	94.6429	2.1129	125.1996
	2	3.6461	1.1926	38.3236	3.2957	78.0411
	3	3.5629	1.2870	35.2668	3.6219	80.7312
	4	3.0381	1.0032	20.8654	2.7271	34.5129
1958	1	3.7262	0.9659	41.5229	2.6271	66.2019
	2	4.3848	1.1877	80.2184	3.2794	162.3934
	3	4.5488	1.0210	94.5197	2.7759	159.1748
	4	4.1164	1.0660	61.3370	2.9037	108.2611
1959	1	4.7269	0.8700	112.9481	2.3870	164.9118
	2	3.6119	1.2450	37.0373	3.4730	80.3958
	3	3.7927	1.0253	44.3740	2.7880	75.0609
	4	4.1739	1.0040	64.9716	2.7293	107.5551
1960	1	3.5687	1.1147	35.4690	3.0488	66.0222
	2	3.9611	1.0556	52.5129	2.8736	91.6675
	3	4.2164	1.0153	67.7919	2.7602	113.5069
	4	4.4589	0.9375	86.3962	2.5535	134.0703
1961	1	2.0601	1.2387	7.8465	3.4512	16.8995
	2	3.8154	0.5982	45.3955	1.8188	54.2889
	3	3.0126	0.8528	20.3409	2.3463	29.2623
	4	3.9514	0.5300	52.0060	1.6990	59.8494
1962	1	2.4602	0.9398	11.7075	2.5595	18.2078
	2	3.9103	0.5839	49.9146	1.7931	59.1934
	3	3.6301	0.7948	37.7183	2.2141	51.7299
	4	3.3465	1.0791	28.4022	2.9419	50.8382
1963	1	2.4188	1.2168	11.2322	3.3763	23.5485
	2	2.7574	0.8825	15.7582	2.4170	23.2612
	3	1.9958	1.5818	7.3584	4.8636	25.7093
	4	2.4319	0.9032	11.3810	2.4674	17.1123
1964	1	2.1856	1.3008	8.8959	3.6723	20.7314
	2	2.1811	1.2667	8.8559	3.5490	19.7529
	3	3.0904	1.2067	21.9863	3.3425	45.5361
	4	2.1823	1.3366	8.8664	3.8062	21.6621
1965	1	2.7352	1.0437	15.4128	2.8396	26.5709
	2	2.4326	1.1580	11.3883	3.1837	22.2673
	3	2.7133	0.9351	15.0795	2.5474	23.3482
	4	3.5052	0.5286	33.2881	1.6965	38.2786
1966	1	1.9772	1.4366	7.2223	4.2062	20.2675
	2	2.4709	1.2845	11.8327	3.6130	27.0013
	3	2.8886	1.4160	17.9675	4.1208	48.9677
	4	2.7667	1.0745	15.9067	2.9285	28.3323
1967	1	2.1120	1.3340	8.2651	3.7962	20.1221
	2	2.4571	1.2213	11.6708	3.3917	24.6041
	3	2.5324	0.9914	12.5839	2.6951	20.5711
	4	2.3066	1.0483	10.0406	2.8528	17.3936
1968	1	2.0275	1.1793	7.5948	3.2521	15.2235
	2	3.9709	0.3359	53.0336	1.3992	56.1115
	3	1.6120	1.1632	5.0130	3.2000	9.8600
	4	3.4677	0.7441	32.0645	2.1046	42.2925
1969	1	2.9932	0.7417	19.9487	2.0994	26.2637
	2	2.9467	0.8831	19.0424	2.4183	28.1224
	3	3.1905	1.0226	24.3011	2.7803	40.9903
	4	2.8390	1.0444	17.0981	2.8417	29.4989
1970	1	2.9383	1.0453	18.8832	2.8442	32.6087
	2	2.3328	0.9323	10.3065	2.5403	15.9164
	3	3.2685	0.9138	26.2714	2.4939	39.8865

Yr	Qtr	μ	σ	GM (reg)	GSD (reg)	E(dose)
	4	2.9826	0.9899	19.7397	2.6910	32.2203
1971	1	3.2304	0.6317	25.2897	1.8808	30.8742
	2	2.0116	1.0196	7.4756	2.7721	12.5717
	3	3.2247	0.7777	25.1451	2.1765	34.0246
	4	2.6512	0.9245	14.1717	2.5207	21.7287
1972	1	2.5615	0.9698	12.9550	2.6373	20.7324
	2	2.0685	1.1157	7.9132	3.0517	14.7452
	3	1.5660	1.1079	4.7873	3.0280	8.8436
	4	1.7225	1.1241	5.5986	3.0774	10.5308
1973	1	2.0587	1.1435	7.8361	3.1377	15.0673
	2	1.7620	1.2384	5.8243	3.4501	12.5393
	3	2.2251	1.0806	9.2547	2.9464	16.5928
	4	1.0047	1.2874	2.7312	3.6233	6.2552
1974	1	3.2767	1.0585	26.4875	2.8820	46.3800
	2	2.2031	1.2222	9.0535	3.3945	19.1056
	3	2.6296	0.9638	13.8678	2.6216	22.0654
	4	1.9974	1.1317	7.3699	3.1009	13.9820
1975	1	2.2088	0.9884	9.1049	2.6869	14.8391
	2	1.6778	1.1706	5.3537	3.2240	10.6224
	3	1.5370	1.1138	4.6508	3.0459	8.6479
	4	1.6097	1.0764	5.0012	2.9340	8.9259
1976	1	2.3905	0.8472	10.9189	2.3331	15.6328
	2	1.8695	1.0656	6.4850	2.9025	11.4411
	3	2.4448	0.9544	11.5278	2.5971	18.1777
	4	1.6694	0.9306	5.3088	2.5361	8.1857
1977	1	1.8246	1.0249	6.2001	2.7868	10.4832
	2	1.8694	0.9248	6.4843	2.5213	9.9441
	3	2.3250	0.9847	10.2263	2.6769	16.6056
	4	1.6465	1.0129	5.1886	2.7535	8.6661
1978	1	1.6841	1.0384	5.3875	2.8248	9.2374
	2	2.2135	0.9717	9.1477	2.6424	14.6669
	3	3.4596	0.7243	31.8027	2.0632	41.3399
	4	1.6158	1.1084	5.0318	3.0295	9.3004
1979	1	1.6718	1.0216	5.3215	2.7777	8.9676
	2	1.9389	0.9249	6.9514	2.5216	10.6618
	3	1.8009	1.1861	6.0554	3.2744	12.2363
	4	1.8403	1.0917	6.2985	2.9792	11.4291

7.3 PARAMETERS FOR LOGNORMAL PREDICTION DENSITIES

Columns 5 and 6 in Table 7-1 contain the GM and GSD of each quarterly lognormal prediction density, which can be used in estimating a dose for an unmonitored quarter. Even though Table 7-1 covers the years from the takeover of Y-12 by UCCND in 1947 to the end of the film badge program in 1979, the GMs and GSDs for earlier and later years were obtained by two distinct processes. The values for 1947 through Q3 of 1956 were calculated using the subgroup regression approach discussed in Section 7.1. In contrast, from Q4 of 1956 through 1979, the GMs and GSDs for each quarter were determined by applying a lognormal model directly to the doses for that quarter, as discussed in Section 7.2.

7.4 APPLICATION OF THE SCALING PROCEDURE

Although it is unlikely that a worker was unmonitored before 1961 while having exposure potential above 10% of the RPGs in effect at that time, a procedure was developed to derive an individual upward scaling factor that provided an additional guarantee against possible underestimation of dose (ORAUT 2004a,b). This factor could be applied for any worker with unmonitored quarterly data before 1961 and satisfying these two conditions: (1) the worker must have monitoring data for at least five calendar quarters from 1961 through 1965, (2) the worker's routine duties and work location must have remained essentially the same during the 1950s and early 1960s. The unmonitored missed dose estimated by this procedure is conceptually equivalent to the recorded quarterly doses at the Y-12 Plant before 1961. These quarterly doses were sums of 13 weekly badge exchanges from May 1948 to September 1958 and sums of 3 monthly exchanges from October 1958 to December 1960.

A Y-12 worker's unmonitored quarterly dose from 1947 through 1960 can be assigned by beginning with the appropriate quarterly GM and GSD from Table 7-1 and applying an individual scaling factor φ as described in Section 5.6. Table 7-2 lists the values of μ, σ, w, and y^o that are based on a value of 30 mrem for the MDL. If the two criteria listed above are met, this individual's monitoring data can be used to "adjust" upward the quarterly dose distribution by increasing the GM and GSD. This method assumes that the individual's potential for exposure from 1947 to 1960 is similar to that from 1961 to 1965, that the individual's doses differ from the population dose by a constant factor, and that an unmonitored quarterly dose can be described by a lognormal distribution. Any calculated scaling factor that is less than one is changed to one so that the value of the expected quarterly dose can be increased but not decreased.

Table 7-2. Parameters used in scaling-factor calculations.

Year	Qtr	t	μ	σ	w	y^0
1961	1	1	2.060	1.239	0.651	1.740
	2	2	3.815	0.598	2.794	3.047
	3	3	3.013	0.853	1.375	2.559
	4	4	3.951	0.530	3.559	3.127
1962	1	5	2.460	0.940	1.132	2.190
	2	6	3.910	0.584	2.933	3.079
	3	7	3.630	0.795	1.583	2.843
	4	8	3.346	1.079	0.859	2.520
1963	1	9	2.419	1.217	0.675	1.975
	2	10	2.757	0.883	1.284	2.406
	3	11	1.996	1.582	0.400	1.473
	4	12	2.432	0.903	1.225	2.196
1964	1	13	2.186	1.301	0.591	1.779
	2	14	2.181	1.267	0.623	1.799
	3	15	3.090	1.207	0.687	2.316
	4	16	2.182	1.337	0.560	1.753
1965	1	17	2.735	1.044	0.918	2.275
	2	18	2.433	1.158	0.746	2.025
	3	19	2.713	0.935	1.143	2.343
	4	20	3.505	0.529	3.575	3.015

Let t indicate a quarter of the year, between the first quarter of 1947 and the last quarter of 1960, for which a dose distribution is required because a worker was unmonitored. Without scaling, the unmonitored dose is lognormal with parameters (on the log scale) μ_t and σ_t (from Table 7-1); that is, $y_t = \log(d_t)$ is normally distributed with mean μ_t and standard deviation σ_t. When applying the scaling procedure, the mean and standard deviation of the adjusted log dose are

$$\mu_t^* = \mu_t + \hat{\phi}$$

$$\sigma_t^* = [\sigma_t^2 + \mathrm{var}(\hat{\varphi})]^{1/2};$$

where the unmonitored dose in quarter t is lognormal with mean μ_t^* and standard deviation σ_t^*. If a worker was unmonitored for all four quarters in a given year, the adjusted lognormal parameters are calculated separately for each quarter and the annual dose estimate is obtained by Monte Carlo sampling as described in ORAUT (2004b).

Example

Consider a worker with recorded dose d_t for each quarter from 1961 to 1965 as listed in column 8 of Table 7-3. The calculated values of y_t and v_t are in columns 9 and 10 of Table 7-3 so that

$$\hat{\varphi} = \Sigma_t w_t v_t / \Sigma_t w_t = 0.4698 \text{ and}$$

$$\text{var}(\hat{\varphi}) = 1/\Sigma_t w_t = 0.0366.$$

Table 7-3. Calculation of scaling factor for Section 7.4 example.

	Year	Qtr	mu	sig	w	y^0	d	y	v
1	1961	1	2.060	1.239	0.651	1.740	12	2.4849	0.4249
2	1961	2	3.815	0.598	2.794	3.047	74	4.3041	0.4891
3	1961	3	3.013	0.853	1.375	2.559	62	4.1271	1.1141
4	1961	4	3.951	0.530	3.559	3.127	98	4.5849	0.6339
5	1962	1	2.460	0.940	1.132	2.190	43	3.7612	1.3012
6	1962	2	3.910	0.584	2.933	3.079	88	4.4774	0.5673
7	1962	3	3.630	0.795	1.583	2.843	46	3.8286	0.1986
8	1962	4	3.346	1.079	0.859	2.520	51	3.9318	0.5858
9	1963	1	2.419	1.217	0.675	1.975	32	3.4657	1.0467
10	1963	2	2.757	0.883	1.284	2.406	52	3.9512	1.1942
11	1963	3	1.996	1.582	0.400	1.473	66	4.1897	2.1937
12	1963	4	2.432	0.903	1.225	2.196	0	2.1960	-0.236
13	1964	1	2.186	1.301	0.591	1.779	0	1.7790	-0.407
14	1964	2	2.181	1.267	0.623	1.799	0	1.7990	-0.382
15	1964	3	3.090	1.207	0.687	2.316	47	3.8502	0.7601
16	1964	4	2.182	1.337	0.560	1.753	8	2.0794	-0.103
17	1965	1	2.735	1.044	0.918	2.275	50	3.9120	1.1770
18	1965	2	2.433	1.158	0.746	2.025	17	2.8332	0.4002
19	1965	3	2.713	0.935	1.143	2.343	25	3.2189	0.5059
20	1965	4	3.505	0.529	3.575	3.015	23	3.1355	-0.369

The values in columns 4 to 7 of Table 7-3 are the same for each worker, whereas the values in columns 8, 9, and 10 are determined by the individual gamma doses recorded for each quarter of employment from 1961 through 1965.

To estimate the unmonitored dose in Q1 of 1957 for the worker in this example, use

$$\hat{\varphi} = 0.4698 \text{ and } \text{var}(\hat{\varphi}) = 0.0366 \text{ from above, so that}$$

$$\mu_t^* = 4.5501 + 0.4698 = 5.020 \text{ and}$$

$$\sigma_t^* = [0.7481^2 + 0.0366]^{1/2} = 0.772$$

where $\mu_t = 4.5501$ and $\sigma_t = 0.7481$ are from Table 7-1. The scaled unmonitored dose for this worker for the quarter is lognormal with $\mu_t^* = 5.020$ and $\sigma_t^* = 0.772$. The adjusted GM is $\exp(\mu_t^*) = 151.41$ and the adjusted GSD is $\exp(\sigma_t^*) = 2.164$.

7.5 Comparison of Regression Model/Scaling Procedure Distributions to Recorded Dose Distributions

Comparisons were made between dose distributions from actual recorded doses during monitored quarters before 1961 and dose distributions created by applying the gamma regression model values and scaling procedure as if these quarters had not been monitored. The dose distributions from actual recorded doses were calculated with the GM equal to the recorded dose and the GSD determined according to the discussion in NIOSH (2007, pp. 14-15), using an MDL of 30 mrem and a 30% standard error. For graphing purposes, for recorded doses of 0, indicating a nondetectable value, the GM = MDL / 2 = 15 and ln(GSD) = ln(MDL / GM) / 1.645=0.195.

Results of comparisons for workers typical of several different situations appear in Figures 7-2 to 7-6. The scaling factor shown in each plot is on the logarithmic scale. For example, in Figure 7-2 the scaling factor is 2.666 on the logarithmic scale, which is exp(2.666) = 14.382 on the original scale. These figures demonstrate a variety of situations, but the scaling procedure should be used only if there were similar job activities and dose potential before 1961 and between 1961 and 1966. These examples demonstrate that dose distributions calculated by the regression and scaling procedures are repeatedly favorable to claimants.

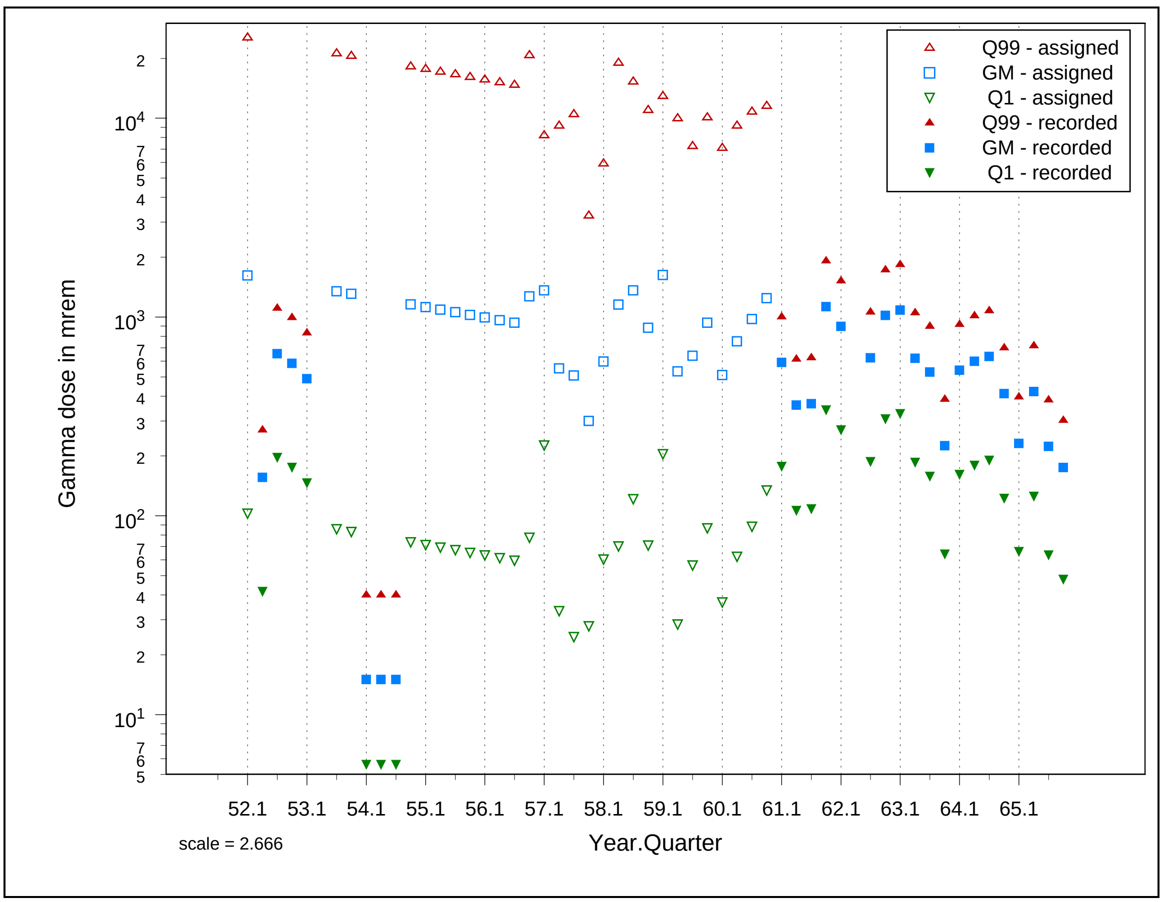

Figure 7-2. Distribution of scaled prediction densities versus actual monitored gamma doses for a worker with earliest doses similar to 1961 to 1965 and other doses lower than 1961 to 1965.

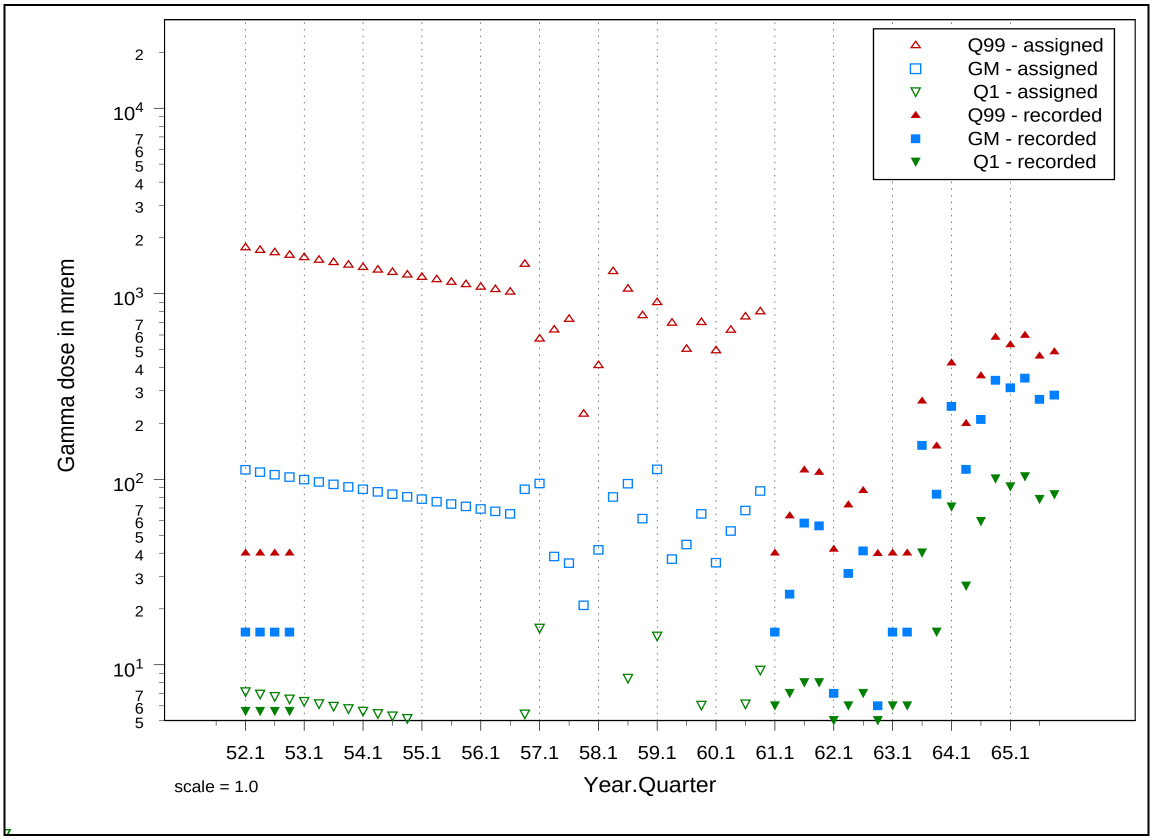

Figure 7-3. Distribution of scaled prediction densities versus actual monitored gamma doses for a worker with zero doses early and mainly higher doses in 1961 to 1965.

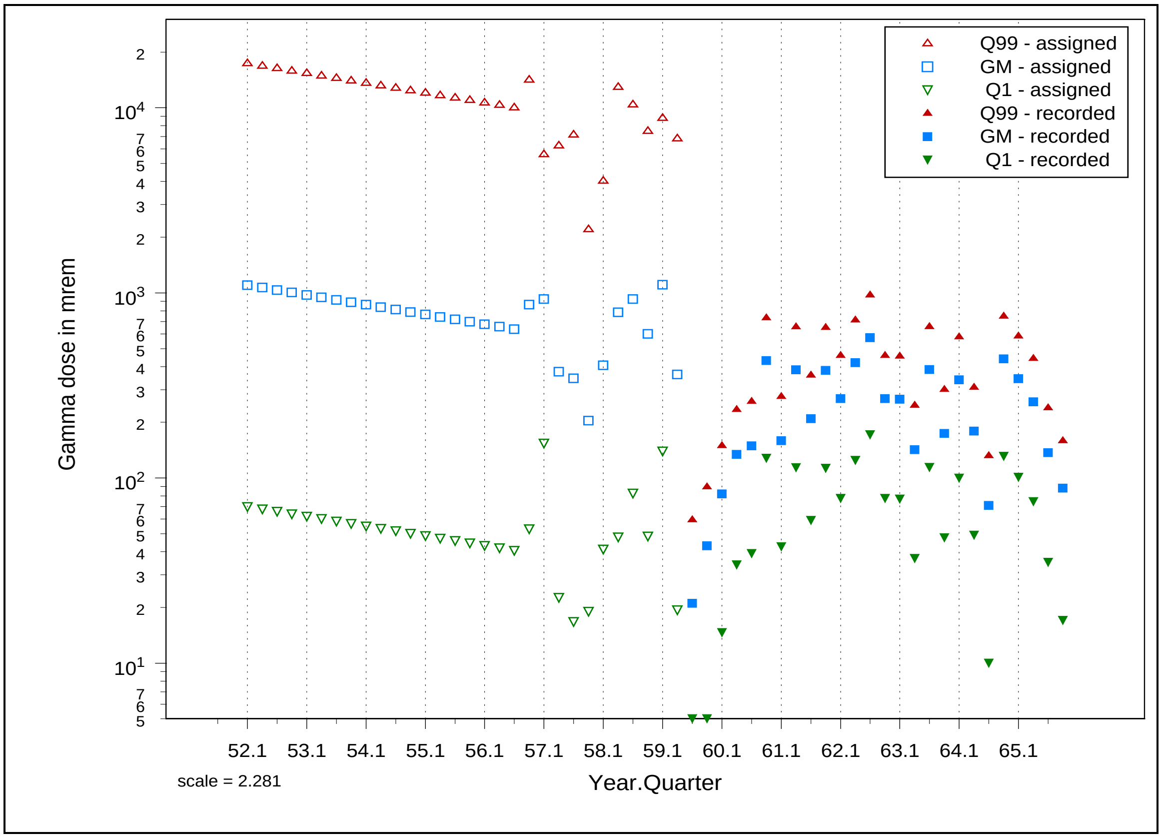

Figure 7-4. Distribution of scaled prediction densities versus actual monitored gamma doses for a worker with somewhat lower doses before 1961 than from 1961 to 1965.

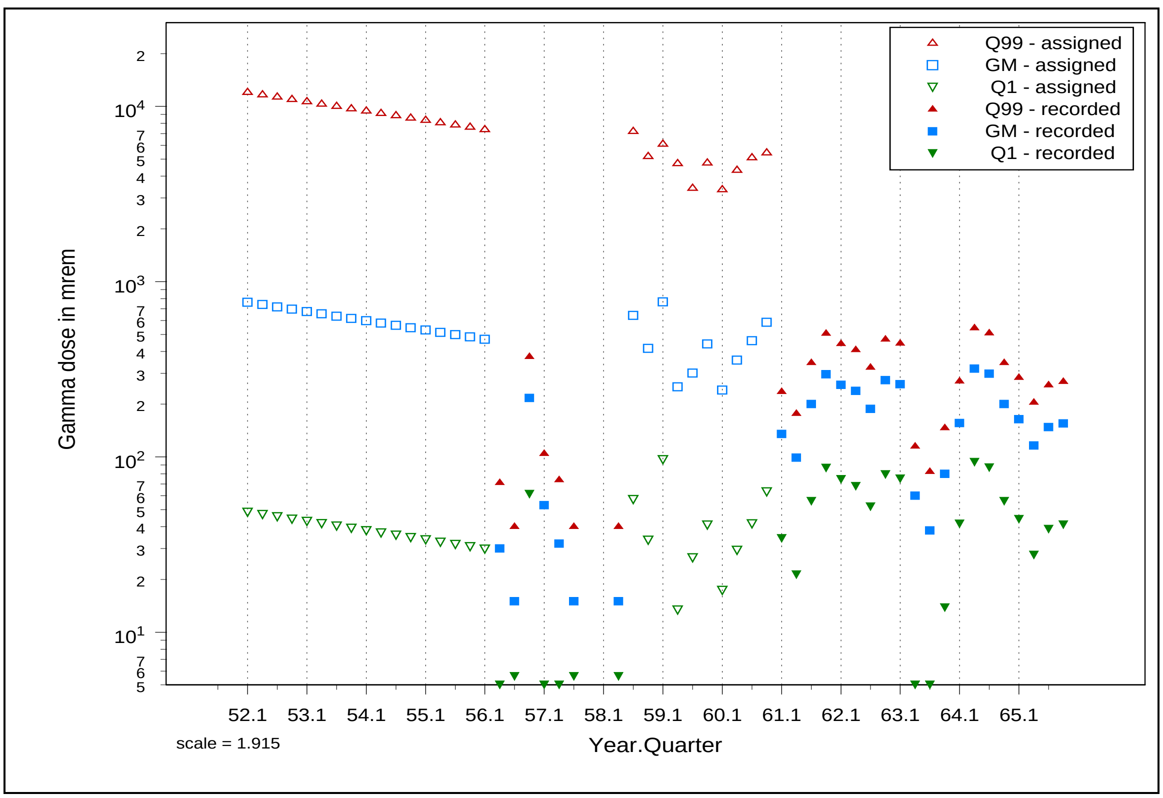

Figure 7-5. Distribution of scaled prediction densities versus actual monitored gamma doses for a worker with similar doses before and after 1961.

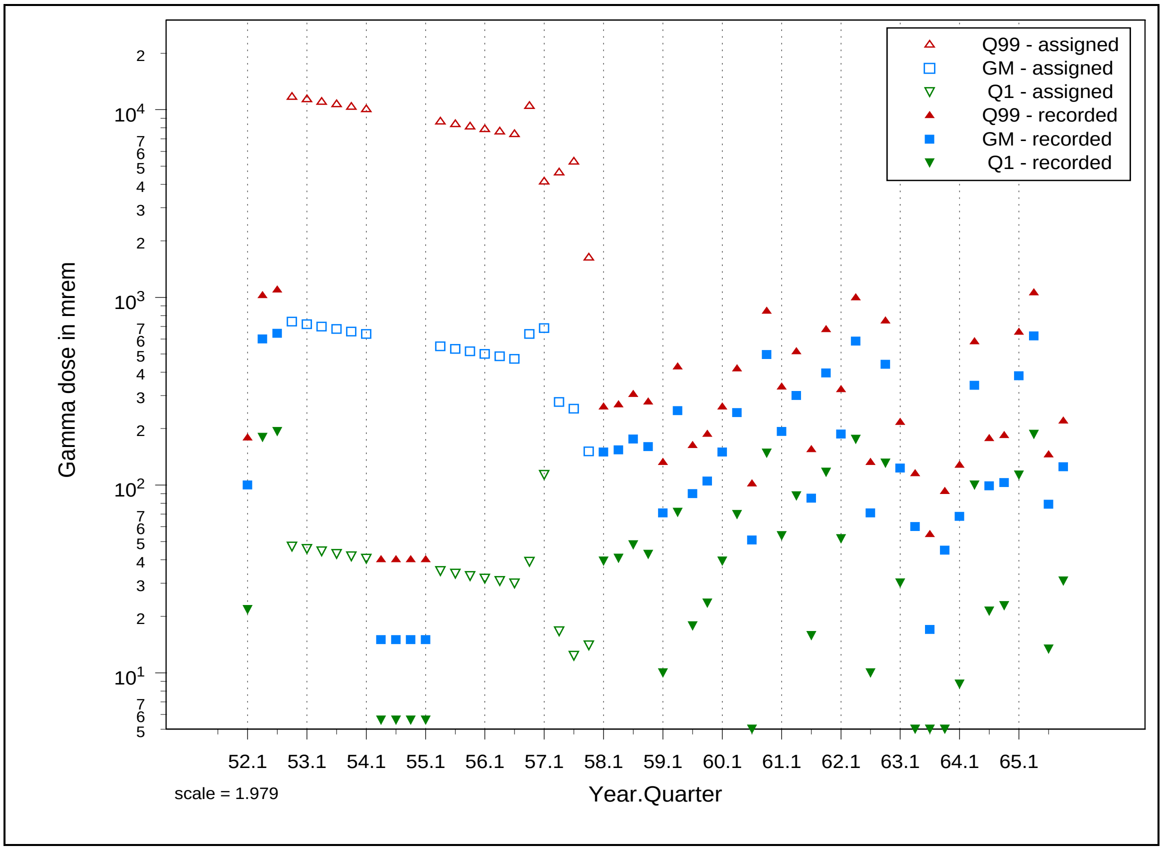

Figure 7-6. Distribution of scaled prediction densities versus actual monitored gamma doses for a worker with very early doses over a wide dose range.

8.0 SUMMARY

The purpose of this TIB is to provide useful, comprehensive, and accurate background information on the film badge program through 1979 at the Y-12 Plant as a resource for dose reconstruction. This closure date was chosen because film badges were replaced by TLD badges for monitoring external radiation in 1980. The statistical methods reported herein were developed for determining prediction densities to estimate gamma doses for Y-12 workers during unmonitored quarters. These prediction densities were derived using different methods before and after 1956. After 1956, the recorded quarterly doses for workers were used to derive parameter estimates by ML methods for quarterly lognormal prediction densities. Before 1956, however, the prediction densities were derived from a ML regression based on data from a subgroup of 147 carefully selected Y-12 workers. Individuals in this subgroup were judged to have had higher exposure potential, as evidenced by their having been selected to be monitored for all four quarters during a year for at least five years before 1961. Subgroup members also had recorded gamma doses for four quarters at least five years after 1961, allowing for investigating a trend with dose levels over time. As extra assurance that the dose estimation process would be favorable to the claimant, the standard deviation of the dose was replaced by its upper 95% confidence limit when calculating the prediction density lognormal parameters from the regression model.

A comparison of the quarterly dose means based on 1948 and 1949 monitored gamma doses to the mean quarterly dose estimates from the regression methods in this report [see E(dose) in Table 7-1] confirm that the regression methods provide values for the late 1940s that are favorable to claimants (see ORAUT 2013, Tables 6-2 and 6-3), even without the scaling factor being applied. The quarterly results from Table 7-1, adjusted for the possibility of missed dose from null dosimeter readings, have been used to derive Y-12 coworker data distributions for use in the evaluation of gamma doses for time periods when workers were potentially exposed but individual monitoring data were not available (ORAUT 2013).

The following items provide a summary of the information that supports the favorability to the claimant of the analytical approach used in this report.

- Beginning in 1961 nearly all workers were monitored with film badges (see Figure 6-1).
- The abrupt drop in dose distributions in 1961 demonstrates that workers excluded from film badge monitoring before 1961 were individuals with lower exposure potential (see Figure 6-2 and Table 6-3).
- Further evidence for higher exposure potential for workers monitored before 1961 came from separating the 1961 doses into two groups. Group 1 doses came from workers who were also monitored in 1960 and Group 2 from workers not monitored in 1960. The 1961 average doses and other statistics for Group 1 were higher than those for Group 2 (see Figures 6-3 and 6-4 and Tables 6-1 and 6-2).
- After 1956 Q3, lognormal models were suitable fits for quarterly data as shown by the figures in Attachment A. The ML lognormal parameters can be used to calculate GMs and GSDs for estimation of gamma doses for unmonitored quarters (see Table 7-1).
- Through 1956 Q3 data for a subgroup of 147 workers employed before and after 1961 (Section 4.2) were used in a ML regression analysis to obtain quarterly GMs and GSDs that can be used to estimate doses for unmonitored quarters (see Figure 7-1).
- As an extra assurance of favorability to the claimant, the standard deviation of the regression analysis was replaced by its upper 95% confidence limit when calculating quarterly GMs and GSDs for 1947 Q3 to 1956 Q3 (see Table 7-1).
- A job analysis of the subgroup of 147 whose data was the basis for the regression analysis found that only 3% were managers and 88% had no supervisory duties (see Table 4-1).
- A scaling factor was calculated to allow for increasing nonmonitored doses before 1961 if the worker had higher than average doses after 1961 (see Table 7-3, the example in Sections 7-4 and 7-5, and Figures 7-2 to 7-6 in Section 7-5).

REFERENCES

Auxier, J. A., 1967, "Special Methods in Radiation Dosimetry," in *Principles of Radiation Protection*, K.Z. Morgan and J. E. Turner, eds., John Wiley & Sons, Inc., New York, New York, pp. 215–241.

Beck, W. J., 1981, "Corrections to 1954 Y-12 Film Badge Data," memorandum to Donna Hudson, Oak Ridge Associated Universities, Oak Ridge, Tennessee, December 9. [SRDB Ref ID: 12503]

BWXT Y-12, LLC., 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]

BWXT Y-12, LLC., 2001, *Technical Basis for the External Dosimetry Program at the Y-12 National Security Complex*, RCO/TBD-007, Revision 3, Y-12 National Security Complex, Oak Ridge, Tennessee, August 2. [SRDB Ref ID: 8467]

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

Chambers, J. M., W. S. Cleveland, B. Kleiner, and P. A. Tukey, 1983, *Graphical Methods for Data Analysis*, Duxbury Press, Boston, Massachusetts.

Cheka, J. S., 1954, "Recent Developments in Film Monitoring of Fast Neutrons," *Nucleonics*, volume 12, number 6, pp. 40–43. [SRDB Ref ID: 25005]

Cohen, A. C., 1991, "Truncated and Censored Samples," *Theory and Applications*, Marcel Dekker, Inc., New York, New York.

Denton, L. F., and H. L. Fore, 1979, *Review of the Current Status of the DOE Health and Mortality Study (HMS) Data at UCC-ND/CSD,* Technical Report No. 0003246, Union Carbide Corporation, Nuclear Division, Oak Ridge, Tennessee, October 11. [SRDB Ref ID: 44453]

Dupree, E. A., J. P. Watkins, J. N. Ingle, P. W. Wallace, C. M. West, and W. G. Tankersley, 1994, "Uranium Dust Exposure and Lung Cancer Risk in Four Uranium Processing Operations," *Epidemiology*, volume 6, number 4, pp. 370–375.

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

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

Frome, E. L., and J. P. Watkins, 2004, *Statistical Analysis of Data with Non-detectable Values*, ORNL/TM-2004/146, Oak Ridge National Laboratory, Oak Ridge, Tennessee, August. [SRDB Ref ID: 24176]

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

Howell, R. L., and Z. Batte, 1982, *Thermoluminescent Dosimetry for Union Carbide Corporation Nuclear Division Personnel*, Y/DK-291, 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 – Part III. Determination of Radiation Doses," *Health Physics*, volume 2, number 2, pp. 21–29. [SRDB Ref ID: 10132]

Inkret, W. C., C. B. Meinhold, and J. C. Taschner, 1995, "Protection Standards," *Los Alamos Science*, volume 23, number 4, pp. 117–123. [SRDB Ref ID: 43192]

Johnson, N. L., and B. L. Welch, 1940, "Application of the Non-Central t-Distribution," *Biometrika*, volume 31, numbers 3/4, pp. 362–389.

Johnson, N. L., S. Kota, and N. Balakrishnan, 1994, *Continuous Univariate Distributions*, volume 1, 2nd edition, John Wiley and Sons, New York, New York.

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

Kaplan, E. L., and P. Meier, 1958, "Nonparametric Estimation from Incomplete Observations," *Journal of the American Statistical Association*, volume 53, pp. 457–481.

Kerr, G. D., T. D. Jones, and J. M. L. Hwang, 1978, "Neutron-to-Dose Conversion Factors for Am-B and Am-Be Sources," *Health Physics*, volume 35, pp. 572–574.

Larson, C. E., 1949, "Finger Film Pad," letter to Hanson Blatz (Manager of Operations, U.S. Atomic Energy Commission), Carbide and Carbon Chemicals Corporation, Oak Ridge, Tennessee, December 16. [SRDB Ref ID: 4298]

Lejeune, M., and G. D. Faulkenberry, 1982, "A Simple Predictive Density Function," *Journal of the American Statistical Association*, volume 77, number 379, pp. 654–657.

Long, E. C., 1950, Weekly Neutron Film Report for the Period Beginning 4-16-50 and Ending 4-23-50, Y-12 Plant, Oak Ridge, Tennessee. [SRDB Ref ID: 30939, p. 20]

Marsden, E. H., 1945, "Clinton – a Monument to Teamwork," *Engineering News-Record*, Special Number Featuring Construction for Atomic Bomb Production Facilities, volume 135, number 24, pp. 115–117. [SRDB Ref ID: 44454]

McLendon, J. D., 1958a, "Change in Y-12 Film Badge Program," internal correspondence to E. W. Bailey et al., Union Carbide Nuclear Company, Oak Ridge, Tennessee, March 31. [SRDB Ref ID: 20093]

McLendon, J. D., 1958b, "Change in Y-12 Film Badge Program," internal correspondence to J. C. Bowles et al., Union Carbide Nuclear Company, Oak Ridge, Tennessee, October 6. [SRDB Ref ID: 20092]

McLendon, J. D., 1960, "Personnel Radiation Exposure Data," internal correspondence to G. W. Flack, Union Carbide Nuclear Company, Oak Ridge, Tennessee, August 25. [SRDB Ref ID: 3694]

McLendon, J. D., 1963, *Y-12 Radiation Safety Manual*, Y/KB-29, Y-12 Plant, Oak Ridge, Tennessee, October 31. [SRDB 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 23. [SRDB Ref ID: 8589]

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. [SRDB Ref ID: 8577]

Morgan, K. Z, 1961, "Dosimetry Requirements for Protection from Ionizing Radiation," in *Selected Topics in Radiation Dosimetry*, Proceeding Series, STI/PUB/25, International Atomic Energy Agency, Vienna, Austria, pp. 3–23. [SRDB Ref ID: 8345]

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 25. [SRDB Ref ID: 12093]

Murray, R., 1948a, *Health Physics Progress Report, December 1-31, 1947*, Y-94 Rev. 1, Y-12 Plant, Oak Ridge, Tennessee. [SRDB Ref ID: 8602, pp. 483–502]

Murray, R., 1948b, *Health Physics Progress Report, January 1-31, 1948*, Y-120, Y-12 Plant, Oak Ridge, Tennessee. [SRDB Ref ID: 8602, pp. 476–482]

Murray, R., 1948c, *Health Physics Progress Report, February 1-29*, 1948, Y-134, Y-12 Plant, Oak Ridge, Tennessee. [SRDB Ref ID: 8602, pp. 469–475]

Nachtigall, D., 1967, "Average and Effective Energies, Fluence-to-Dose Conversion Factors and Quality Factors of the Neutron Spectra of Some (α,n) Sources," *Health Physics*, volume 13, pp. 213–219.

NIOSH (National Institute for Occupational Health and Safety), 2007, *External Dose Reconstruction Implementation Guideline*, OCAS-IG-001, Rev. 03, Office of Compensation Analysis and Support, Cincinnati, Ohio, November 1.

ORAUT (Oak Ridge Associated Universities Team), 2004a, *Accounting for Incomplete Personal Monitoring Data on Penetrating Gamma-Ray Doses to Workers in Radiation Areas at the Oak Ridge Y-12 Plant Prior to 1961*, ORAUT-PROC-0042, Rev. 00, Oak Ridge, Tennessee, September 9.

ORAUT (Oak Ridge Associated Universities Team), 2004b, *Individual Dose Adjustment Procedure for Y-12 Dose Reconstruction*, ORAUT-OTIB-0013, Rev. 00, Oak Ridge, Tennessee, September 9.

ORAUT (Oak Ridge Associated Universities Team), 2006, *External Radiation Dose Estimates for Individuals Near the 1958 Criticality Accident at the Oak Ridge Y-12 Plant*, ORAUT-OTIB-0057, Rev. 00, Oak Ridge, Tennessee, May 15.

ORAUT (Oak Ridge Associated Universities Team), 2007, *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), 2009a, *Technical Basis Document for the Y-12 National Security Complex – Occupational External Dosimetry*, ORAUT-TKBS-0014-6, Rev. 02, Oak Ridge, Tennessee, December 18.

ORAUT (Oak Ridge Associated Universities Team), 2009b, *Historical Evaluation of the Film Badge Dosimetry Program at the Y-12 Plant in Oak Ridge, Tennessee: Part 2 – Neutron Radiation*, ORAUT-OTIB-0045, Rev. 01, Oak Ridge, Tennessee, November 30.

ORAUT (Oak Ridge Associated Universities Team), 2013, *Coworker External Dosimetry Data for the Y-12 National Security Complex*, ORAUT-OTIB-0064, Rev. 02, Oak Ridge, Tennessee, April 29.

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

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

Reavis, J. P., 1958, "Frequency of Film Badge Analysis," internal correspondence to J. C. Bowles et al., Union Carbide Nuclear Company, Oak Ridge, Tennessee, September 30. [SRDB Ref ID: 20092]

Royster, P., 1982, "An Extension of Shapiro and Wilk's W Test for Normality to Large Samples," *Applied Statistics*, volume 31, pp. 115–124.

Schmoyer, R. L., J. J. Beauchamp, C. C. Brandt, and F. O. Hoffman, Jr., 1996, "Difficulties with the Lognormal Model in Mean Estimation and Testing," *Environmental and Ecological Statistics*, volume 3, pp. 81–97.

Sherrill, M. W., and W. O. Tucker, 1973, *Evaluation of New Film Badge Reader and Revised Exposure Computations*, Y/DK-11, Y-12 Plant, Oak Ridge, Tennessee, October 12. [SRDB Ref ID: 8590]

Shleien, B., L. A. Slabeck, Jr., and B. K. Birkey, editors, 1998, *Handbook of Health Physics and Radiological Health*, *Third Edition*, Williams & Wilkins, Baltimore, Maryland, January.

Souleyrette, M. L., 2003, *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]

Strom, D. J., M. H. Smith, K. L. Swinth, and H. J. Pettengill, 1996, "Dose to Workers in the United States Nuclear Weapons Program Due to External Irradiation at the Dawn of the Atomic Era (1940-1960)," *Health Physics*, volume 71, pp. 50–57.

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

Struxness, E. G., 1949a, *Maximum Permissible Dose Limits*, Memorandum to distribution, Y-12 Plant, Oak Ridge Tennessee, October 21. [SRDB Ref ID: 12503]

Struxness, E. G., 1949b, *Health Physics– Industrial Hygiene Progress Report, May 1-31*, 1948, Y-429/Rev. 1, Y-12 Plant, Oak Ridge, Tennessee, July 11. [SRDB Ref ID: 8602, pp. 296–305]

Struxness, E. G., 1949c, *Health Physics–Industrial Hygiene Progress Report, December 1-31, 1948*, Y-318/Rev. 1, Y-12 Plant, Oak Ridge, Tennessee, January 11. [SRDB Ref ID: 8602, pp. 364–374]

Struxness, E. G., 1951a, *Health Physics Progress Report, November 1, 1950 – December 31, 1950*, Y-780, Y-12 Plant, Oak Ridge, Tennessee, June 14. [SRDB Ref ID: 8602, pp. 215–256]

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

Struxness, E. G., 1952, *Health Physics Progress Report, July 1, 1951 – December 31, 1951*, Y-858, Y-12 Plant, Oak Ridge, Tennessee, March 15. [SRDB Ref ID: 8620, pp. 110–178]

Struxness, E. G., 1953, *Health Physics Progress Report, January 1, 1952 – July 1, 1952*, Y-940, Y-12 Plant, Oak Ridge, Tennessee, February 19. [SRDB Ref ID: 8620, pp. 180–214]

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 5. [SRDB Ref ID: 8573]

UCNC (Union Carbide Nuclear Company), 1958, *Accidental Radiation Excursion at the Y-12 Plant, June 16, 1958*, Y-1234, Y-12 Plant, Oak Ridge, Tennessee, June 16. [SRDB Ref ID: 8387]

UCNC (Union Carbide Nuclear Company), 1963, *Y-12 Plant Quarterly Health Physics Report – Third Quarter CY 1962*, Y/KB-24, Y-12 Plant, Oak Ridge, Tennessee, February 7. [SRDB Ref ID: 23617]

Waller, L. A., and B. W. Turnbull, 1992, “Probability Plotting with Censored Data,” *The American Statistician*, volume 46, number 1, pp. 5–12.

Watkins, J. P., J. L. Reagan, 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,* Technical Report ORISE 93/J-42, Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee. [SRDB Ref ID: 10133]

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

West, C. M., 1980, “Names of Persons Having Dosimetry Information in the 1947-1950 Period in the Y-12 Record Center,” internal correspondence to H. B. McBride, Jr., Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, October 16. [SRBD Ref ID: 24018]

West, C. M., 1981, “Discrepancy in 1954 Y-12 Film Badge Results,” internal correspondence to H. L. Fore (Oak Ridge Gaseous Diffusion Plant), Union Carbide Corporation, Nuclear Division, Oak Ridge, Tennessee, August 18. [SRDB Ref ID: 28125]

West, C. M., 1993a, "Brief History of the Y-12 External Monitoring Program," memorandum to Donna Cragle, Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee, June 7. [SRDB Ref ID: 8532]

West, C. M., 1993b, "Addendum to 'Brief History of the Y-12 External Monitoring Program,'" memorandum to Donna Cragle, Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee, June 15. [SRDB Ref ID: 13296]

Wiley, S. W., 2004, "Y-12 Historical Radiation Standards," letter to G. D. Kerr (Kerr Consulting), BWXT Y-12, Oak Ridge, Tennessee, June 3. [SRDB Ref ID: 28131]

Wilson, R. H., 1987, *Historical Review of Personnel Dosimetry Development and Its Use in Radiation Protection Programs at Hanford 1944 to the 1980's*," PNL-6125, Pacific Northwest Laboratory, Richland, Washington, February. [SRDB Ref ID: 262]

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

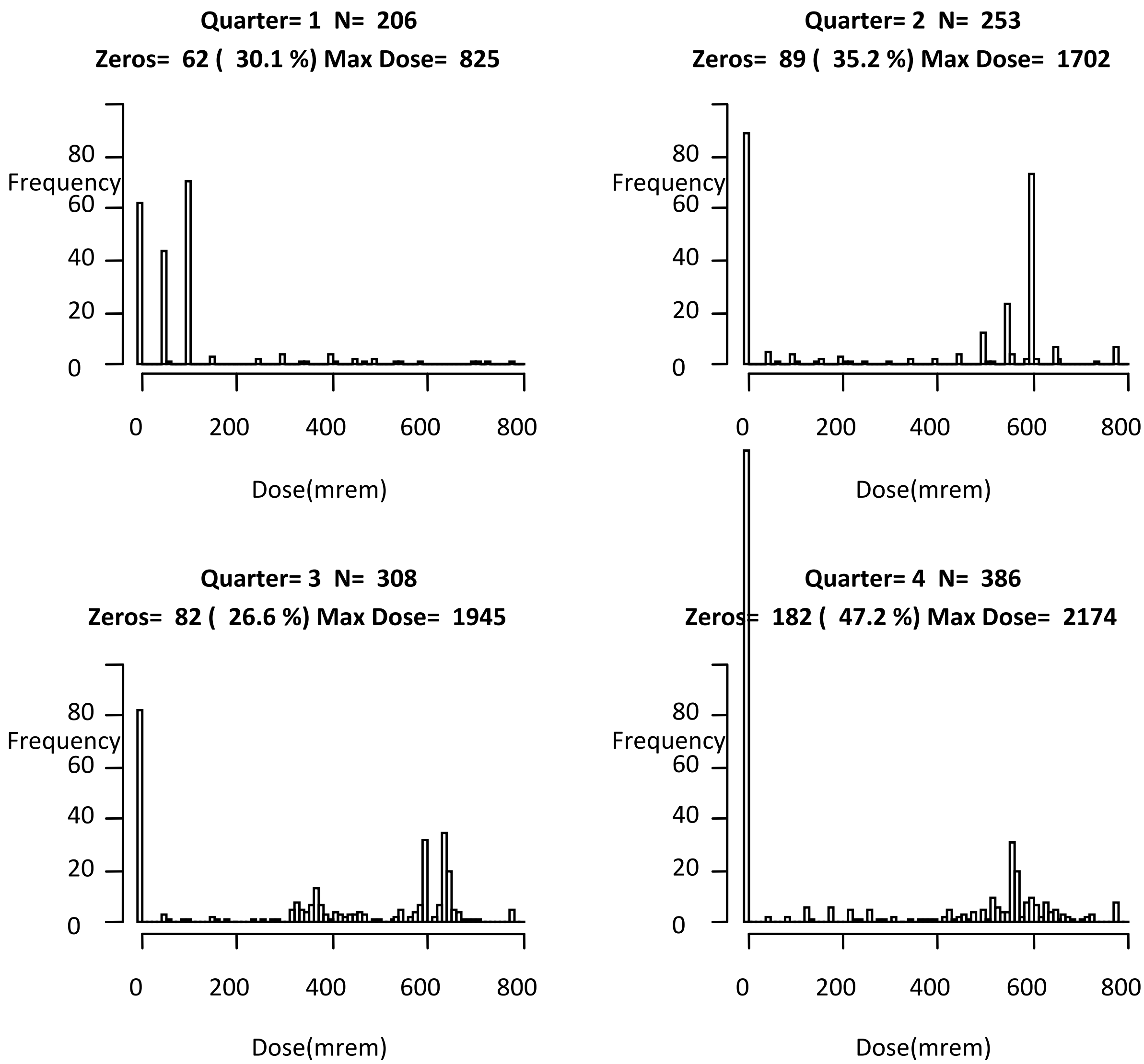

Figure A-1. Quarterly Y-12 film badge gamma dose for 1952.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

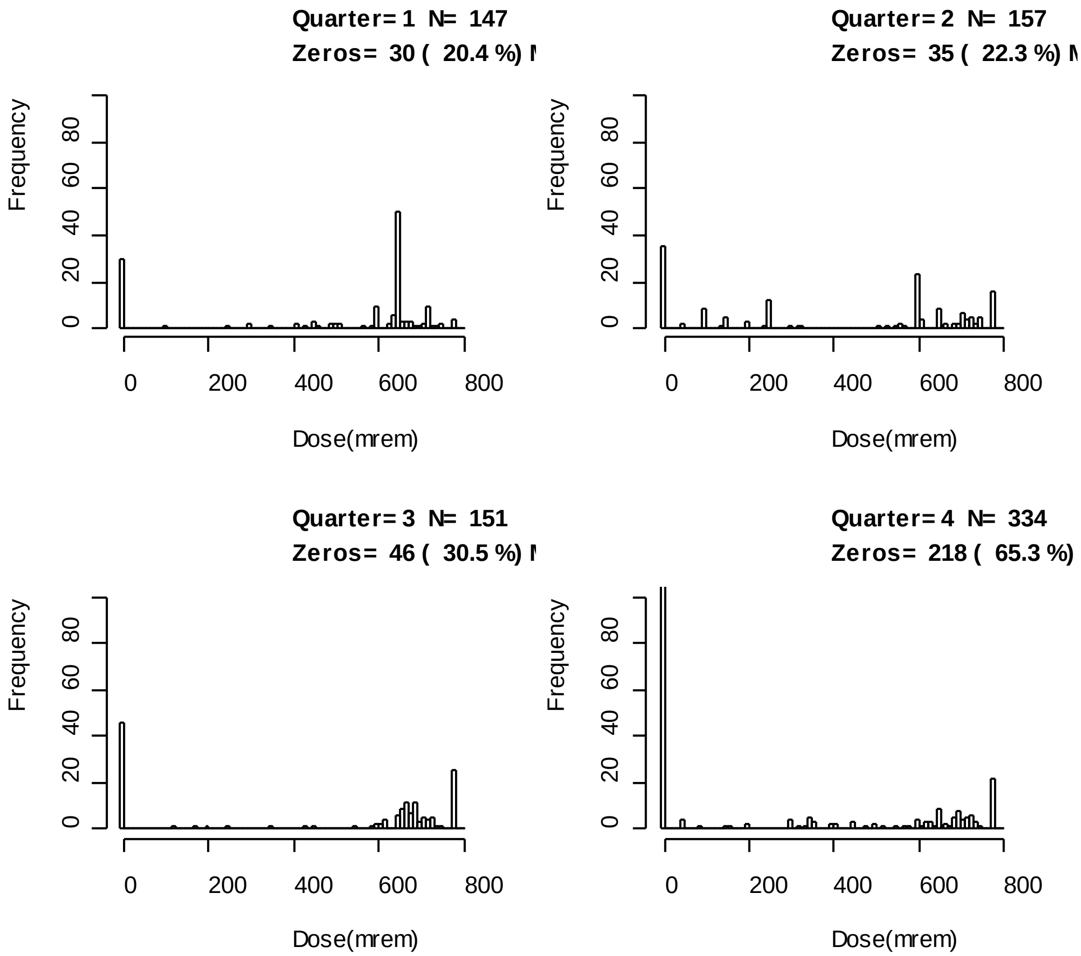

Figure A-2. Quarterly Y-12 film badge gamma dose for 1953.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR
Page 3 of 28

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

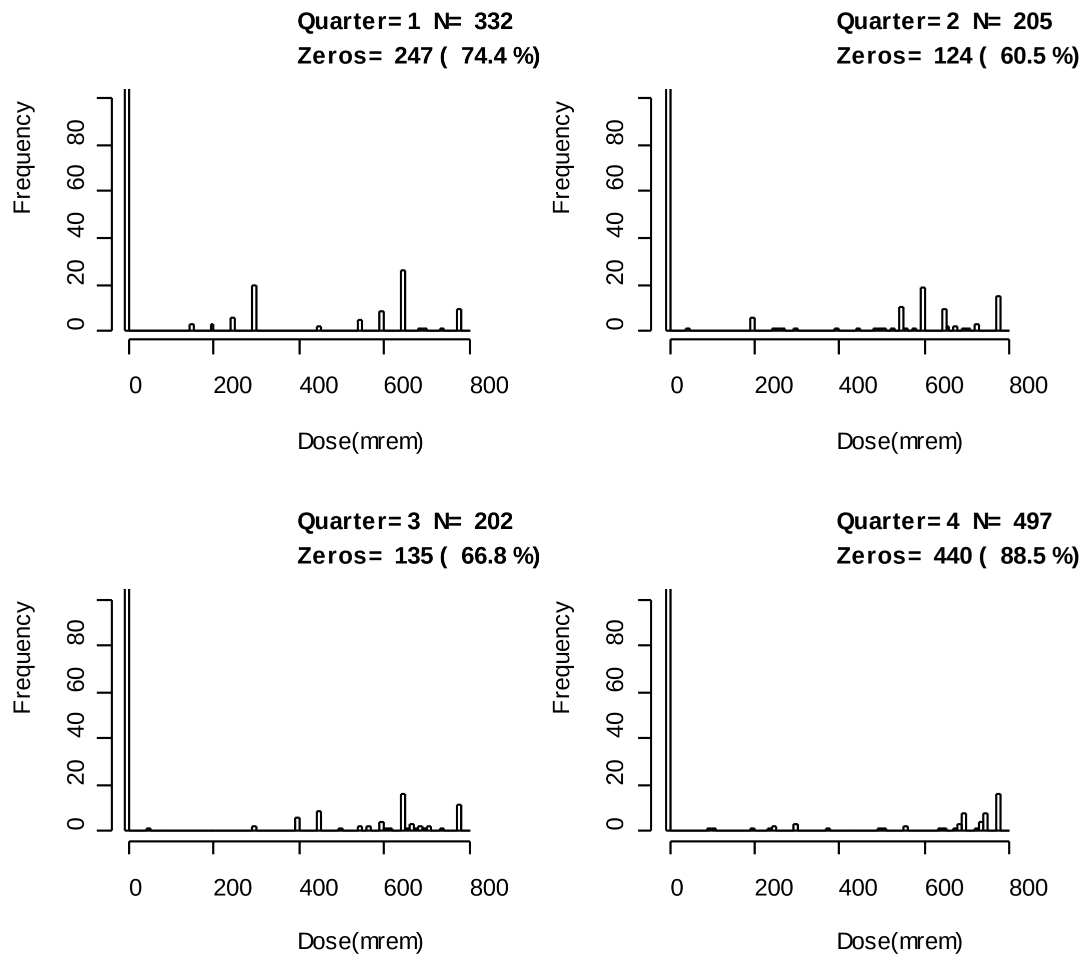

Figure A-3. Quarterly Y-12 film badge gamma dose for 1954.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

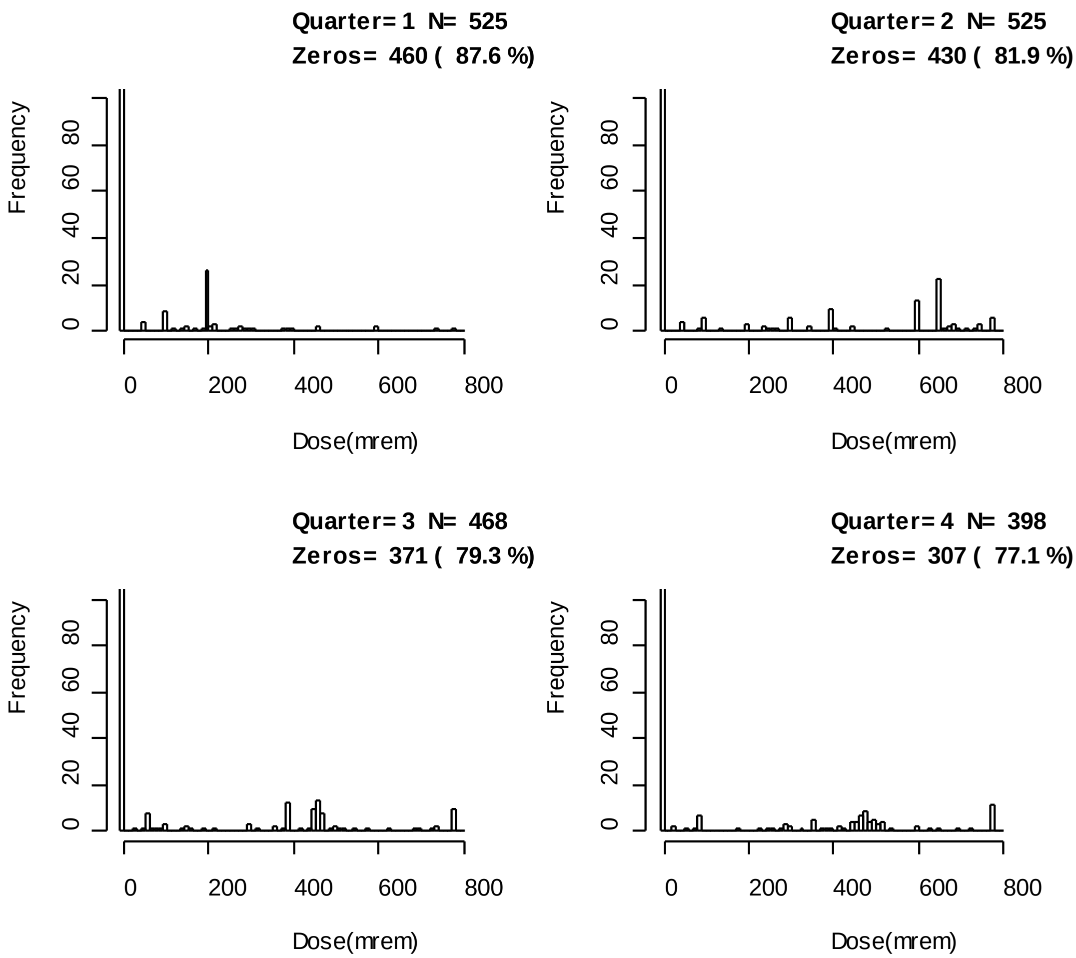

Figure A-4. Quarterly Y-12 film badge gamma dose for 1955.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

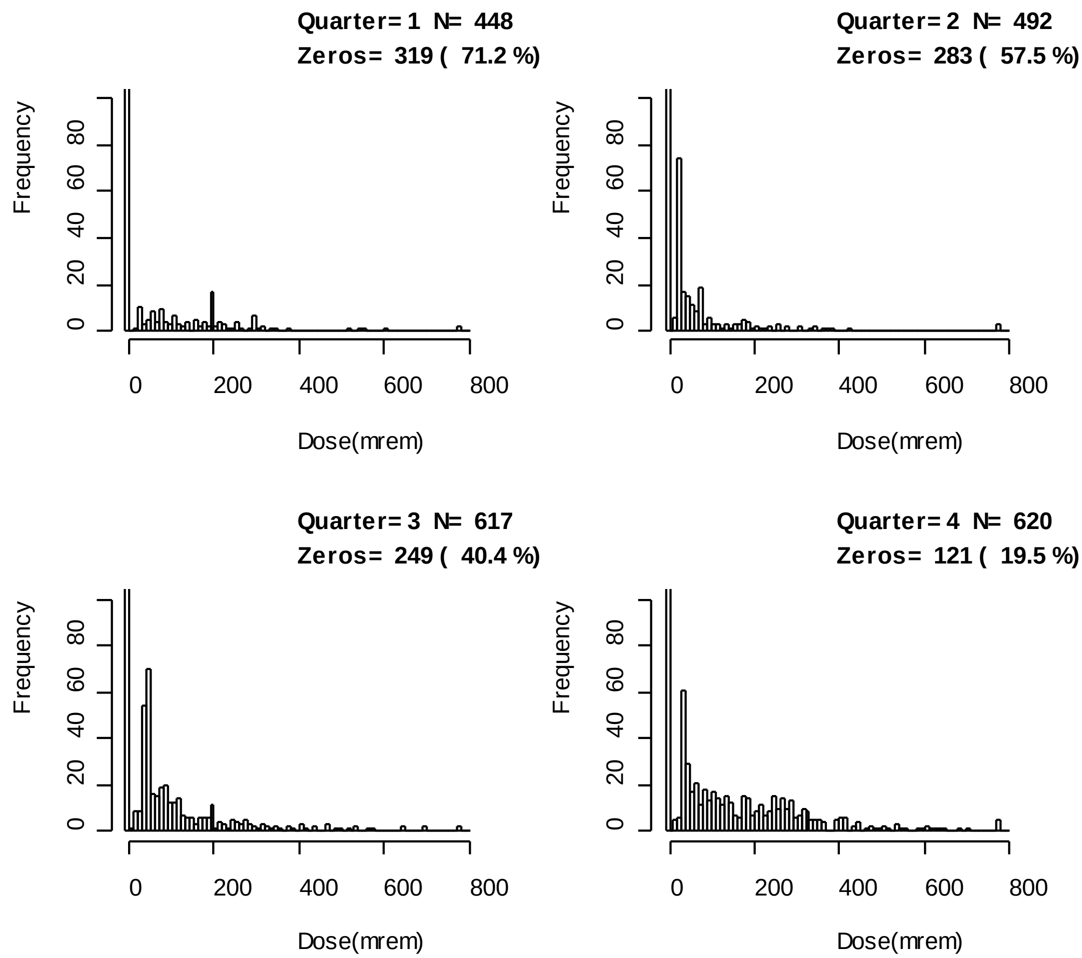

Figure A-5. Quarterly Y-12 film badge gamma dose for 1956.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

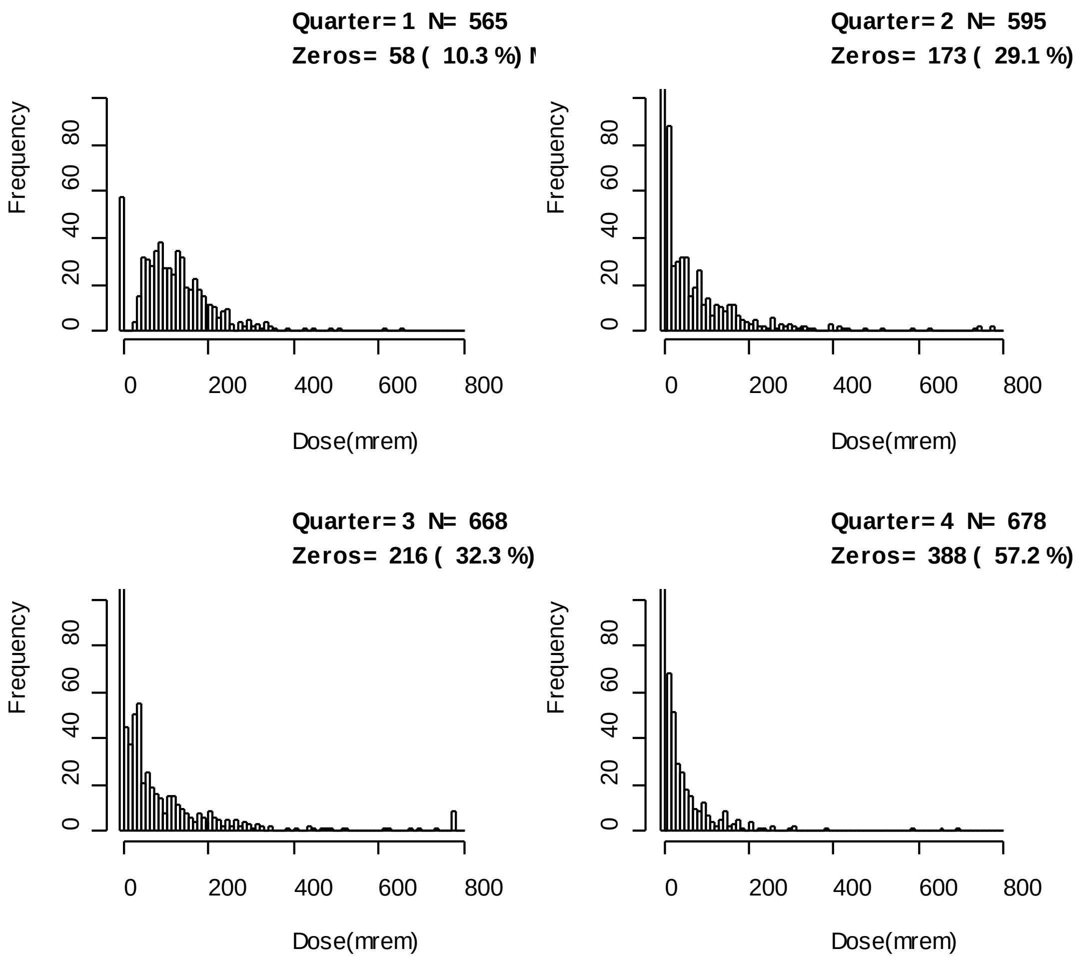

Figure A-6. Quarterly Y-12 film badge gamma dose for 1957.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

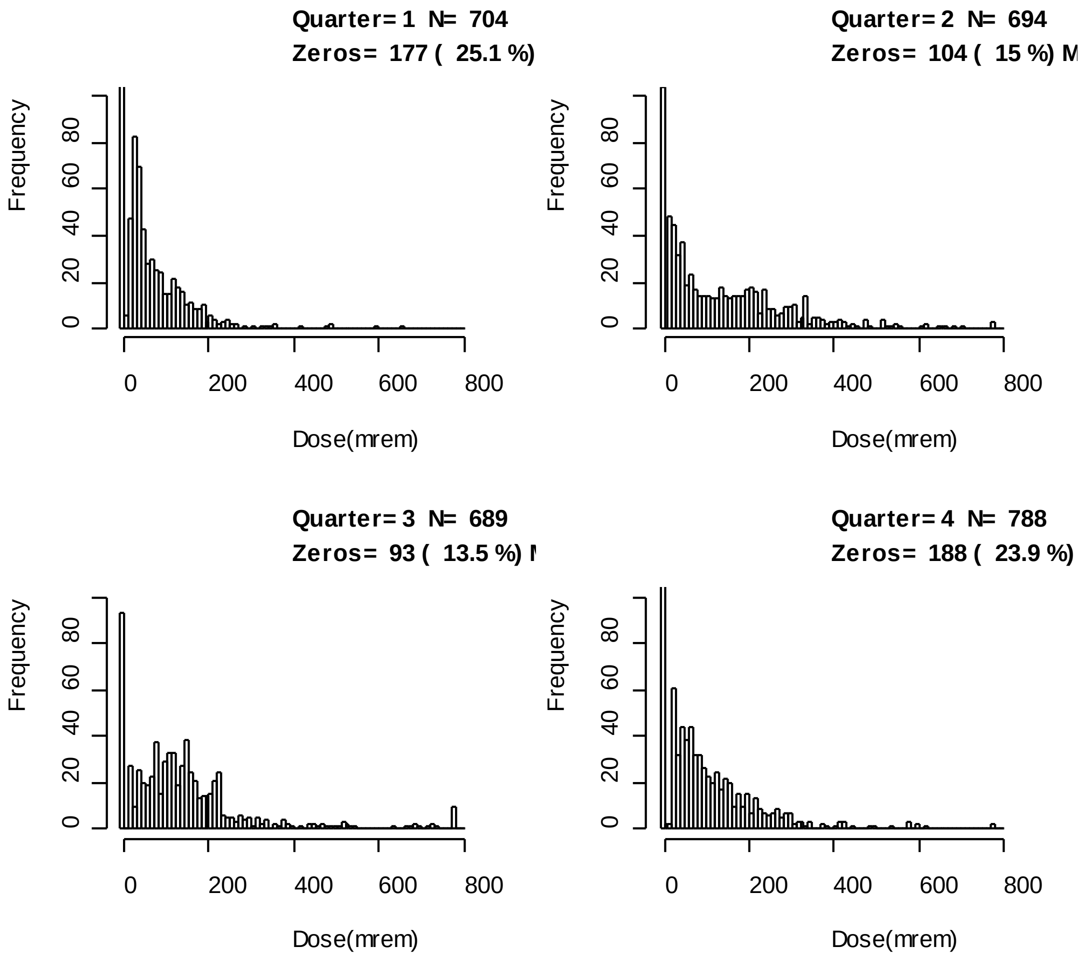

Figure A-7. Quarterly Y-12 film badge gamma dose for 1958.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

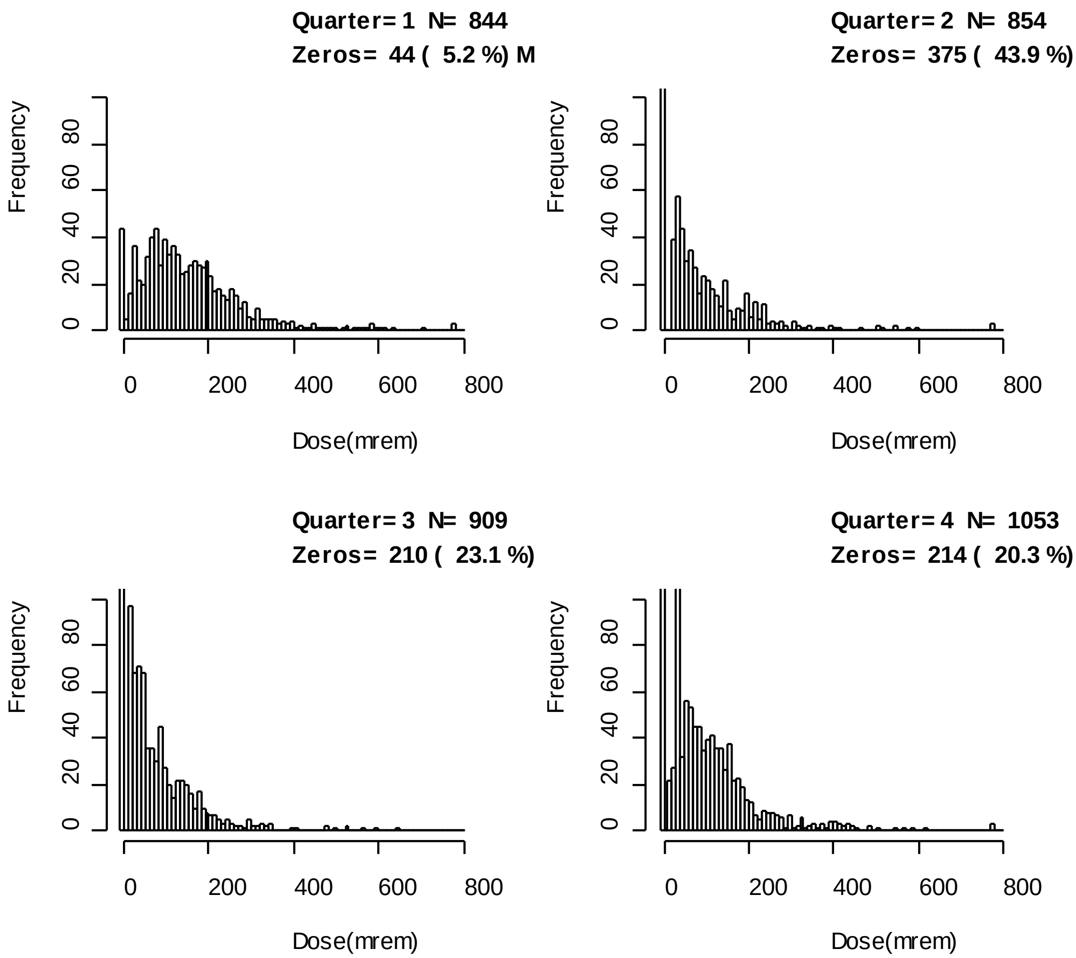

Figure A-8. Quarterly Y-12 film badge gamma dose for 1959.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

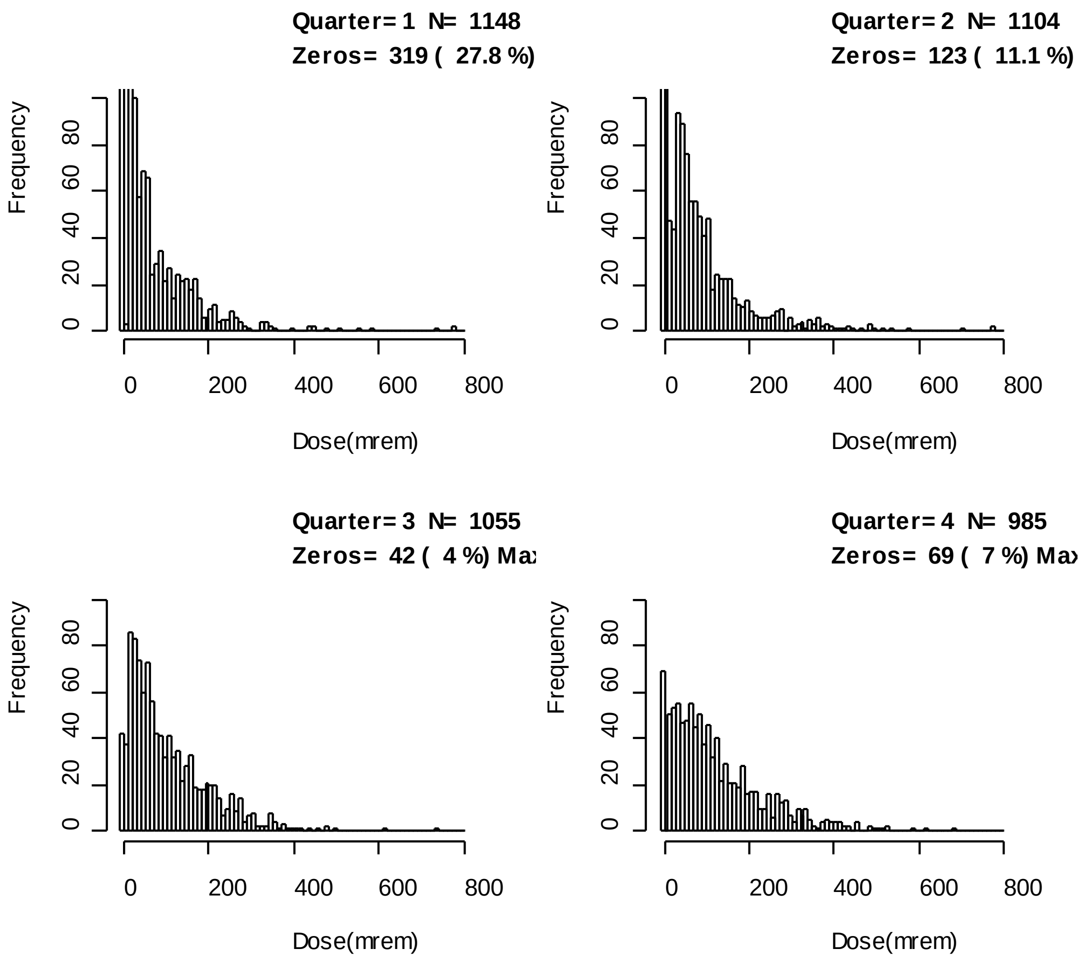

Figure A-9. Quarterly Y-12 film badge gamma dose for 1960.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

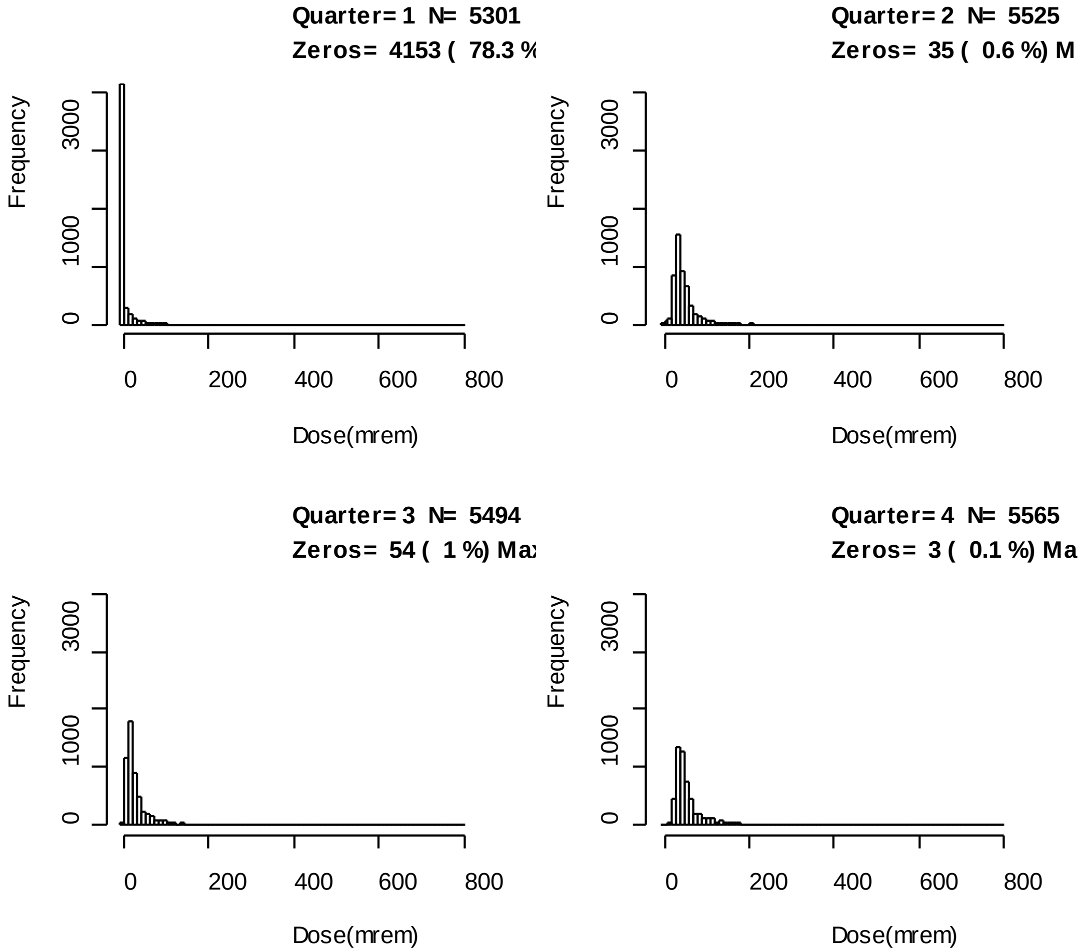

Figure A-10. Quarterly Y-12 film badge gamma dose for 1961.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

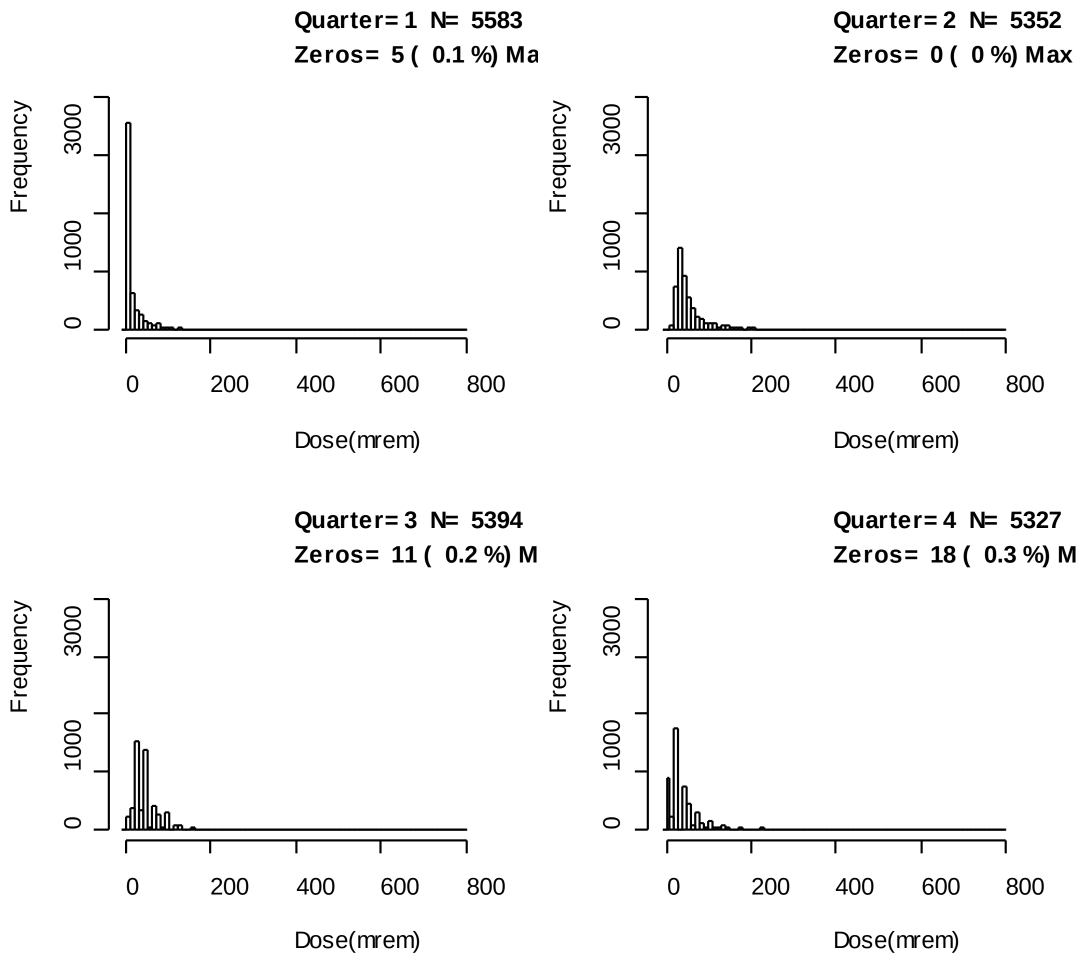

Figure A-11. Quarterly Y-12 film badge gamma dose for 1962.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

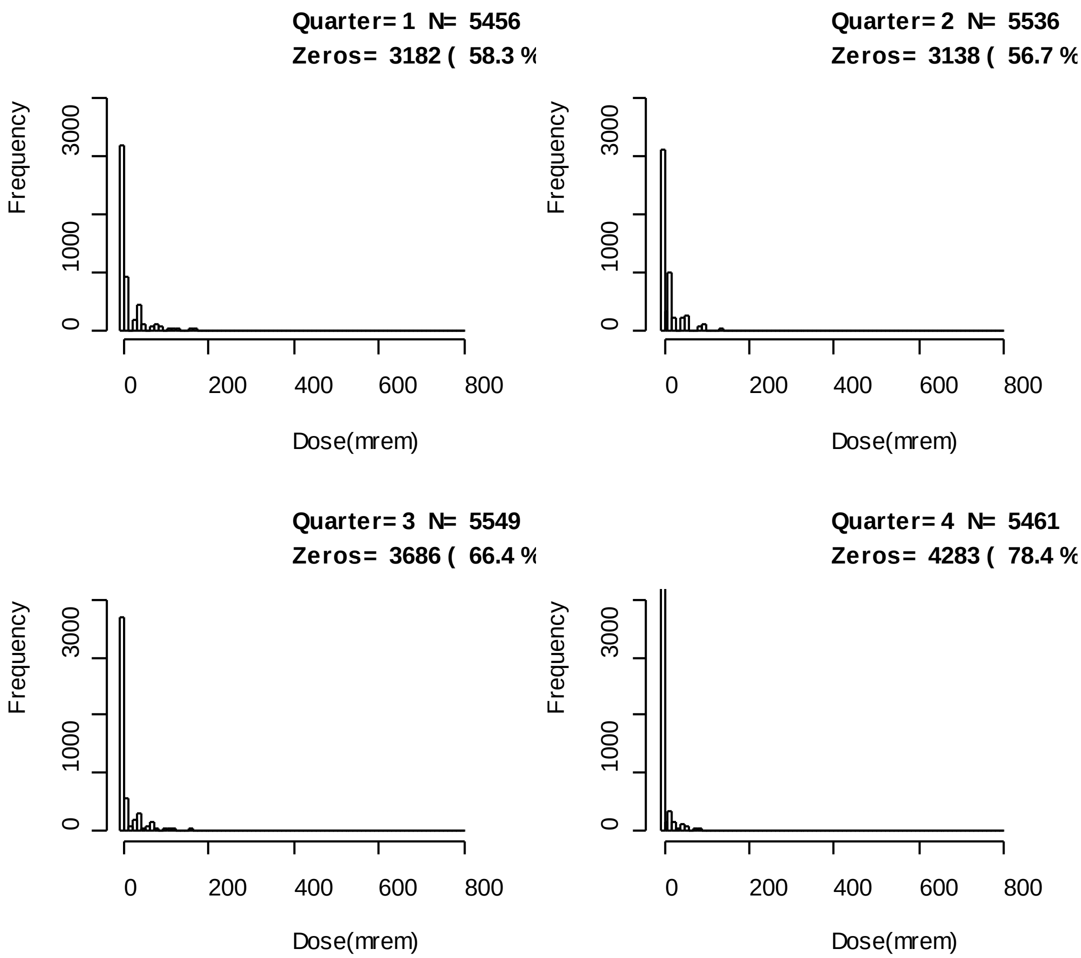

Figure A-12. Quarterly Y-12 film badge gamma dose for 1963.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

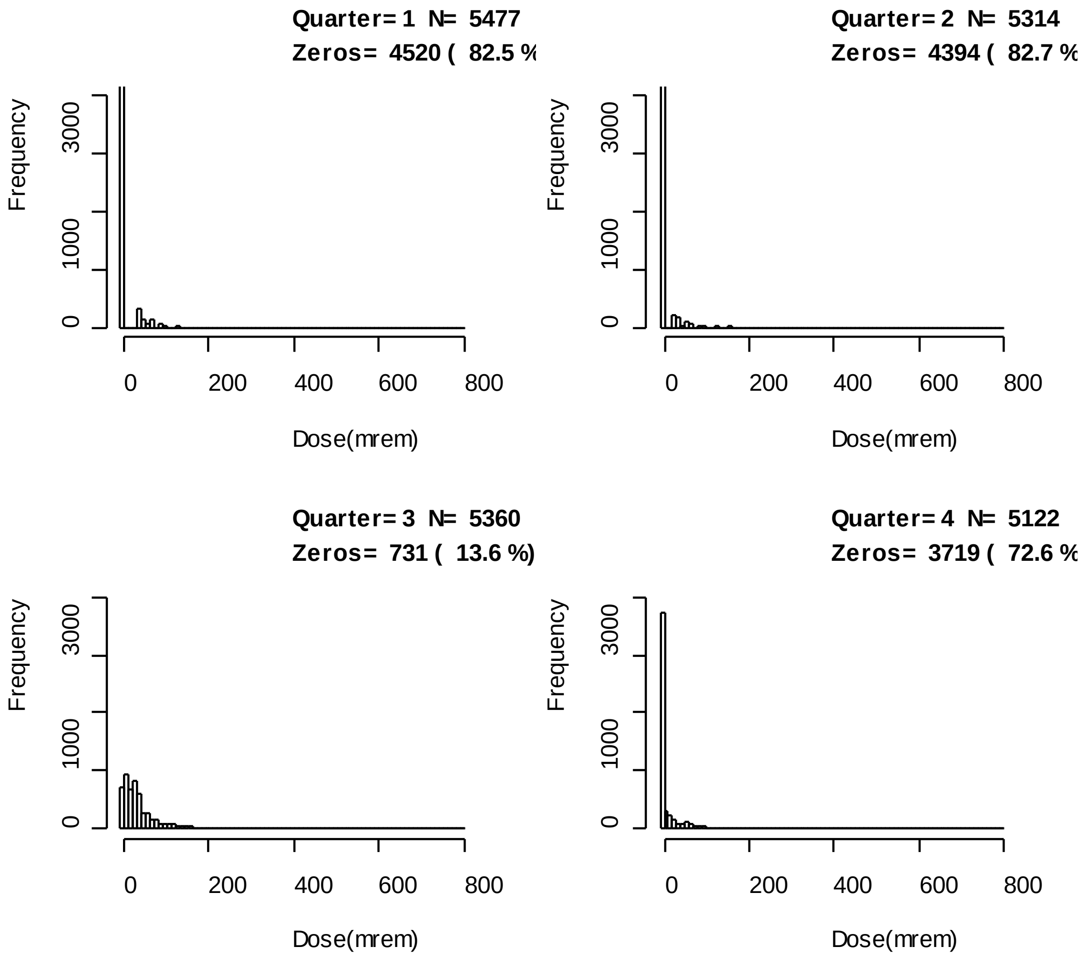

Figure A-13. Quarterly Y-12 film badge gamma dose for 1964.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

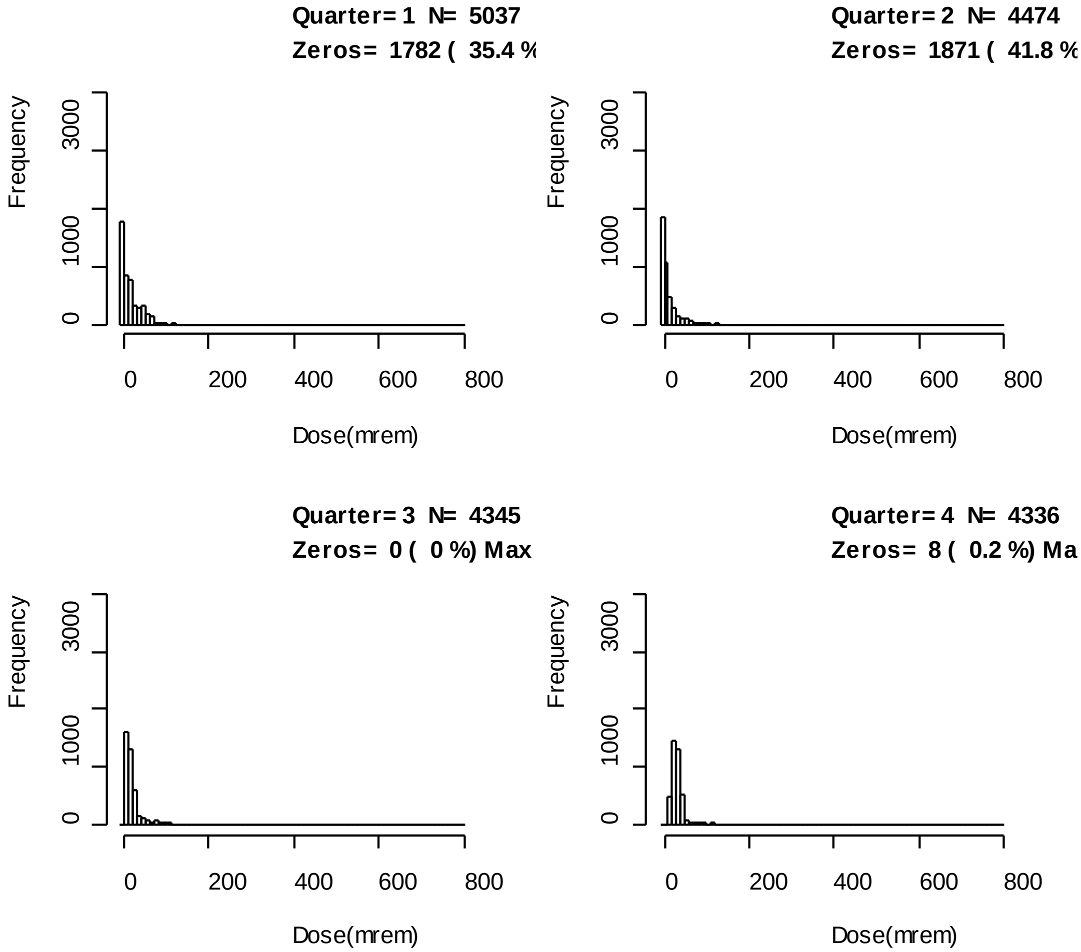

Figure A-14. Quarterly Y-12 film badge gamma dose for 1965.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR
Page 15 of 28

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

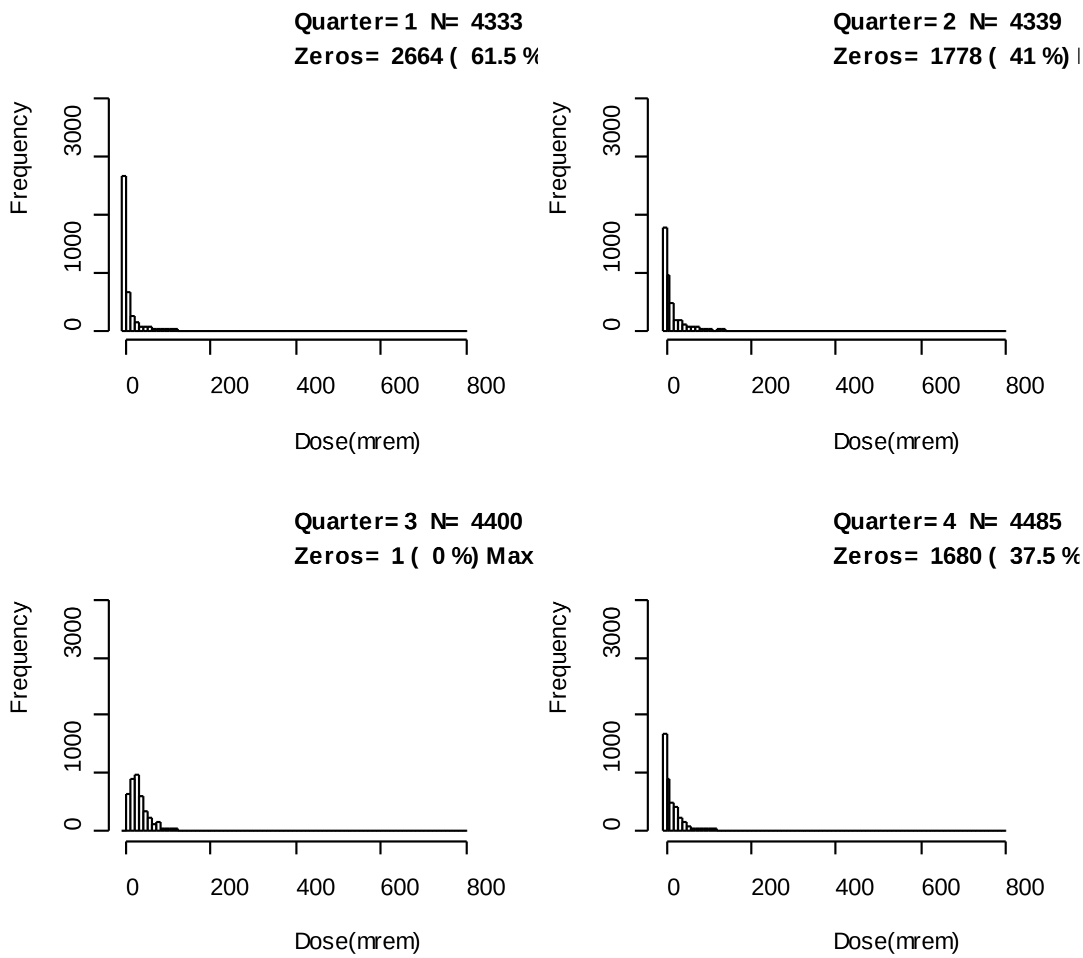

Figure A-15. Quarterly Y-12 film badge gamma dose for 1966.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

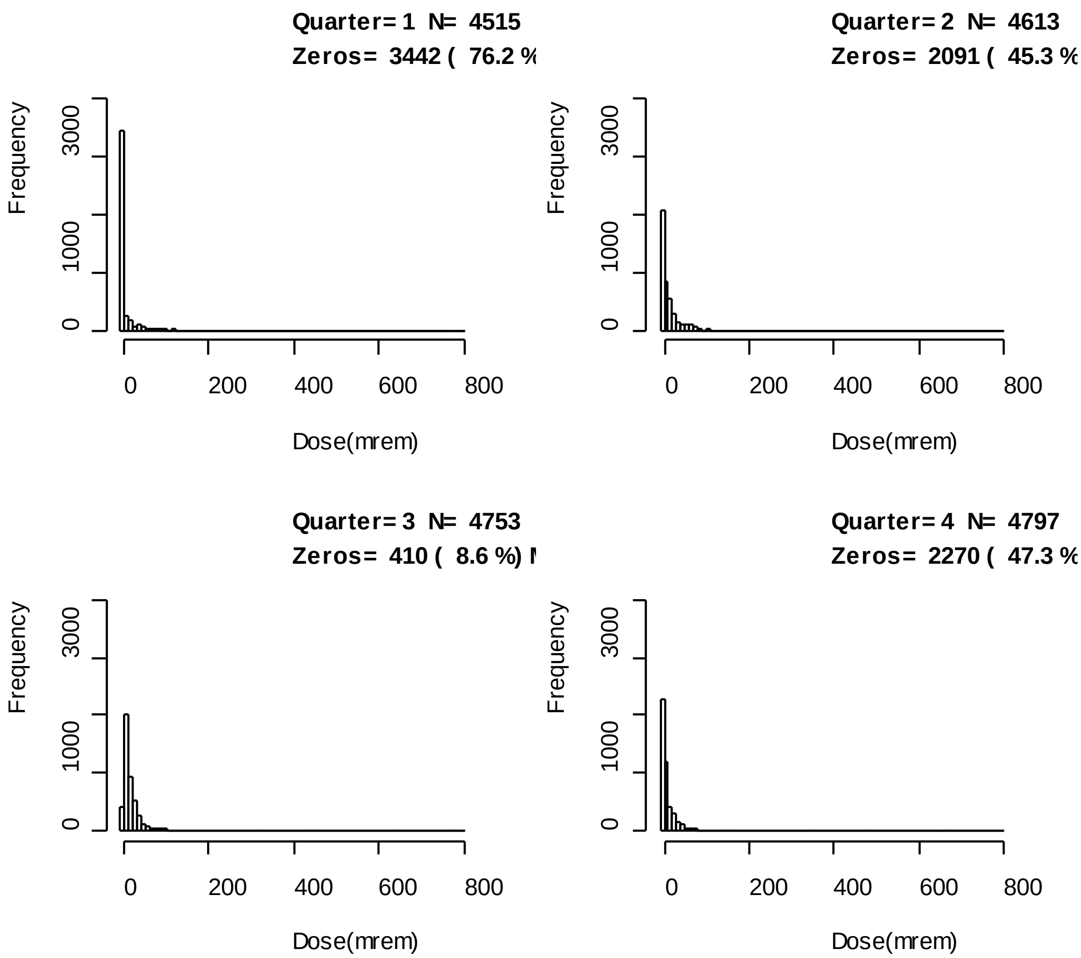

Figure A-16. Quarterly Y-12 film badge gamma dose for 1967.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

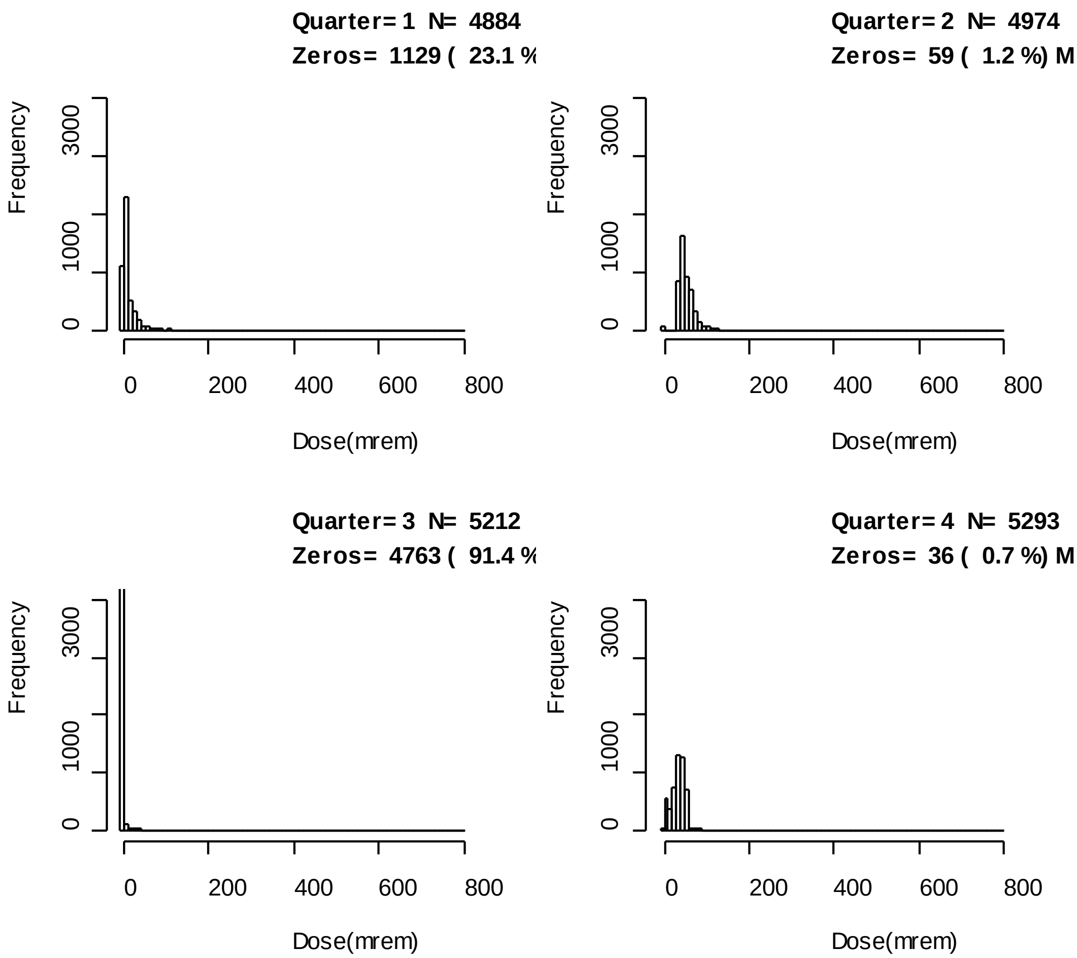

Figure A-17. Quarterly Y-12 film badge gamma dose for 1968.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

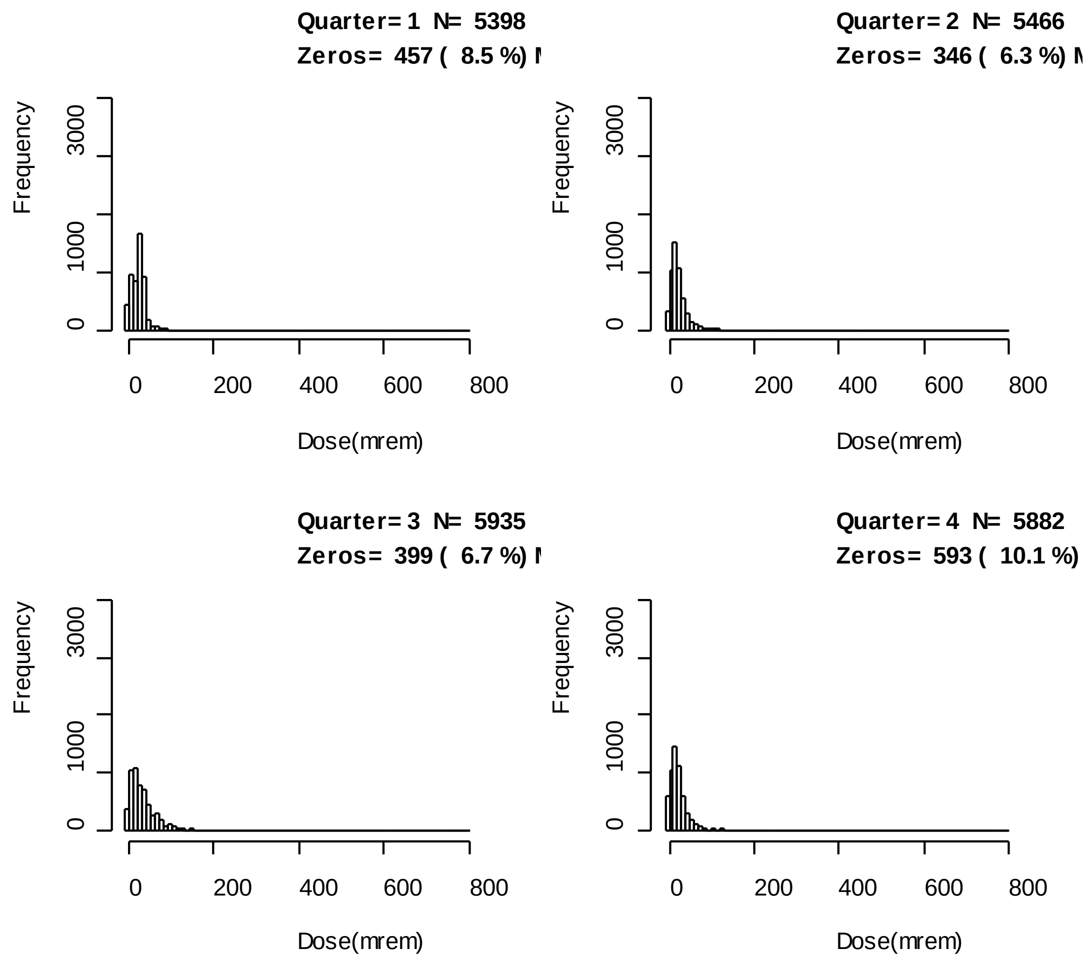

Figure A-18. Quarterly Y-12 film badge gamma dose for 1969.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

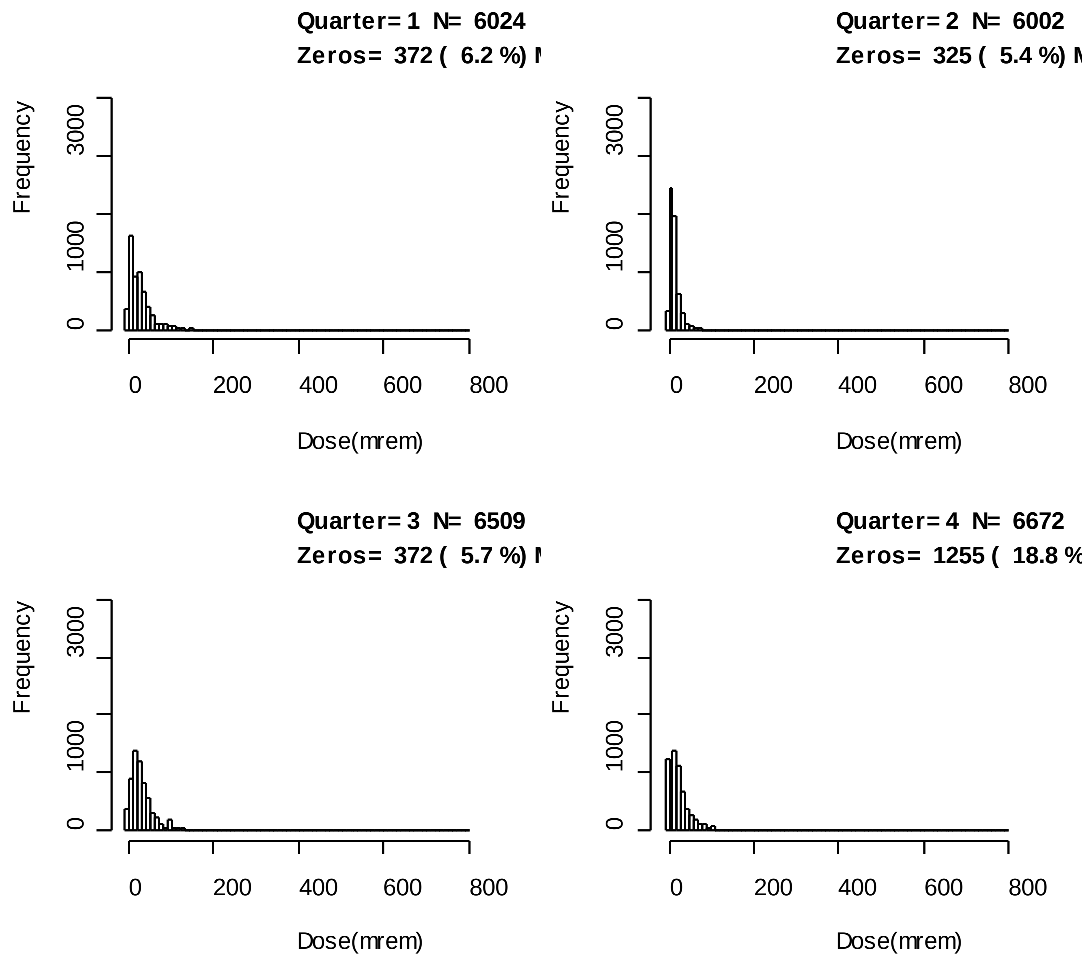

Figure A-19. Quarterly Y-12 film badge gamma dose for 1970.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR
Page 20 of 28

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

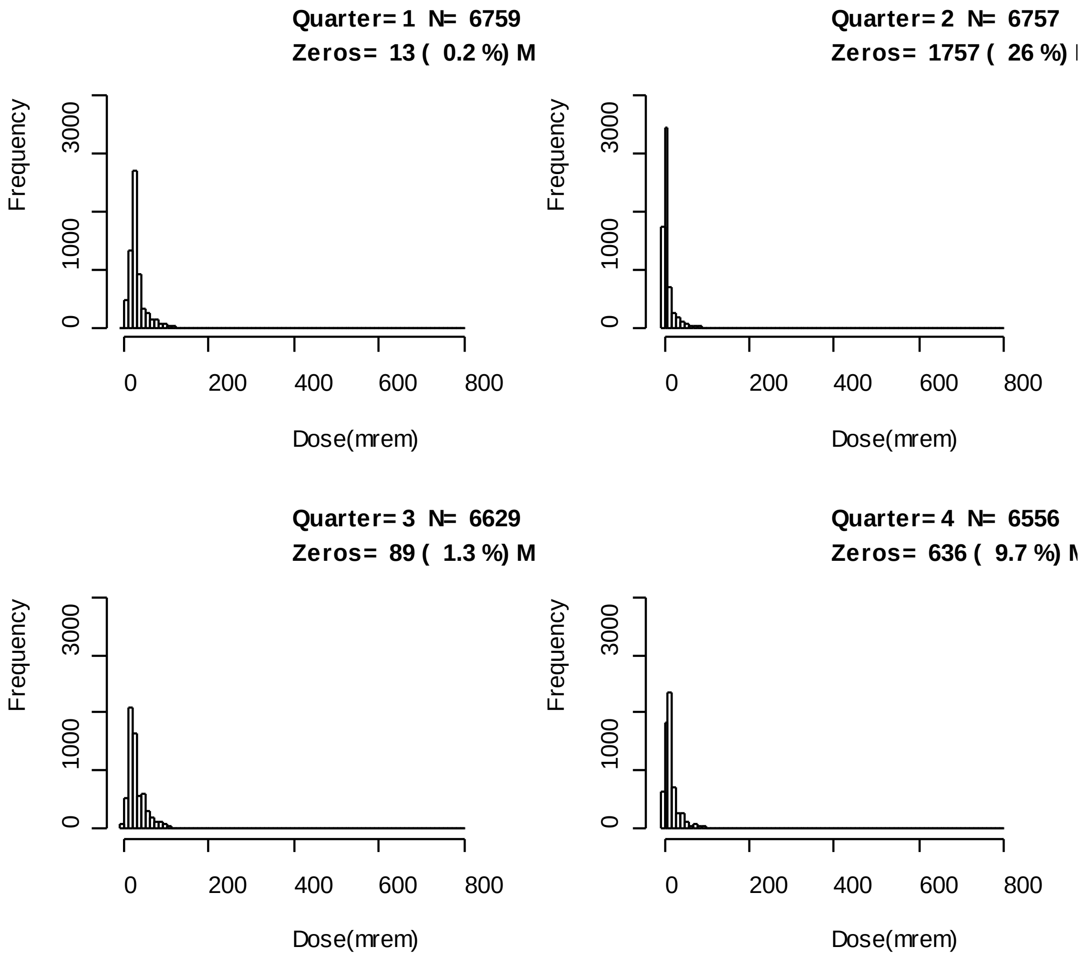

Figure A-20. Quarterly Y-12 film badge gamma dose for 1971.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

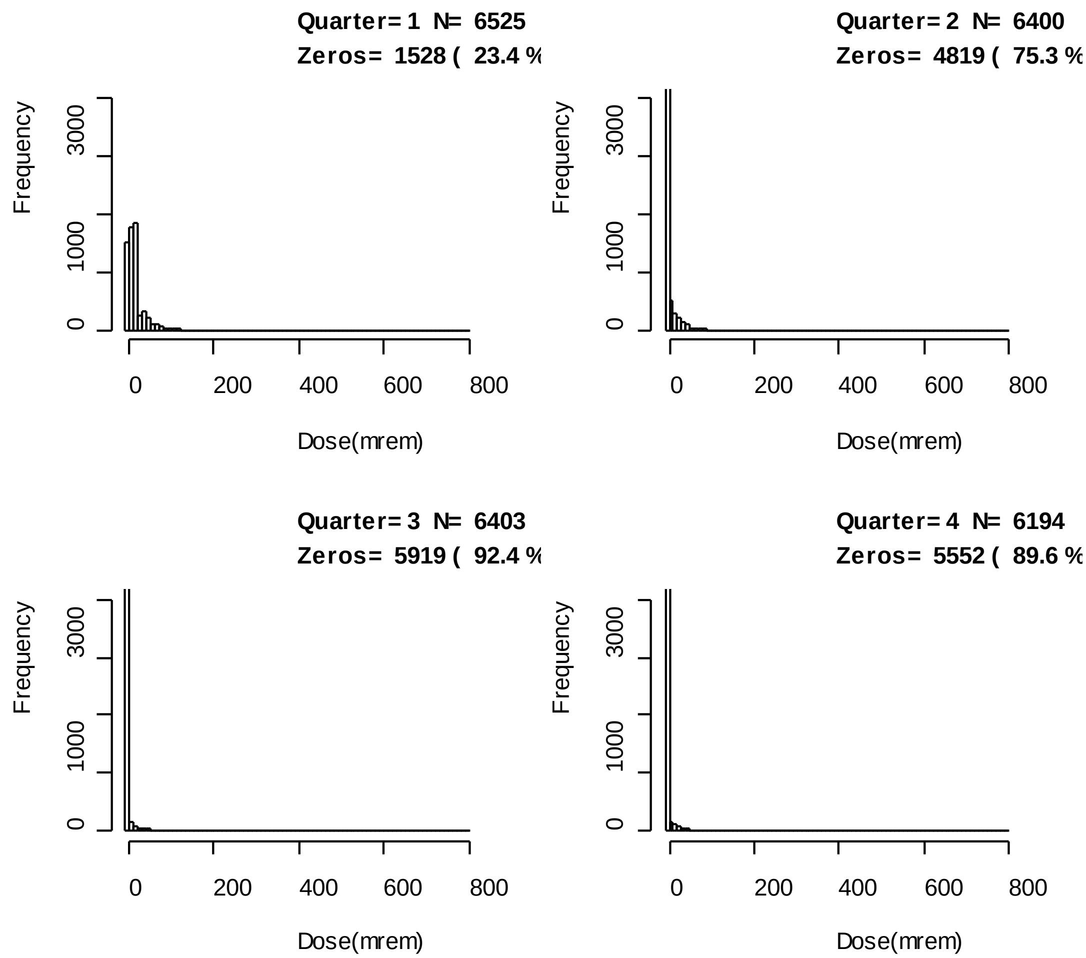

Figure A-21. Quarterly Y-12 film badge gamma dose for 1972.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

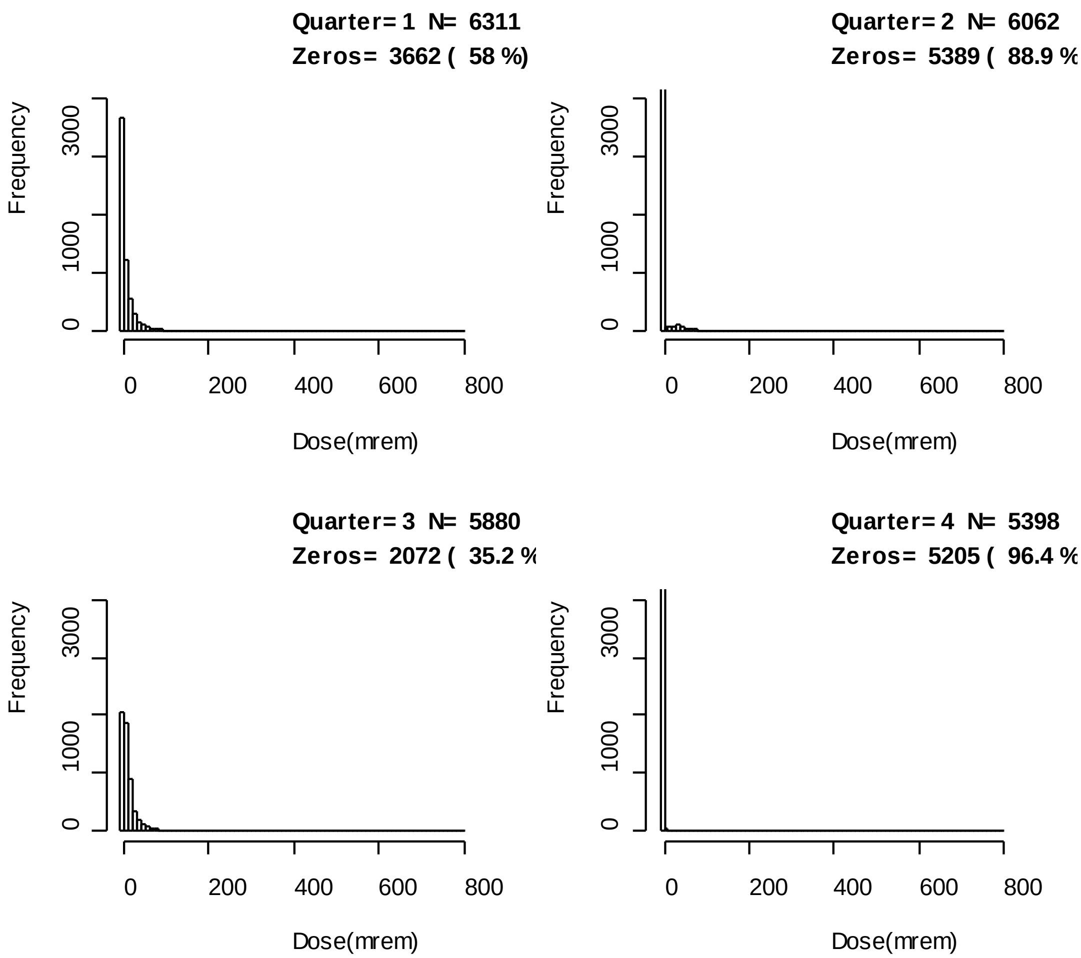

Figure A-22. Quarterly Y-12 film badge gamma dose for 1973.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

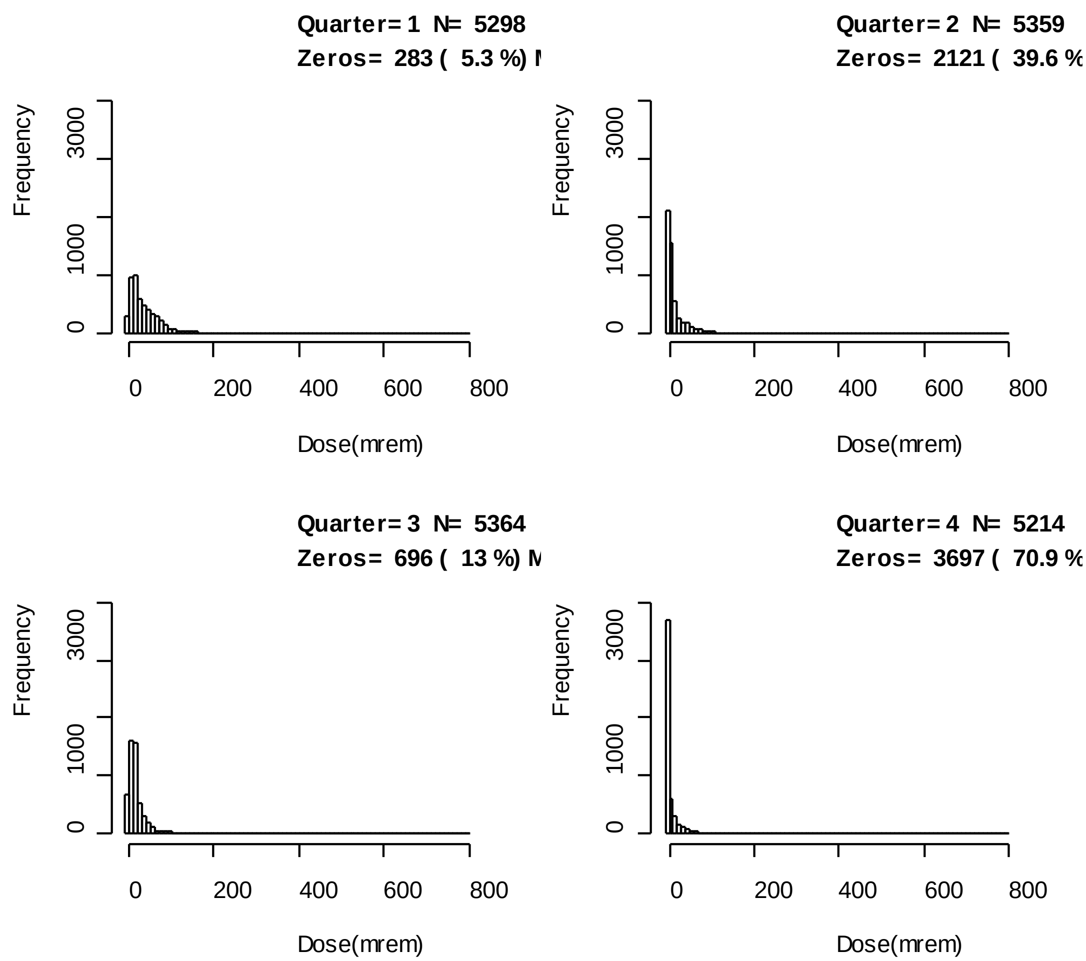

Figure A-23. Quarterly Y-12 film badge gamma dose for 1974.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

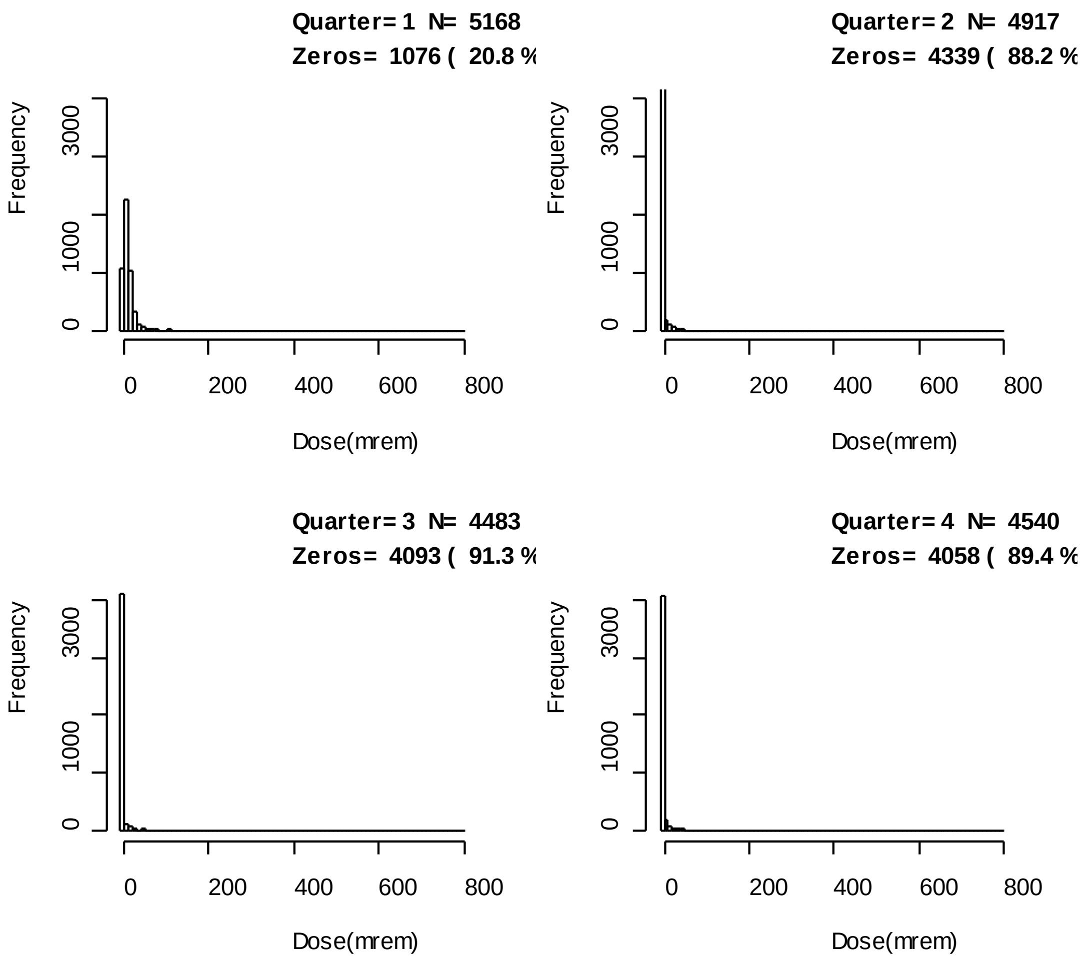

Figure A-24. Quarterly Y-12 film badge gamma dose for 1975.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

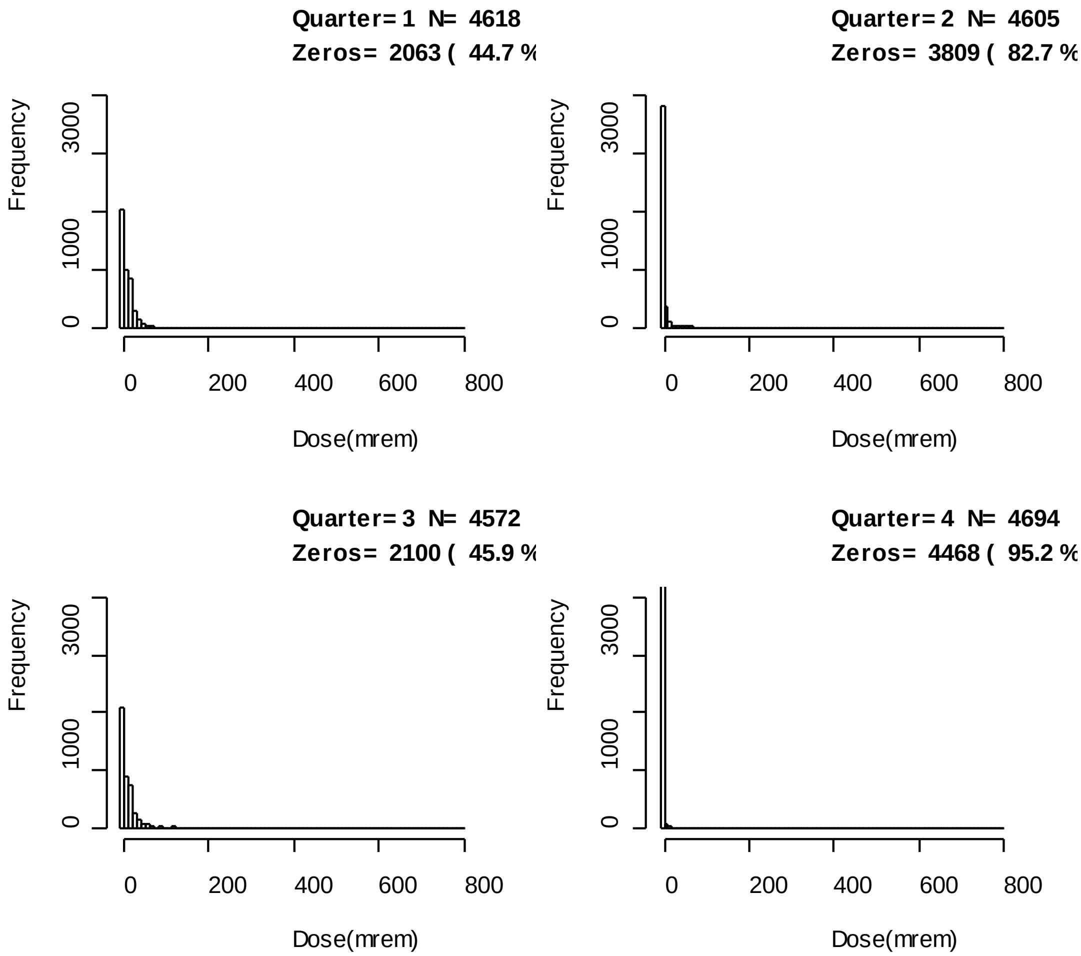

Figure A-25. Quarterly Y-12 film badge gamma dose for 1976.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

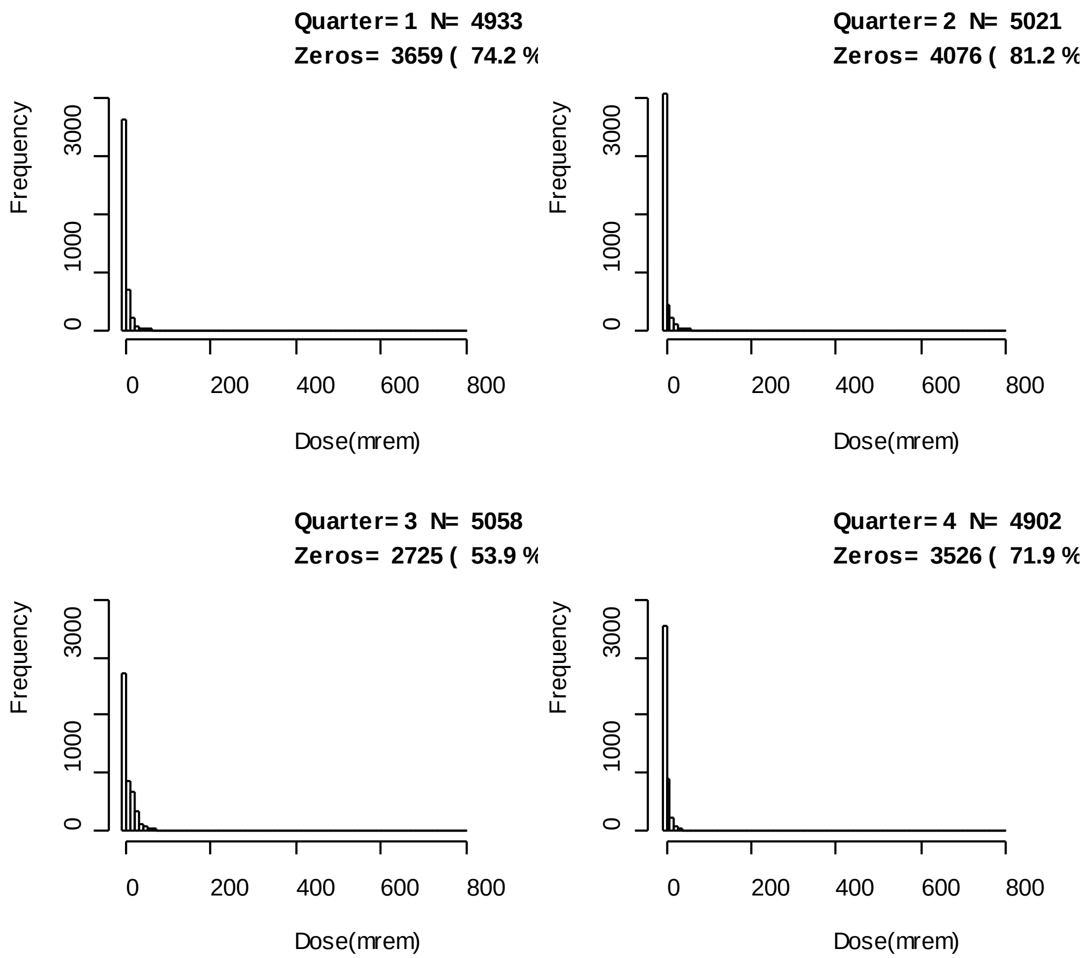

Figure A-26. Quarterly Y-12 film badge gamma dose for 1977.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

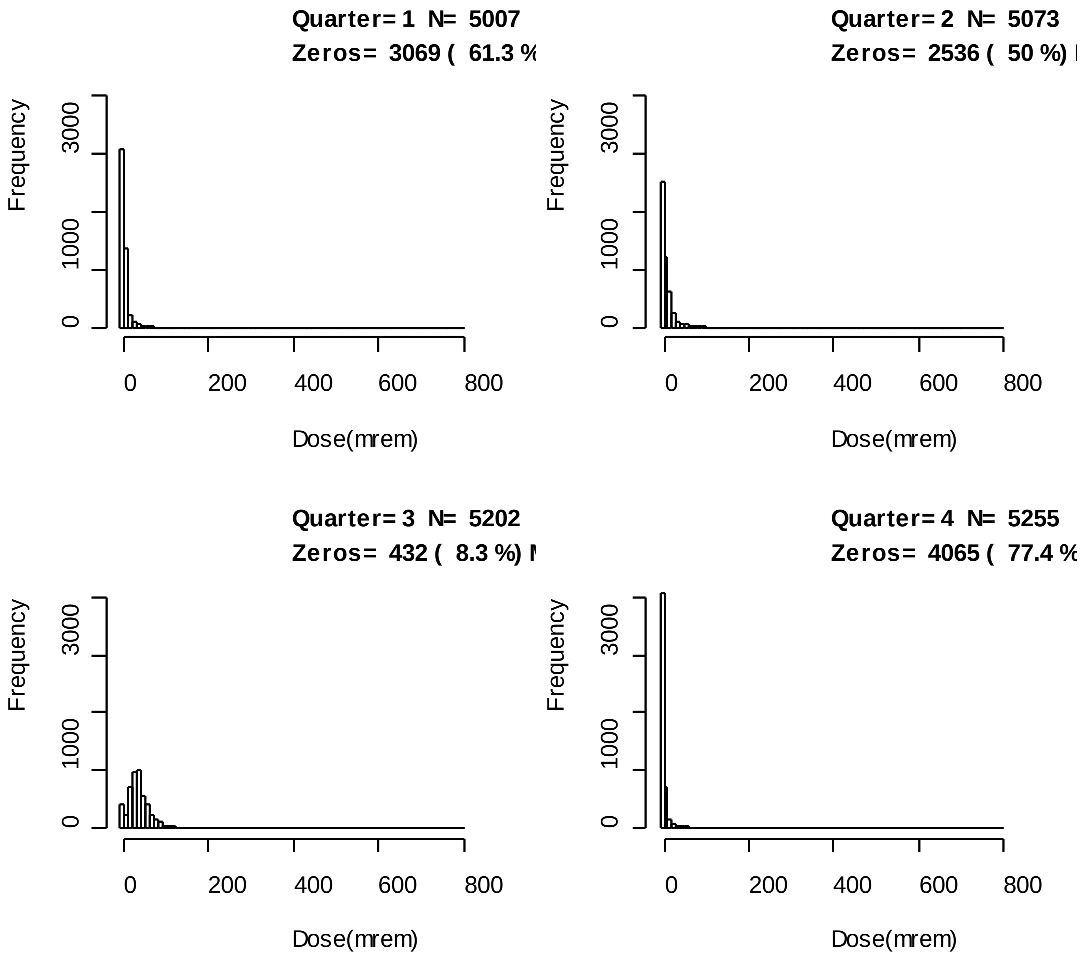

Figure A-27. Quarterly Y-12 film badge gamma dose for 1978.

ATTACHMENT A
DISTRIBUTIONS OF QUARTERLY GAMMA DOSES BY YEAR

Note change in vertical scale, frequency, or number of workers having dose of a given range. Vertical axis ranges from 0 to 100 for 1952 to 1960 and from 0 to 4,000 for 1961 to 1979, which corresponds to the policy change in 1961 to monitor all Y-12 workers for external radiation.

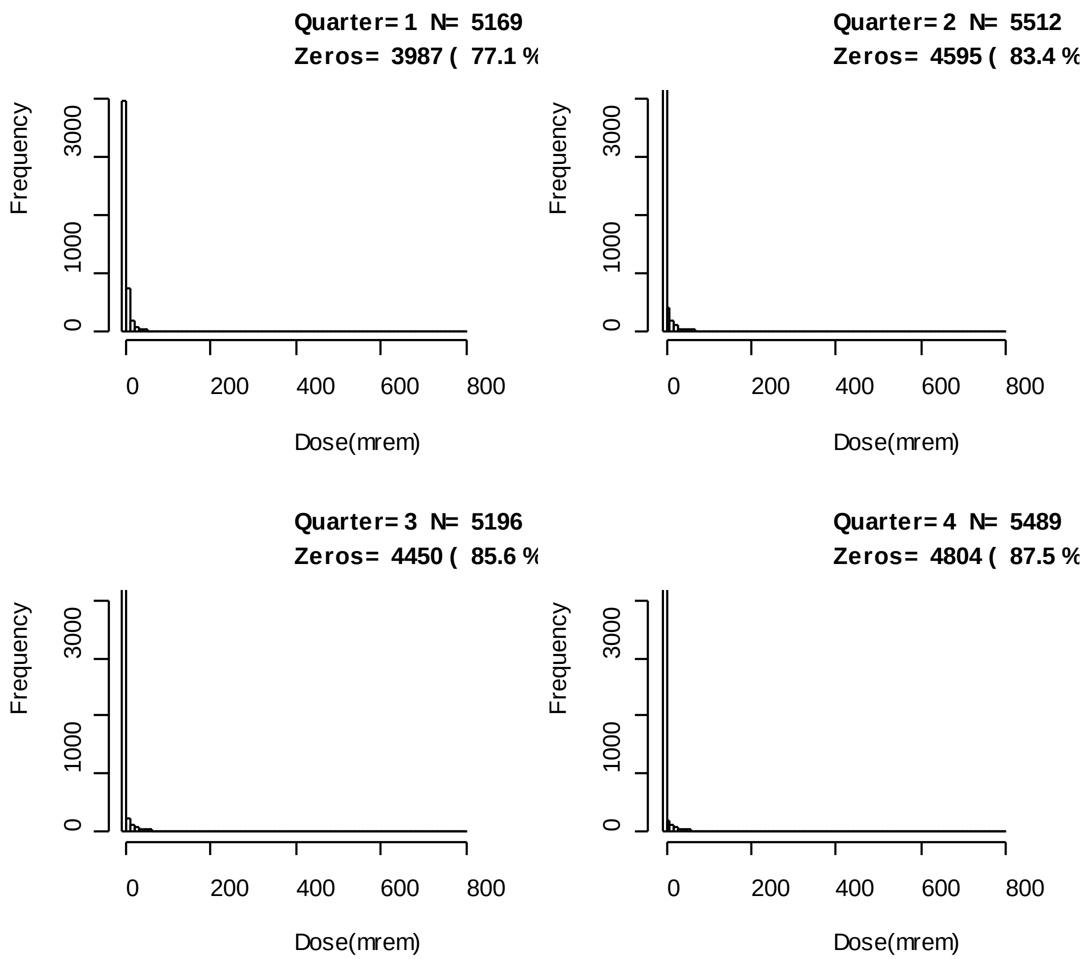

Figure A-28. Quarterly Y-12 film badge gamma dose for 1979.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

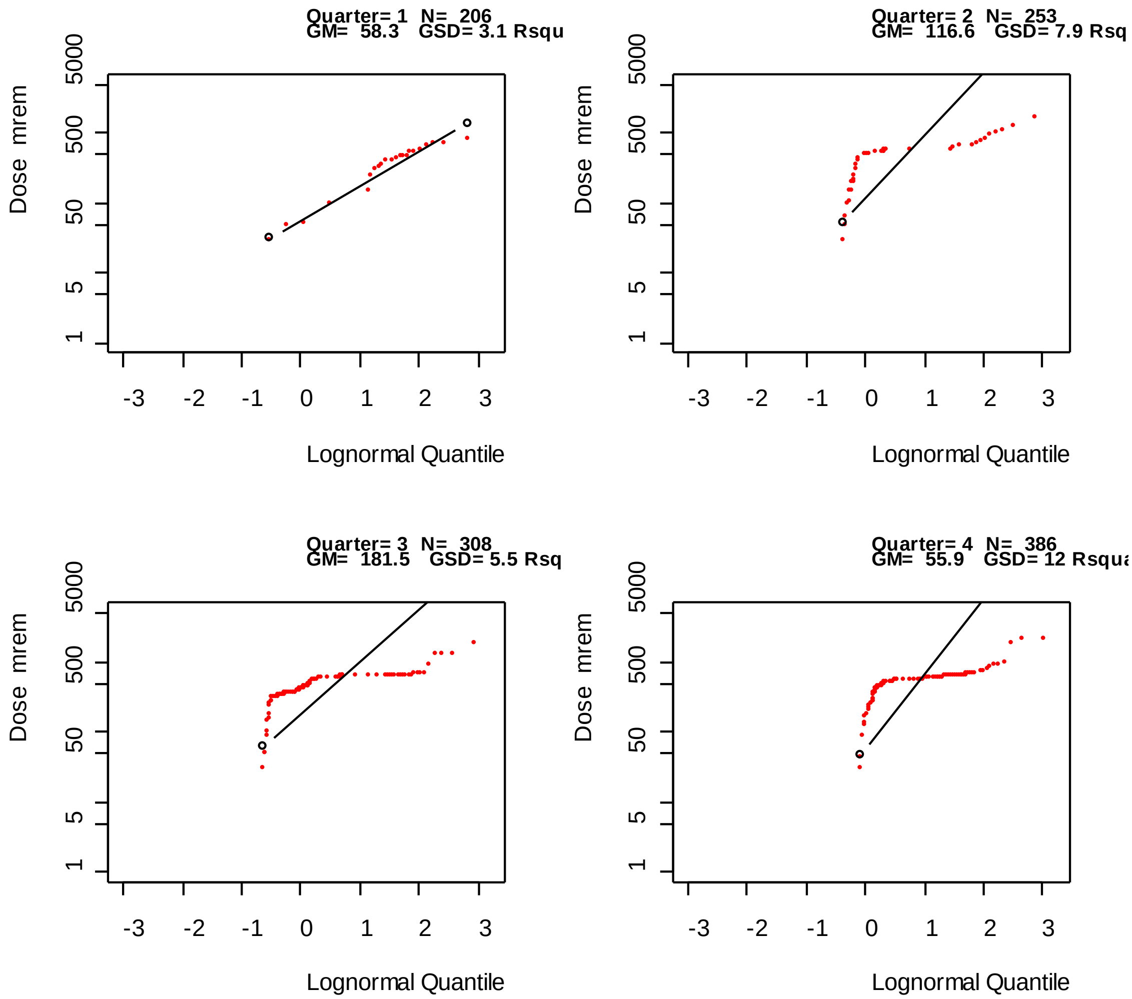

Figure B-1. Quarterly Y-12 film badge gamma dose for 1952.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979
Page 2 of 28

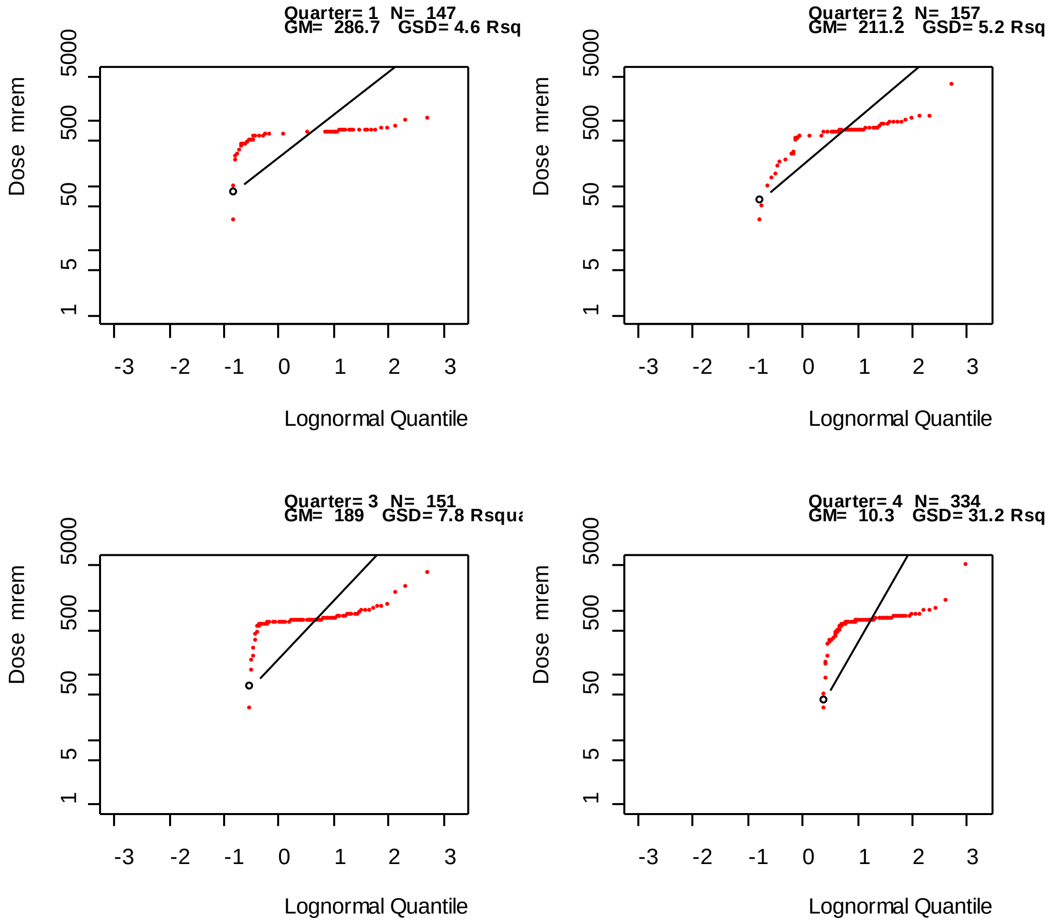

Figure B-2. Quarterly Y-12 film badge gamma dose for 1953.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

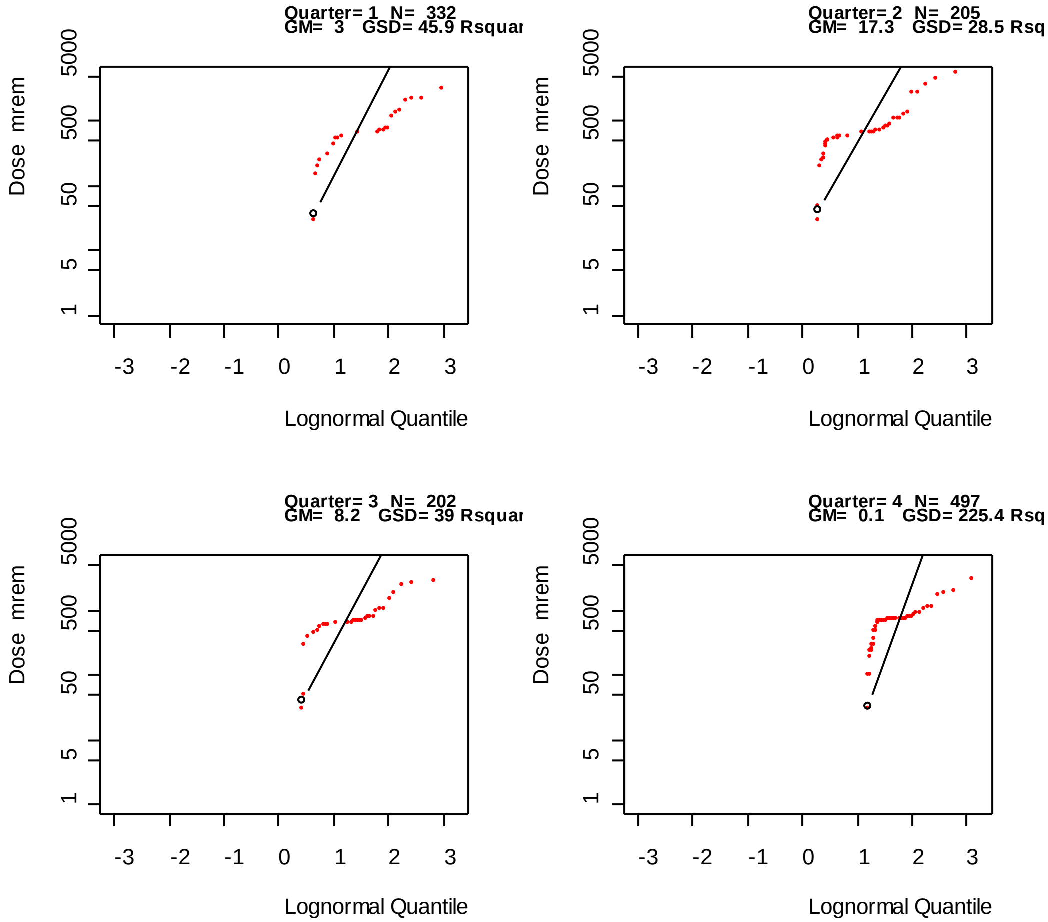

Figure B-3. Quarterly Y-12 film badge gamma dose for 1954.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

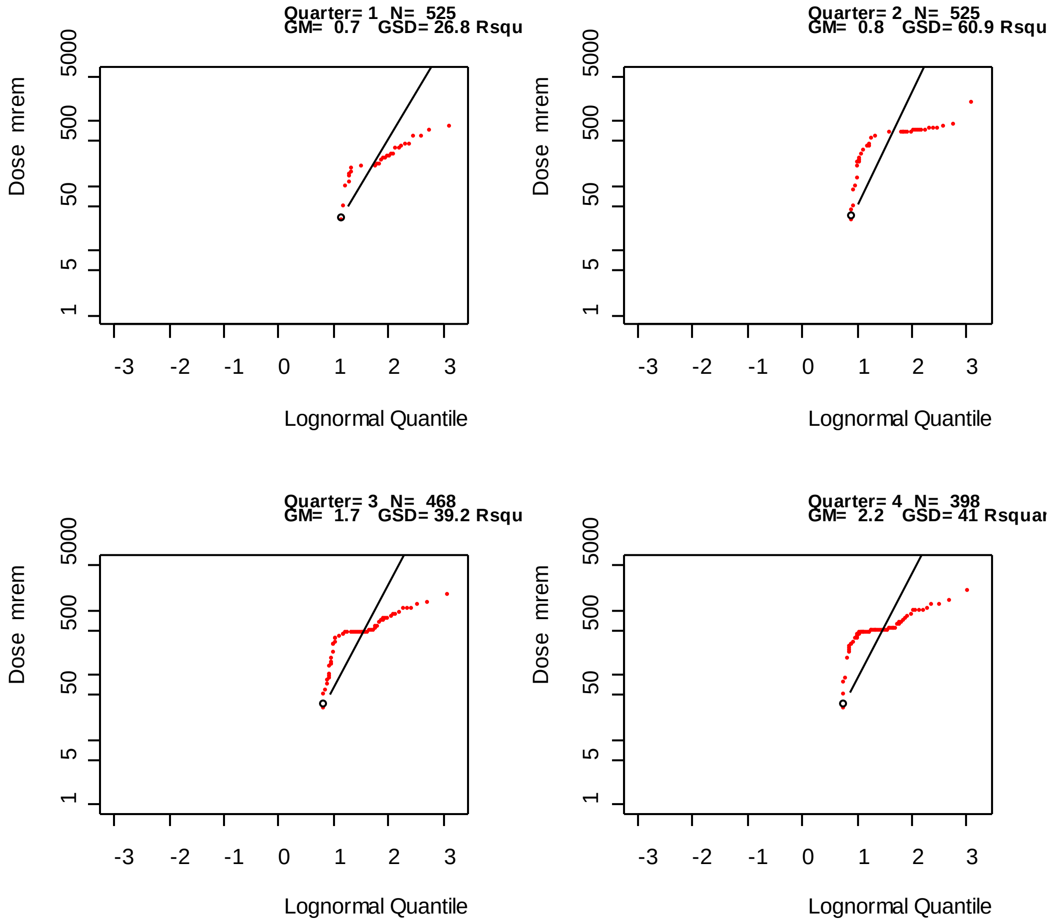

Figure B-4. Quarterly Y-12 film badge gamma dose for 1955.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979
Page 5 of 28

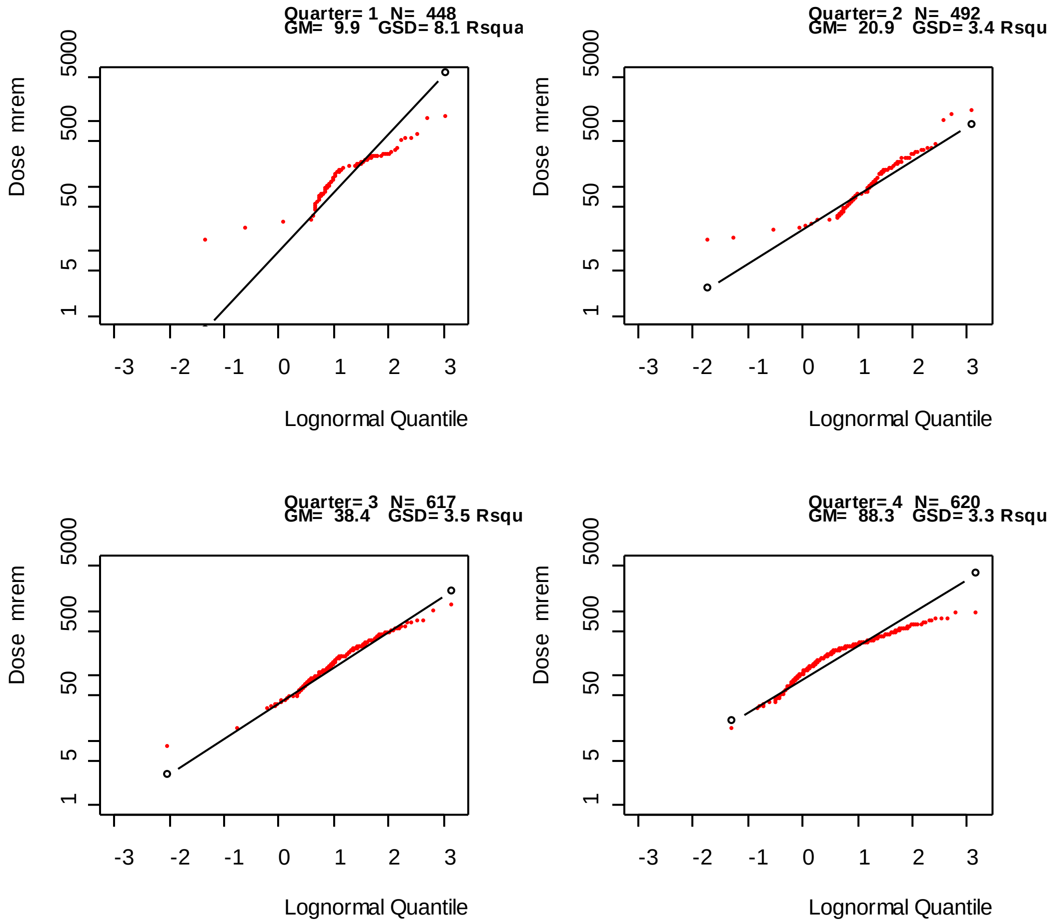

Figure B-5. Quarterly Y-12 film badge gamma dose for 1956.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

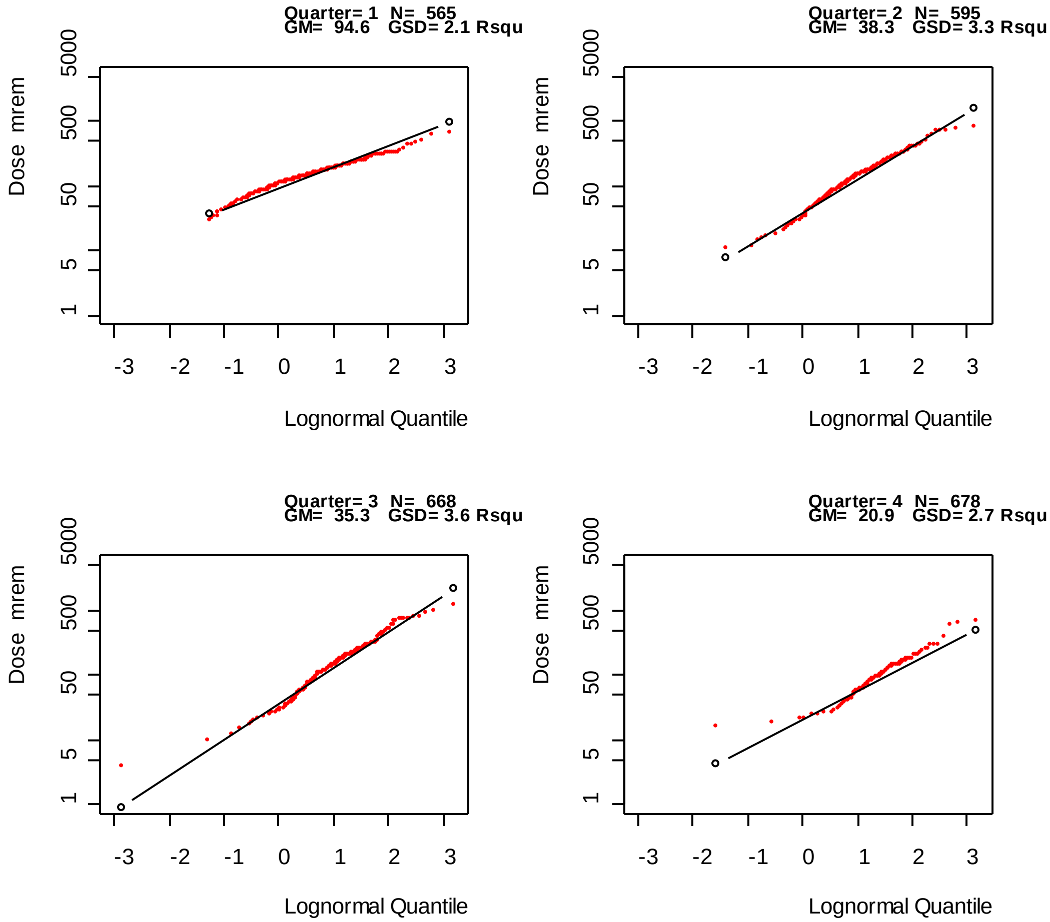

Figure B-6. Quarterly Y-12 film badge gamma dose for 1957.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

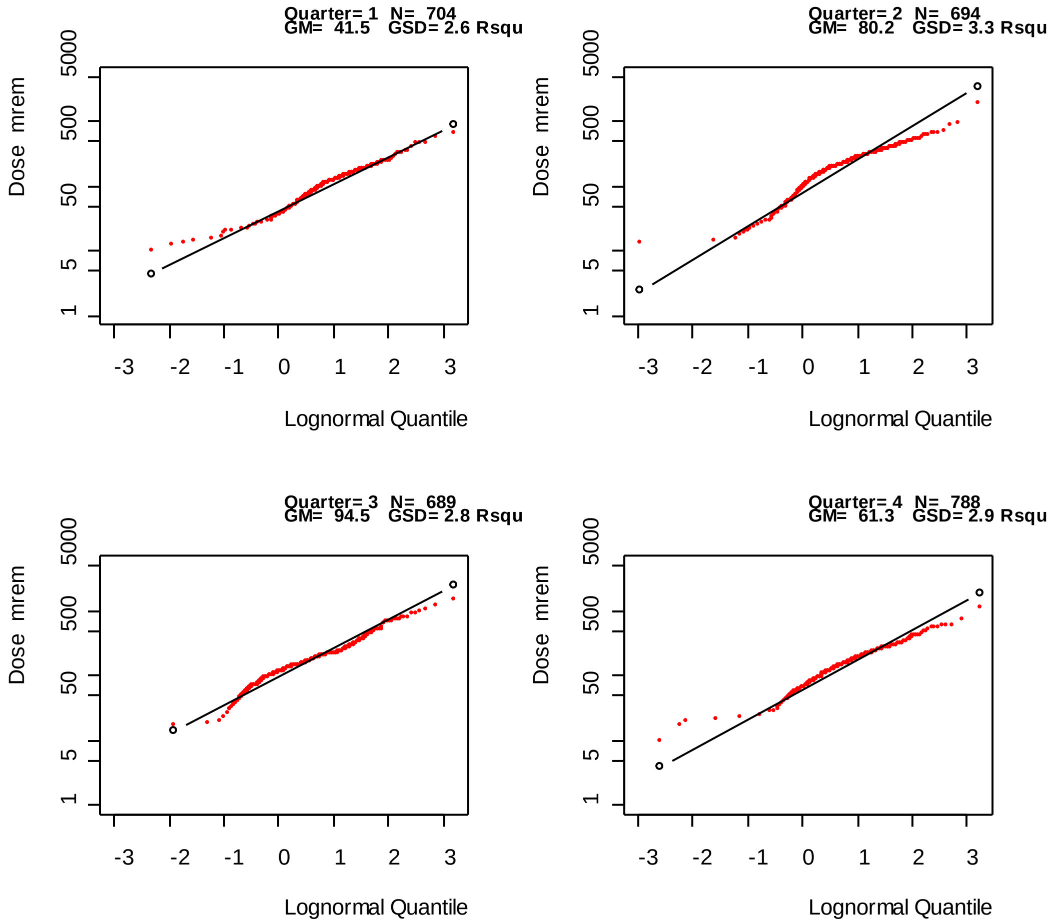

Figure B-7. Quarterly Y-12 film badge gamma dose for 1958.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

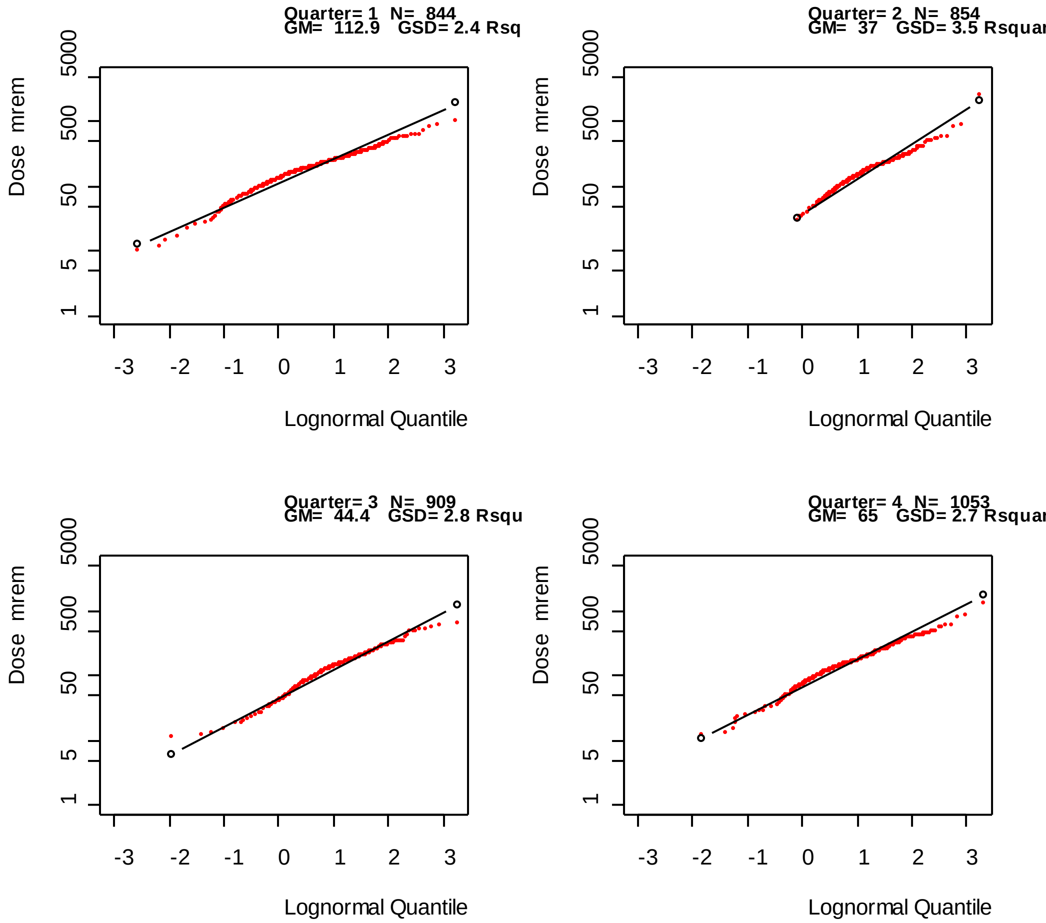

Figure B-8. Quarterly Y-12 film badge gamma dose for 1959.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

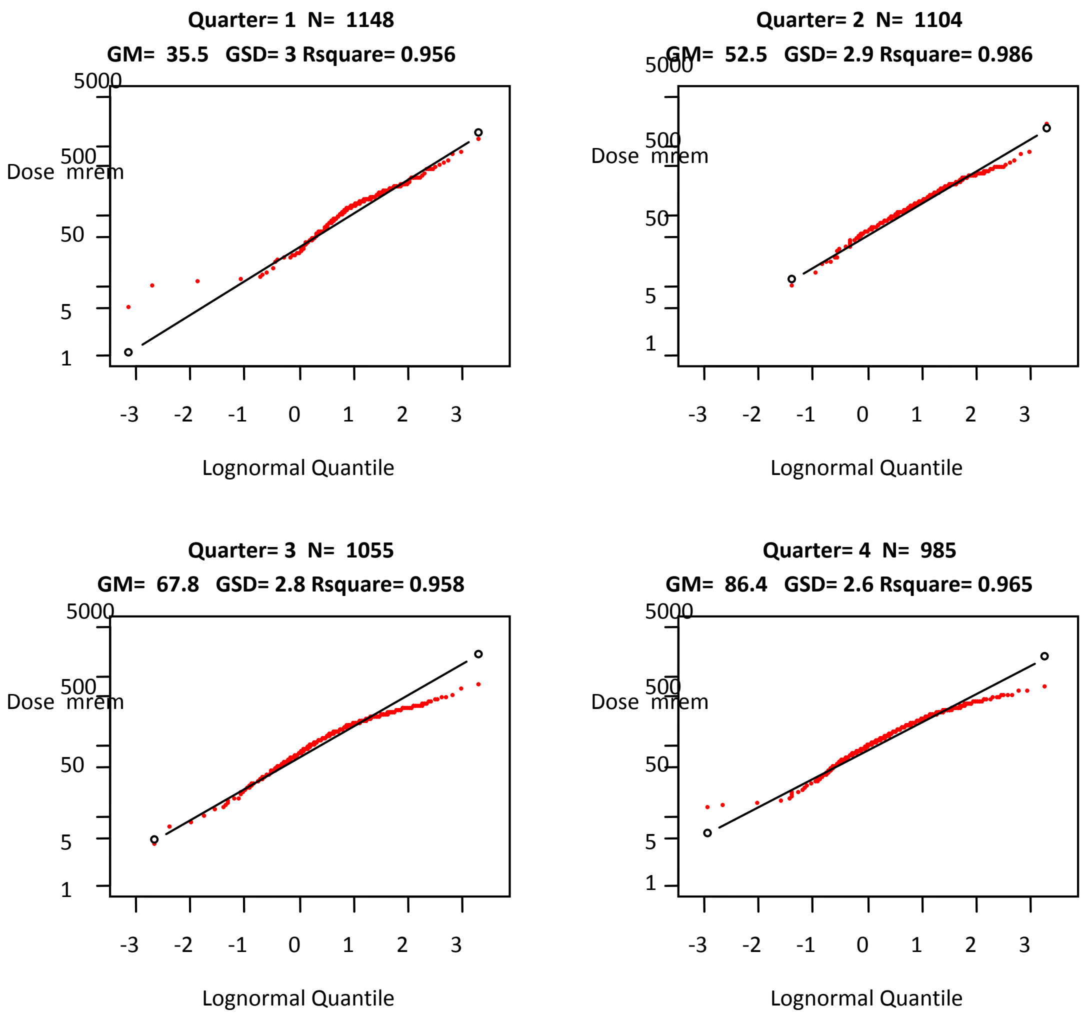

Figure B-9. Quarterly Y-12 film badge gamma dose for 1960.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979
Page 10 of 28

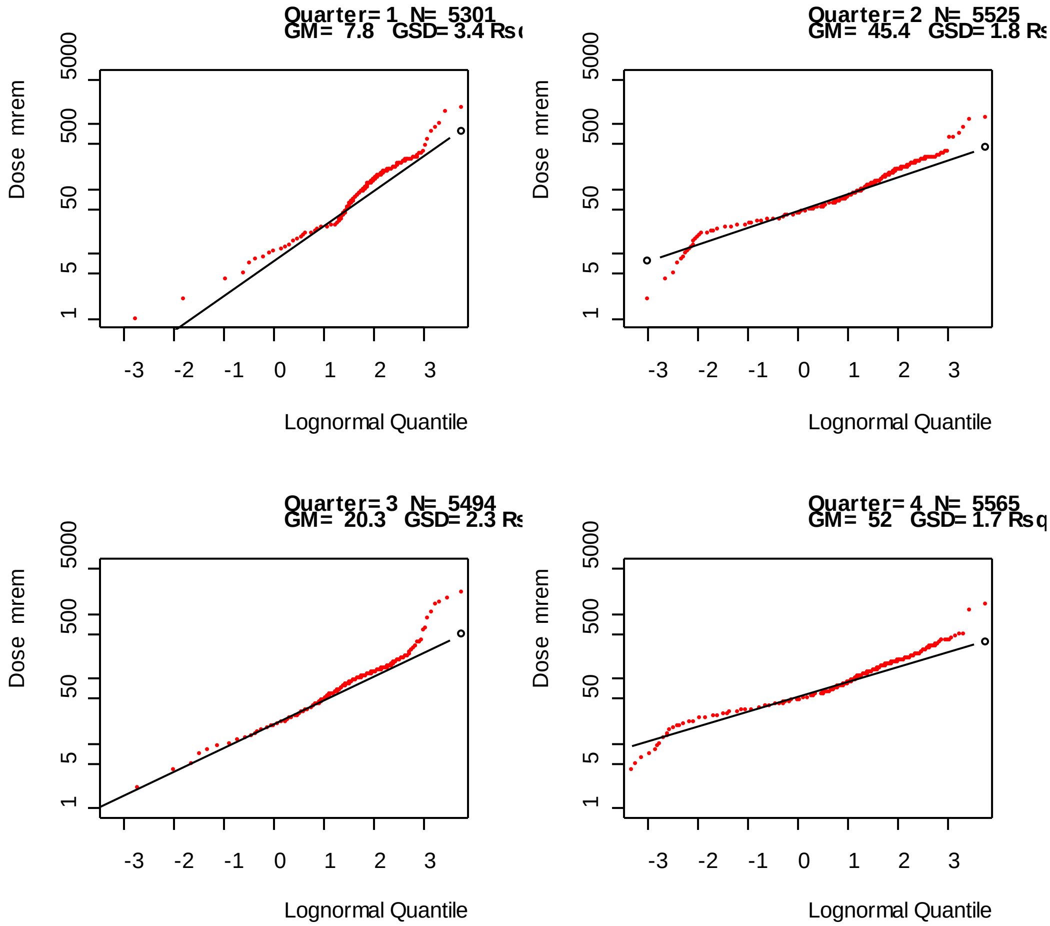

Figure B-10. Quarterly Y-12 film badge gamma dose for 1961.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979
Page 11 of 28

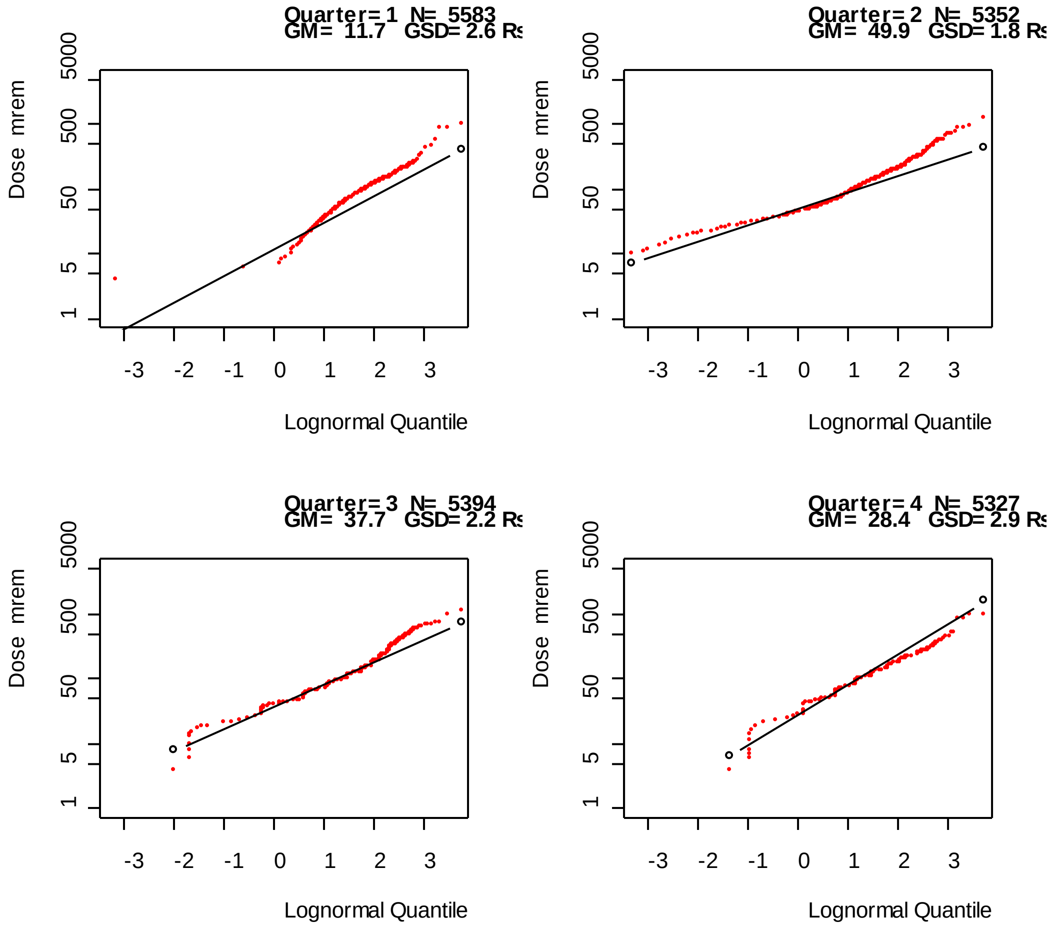

Figure B-11. Quarterly Y-12 film badge gamma dose for 1962.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

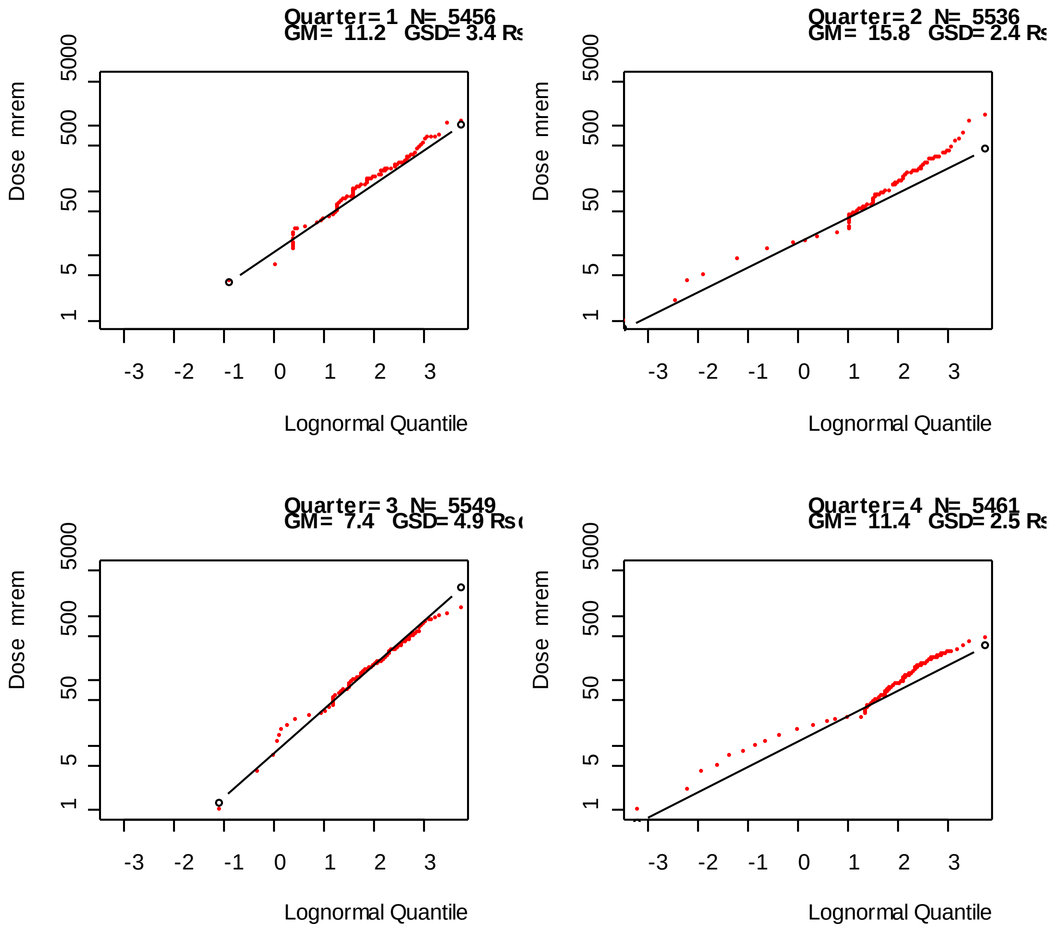

Figure B-12. Quarterly Y-12 film badge gamma dose for 1963.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979
Page 13 of 28

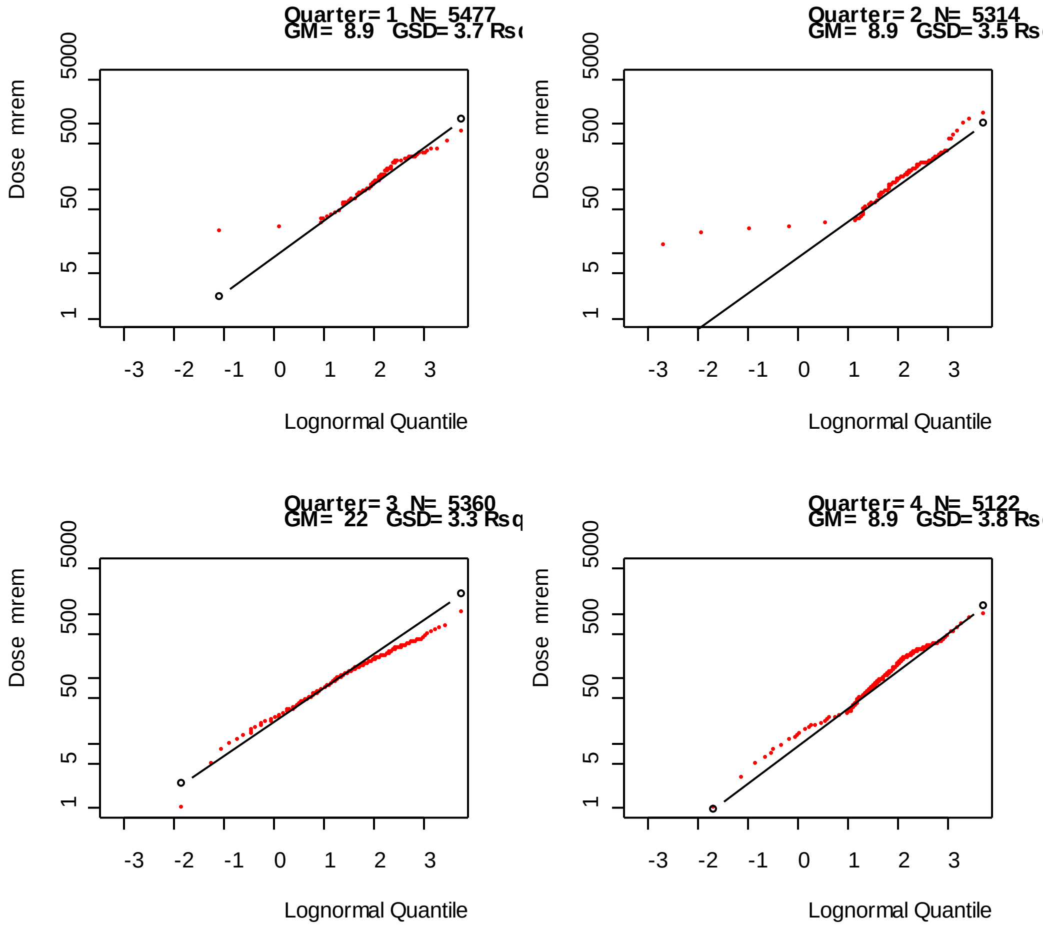

Figure B-13. Quarterly Y-12 film badge gamma dose for 1964.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

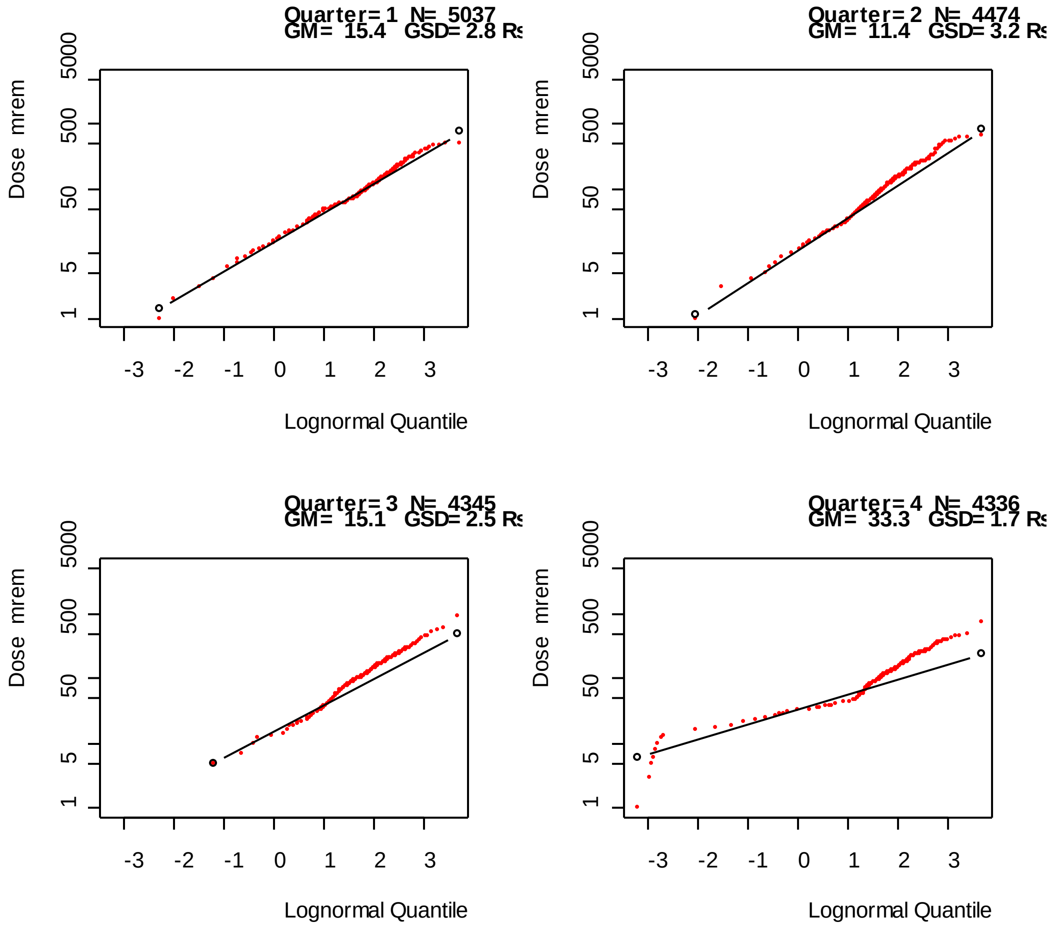

Figure B-14. Quarterly Y-12 film badge gamma dose for 1965.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

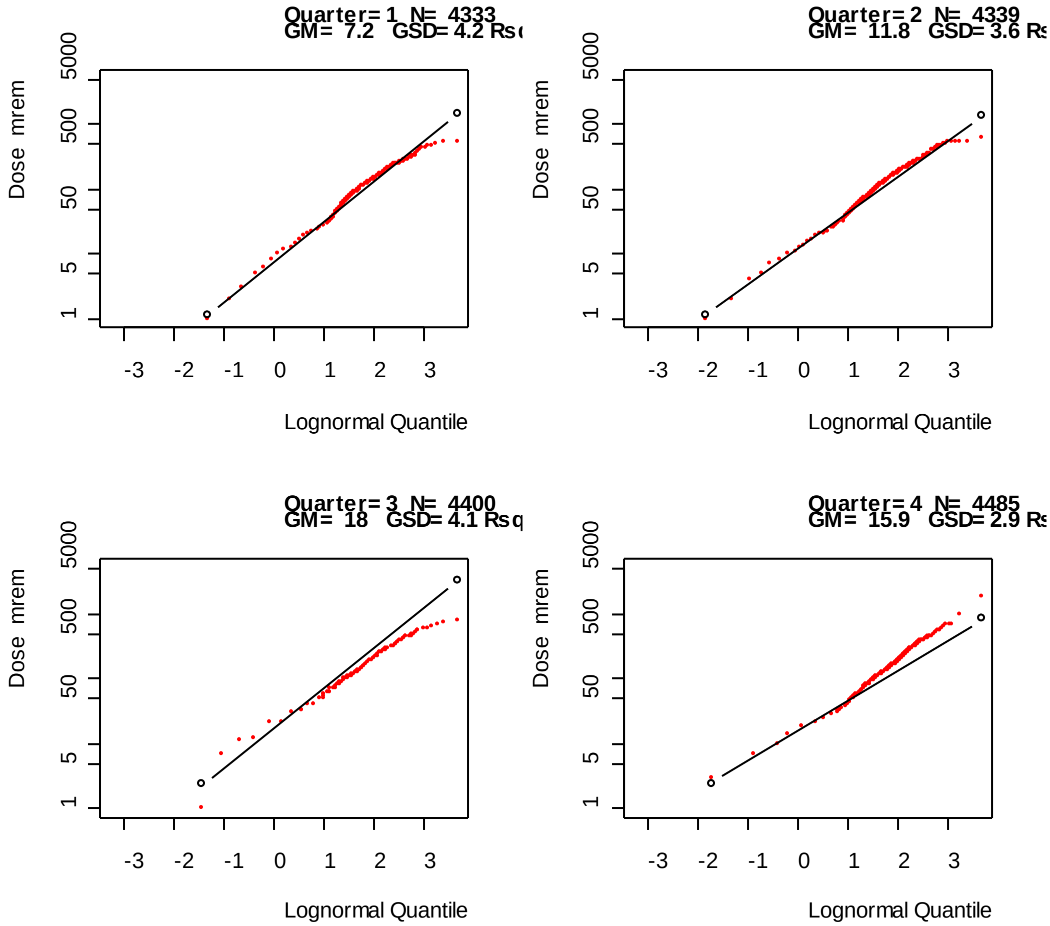

Figure B-15. Quarterly Y-12 film badge gamma dose for 1966.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

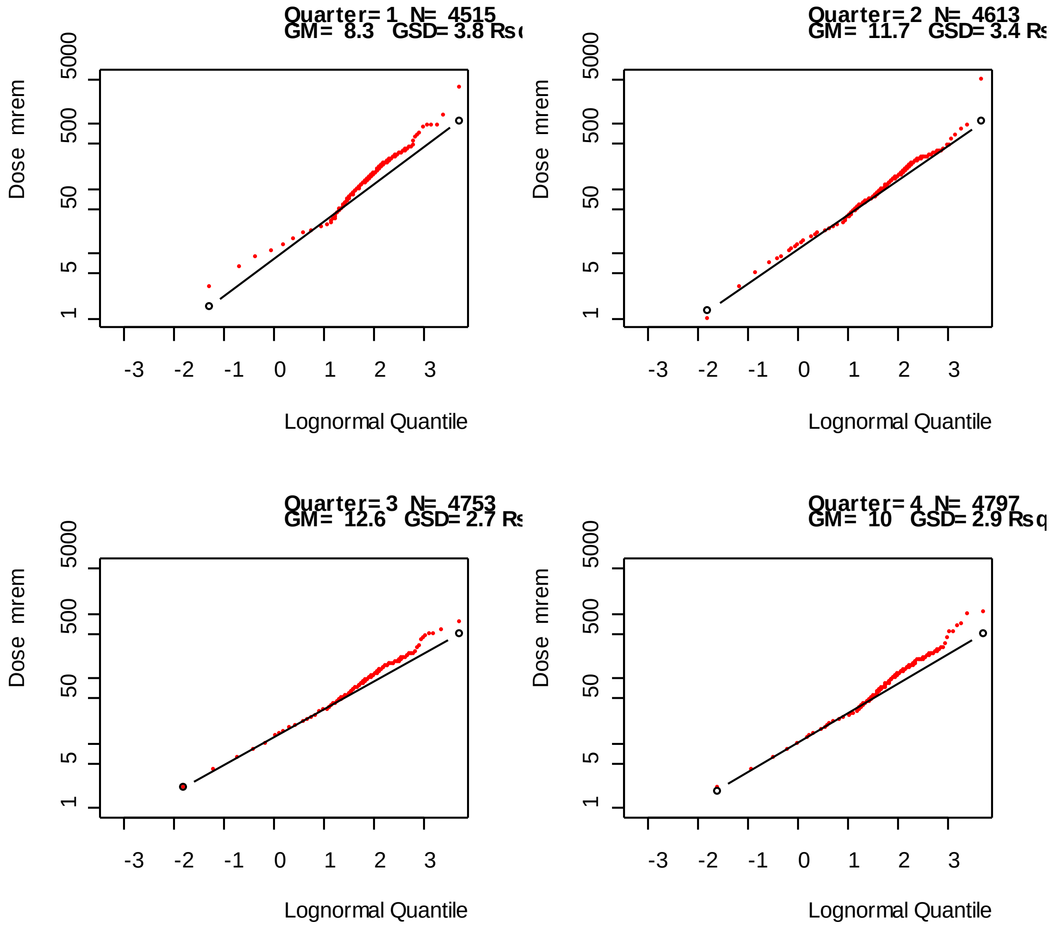

Figure B-16. Quarterly Y-12 film badge gamma dose for 1967.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

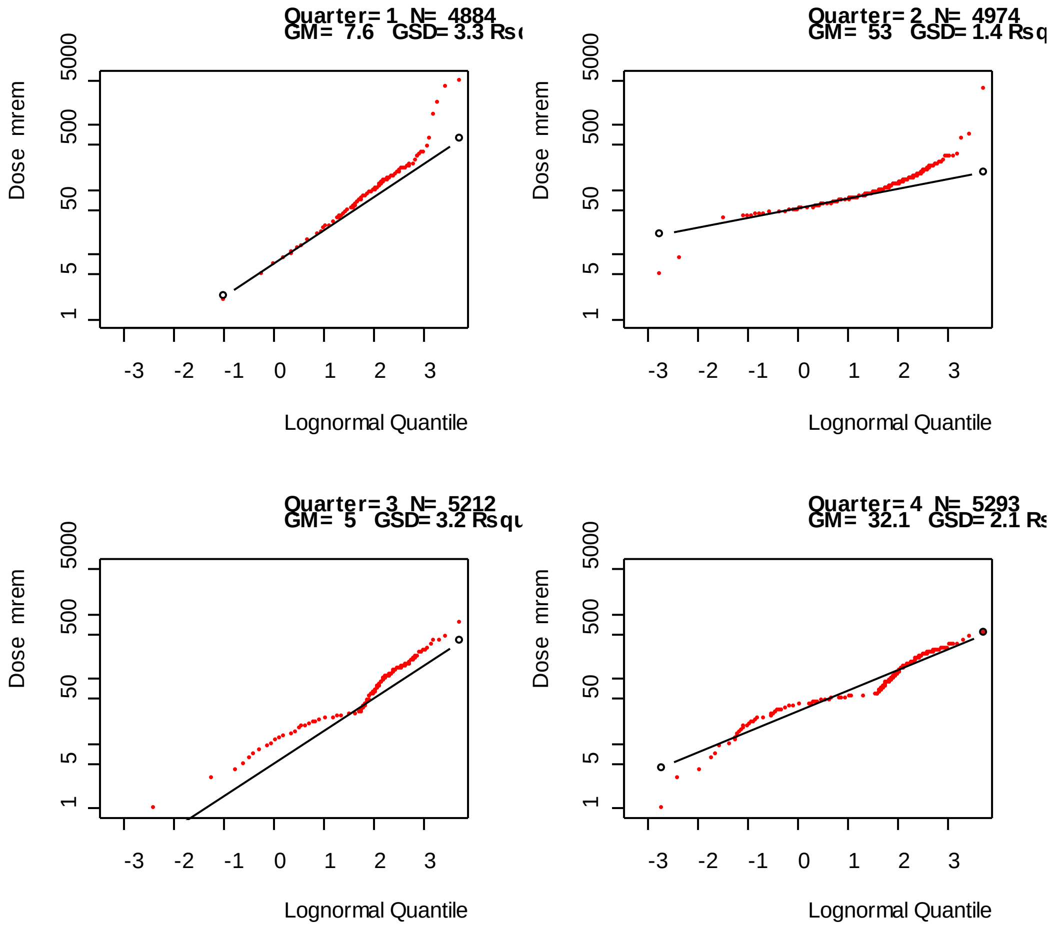

Figure B-17. Quarterly Y-12 film badge gamma dose for 1968.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

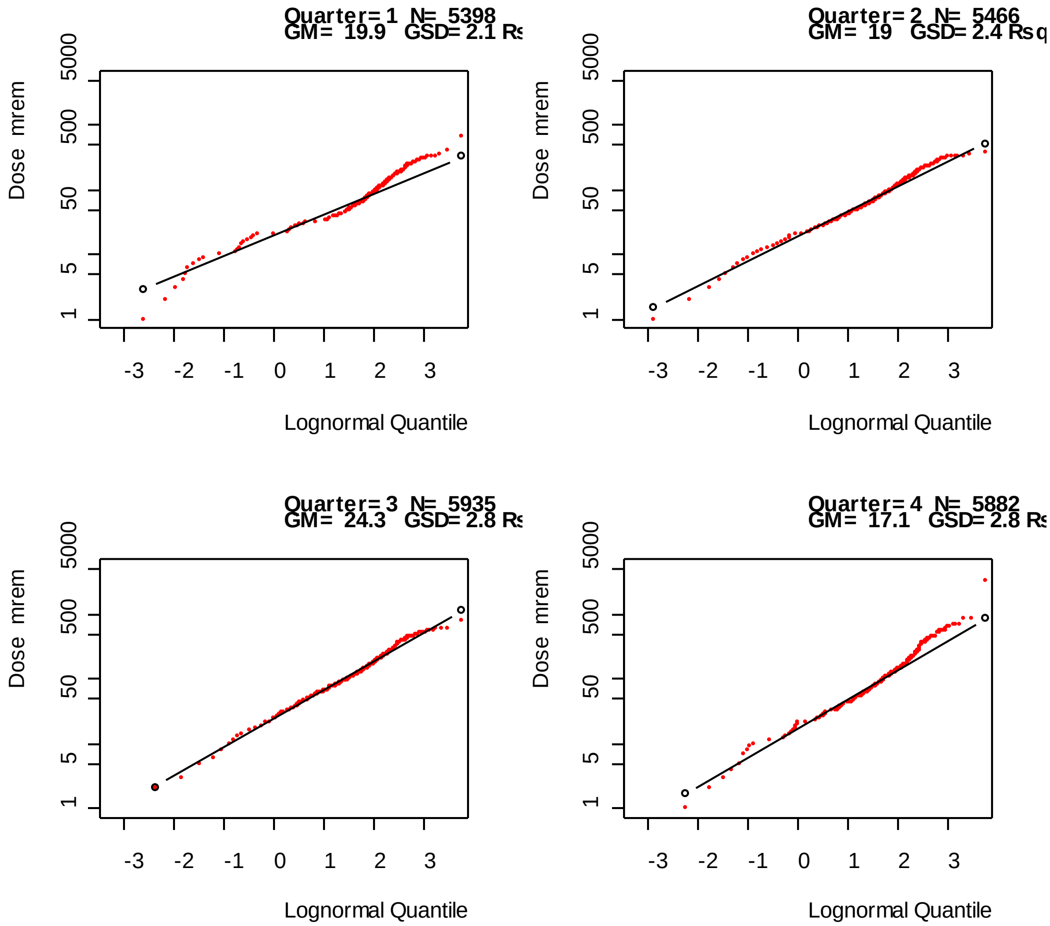

Figure B-18. Quarterly Y-12 film badge gamma dose for 1969.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

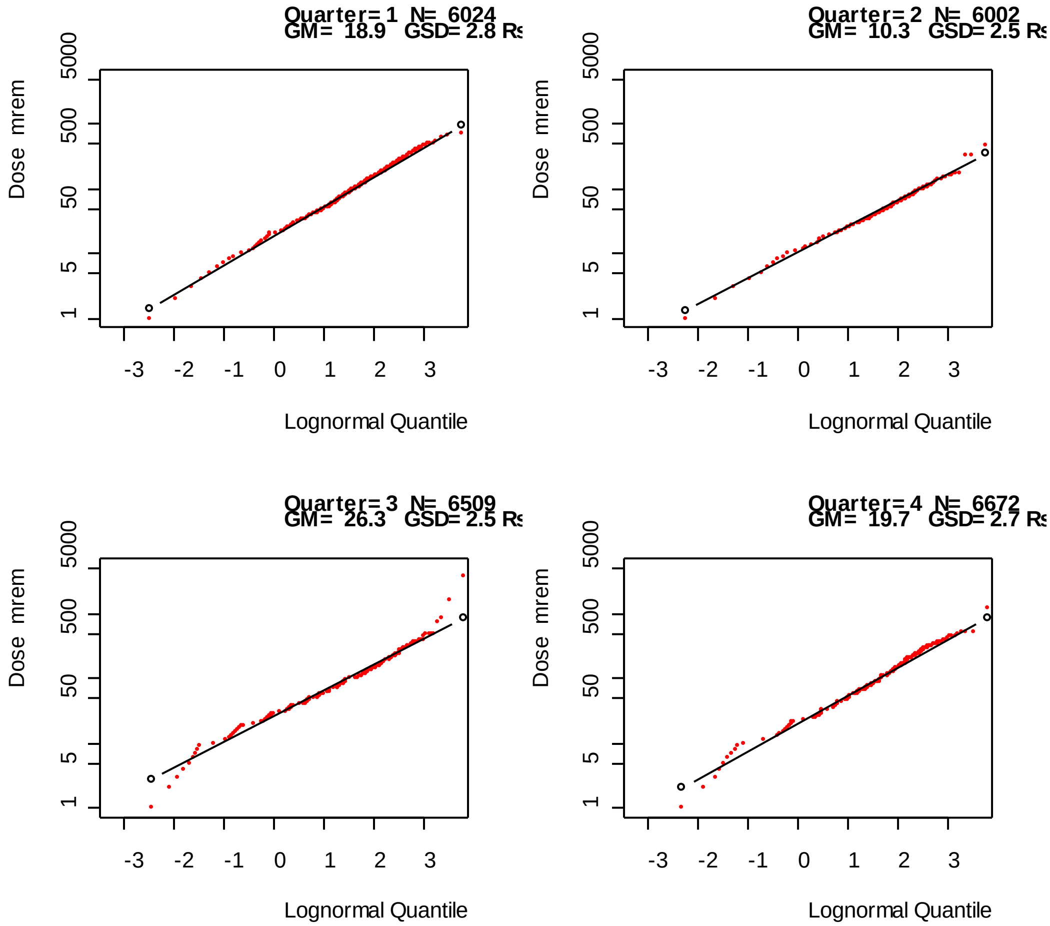

Figure B-19. Quarterly Y-12 film badge gamma dose for 1970.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

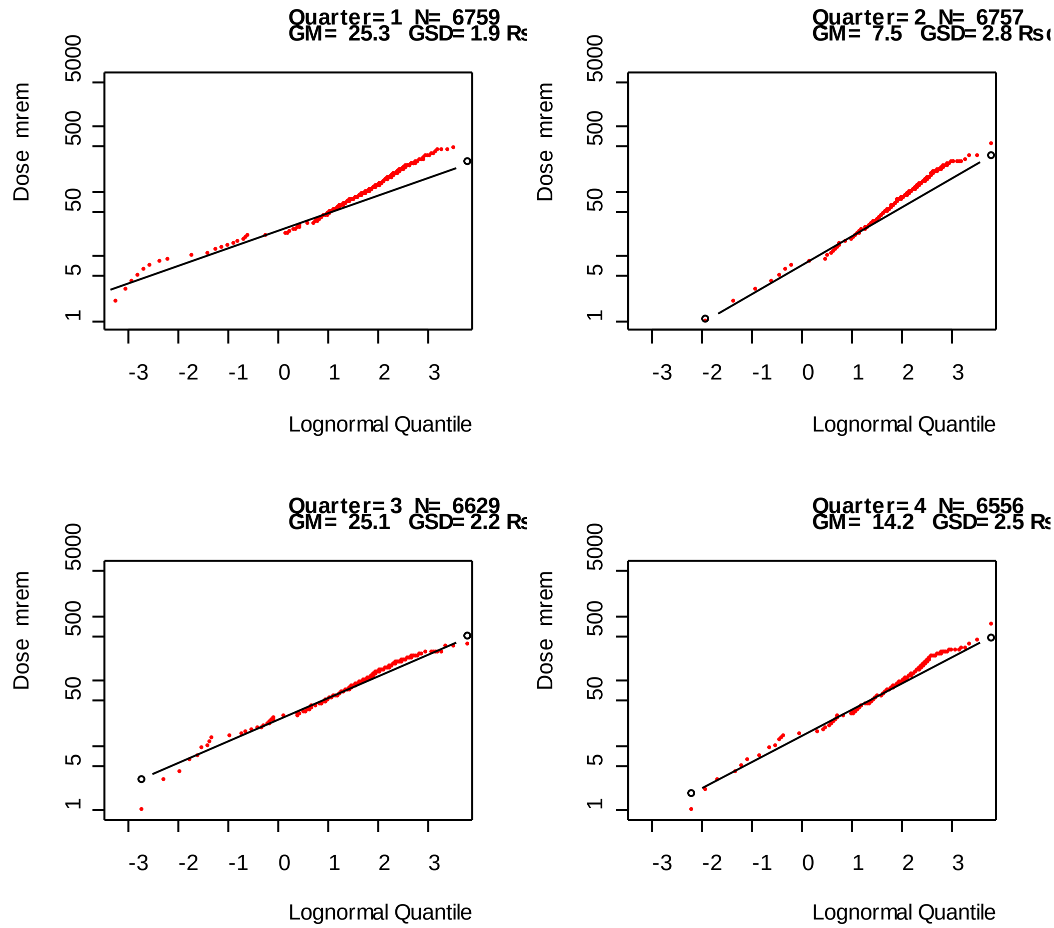

Figure B-20. Quarterly Y-12 film badge gamma dose for 1971.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979
Page 21 of 28

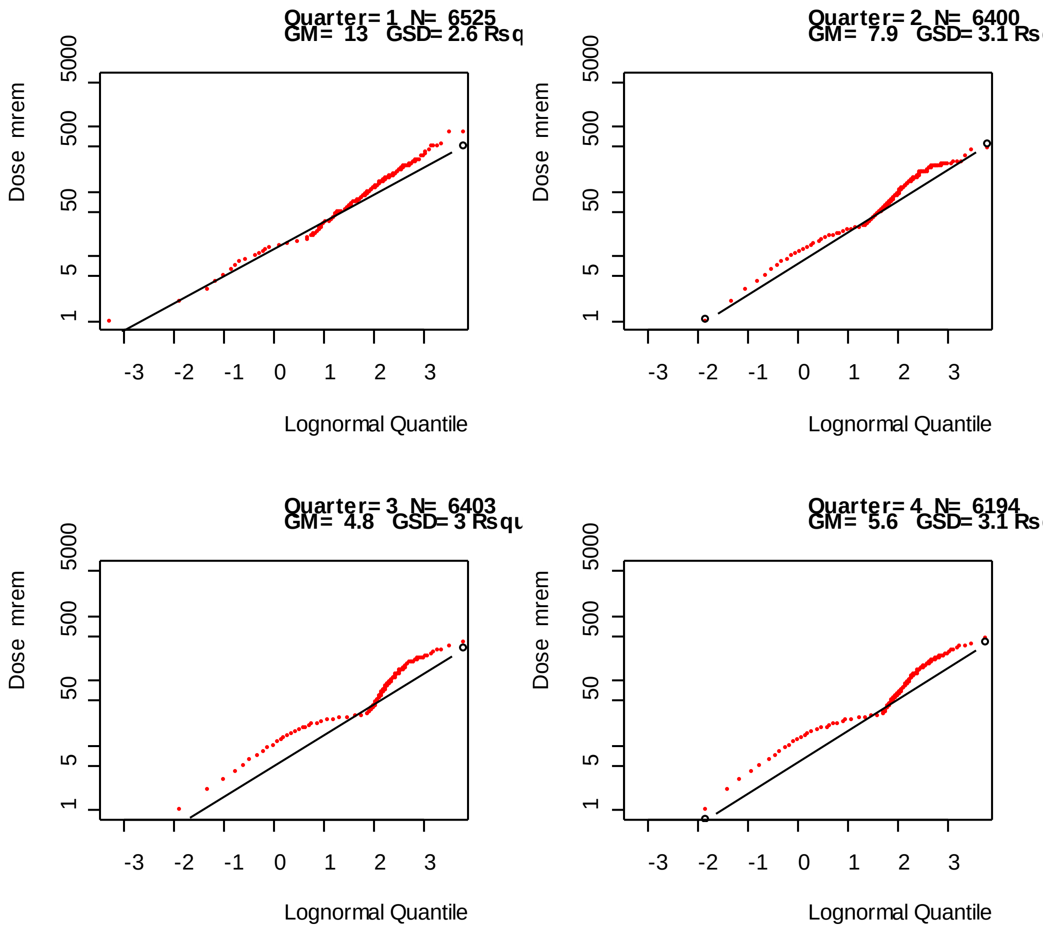

Figure B-21. Quarterly Y-12 film badge gamma dose for 1972.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

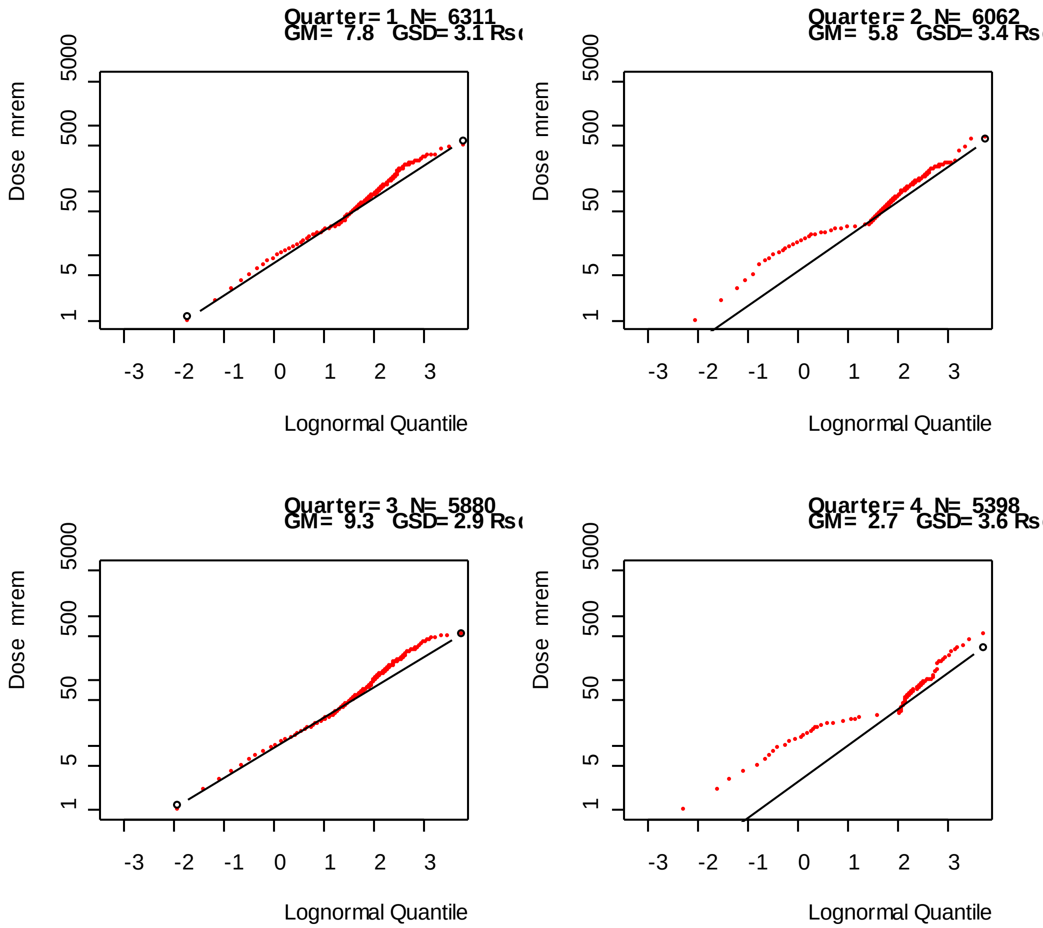

Figure B-22. Quarterly Y-12 film badge gamma dose for 1973.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

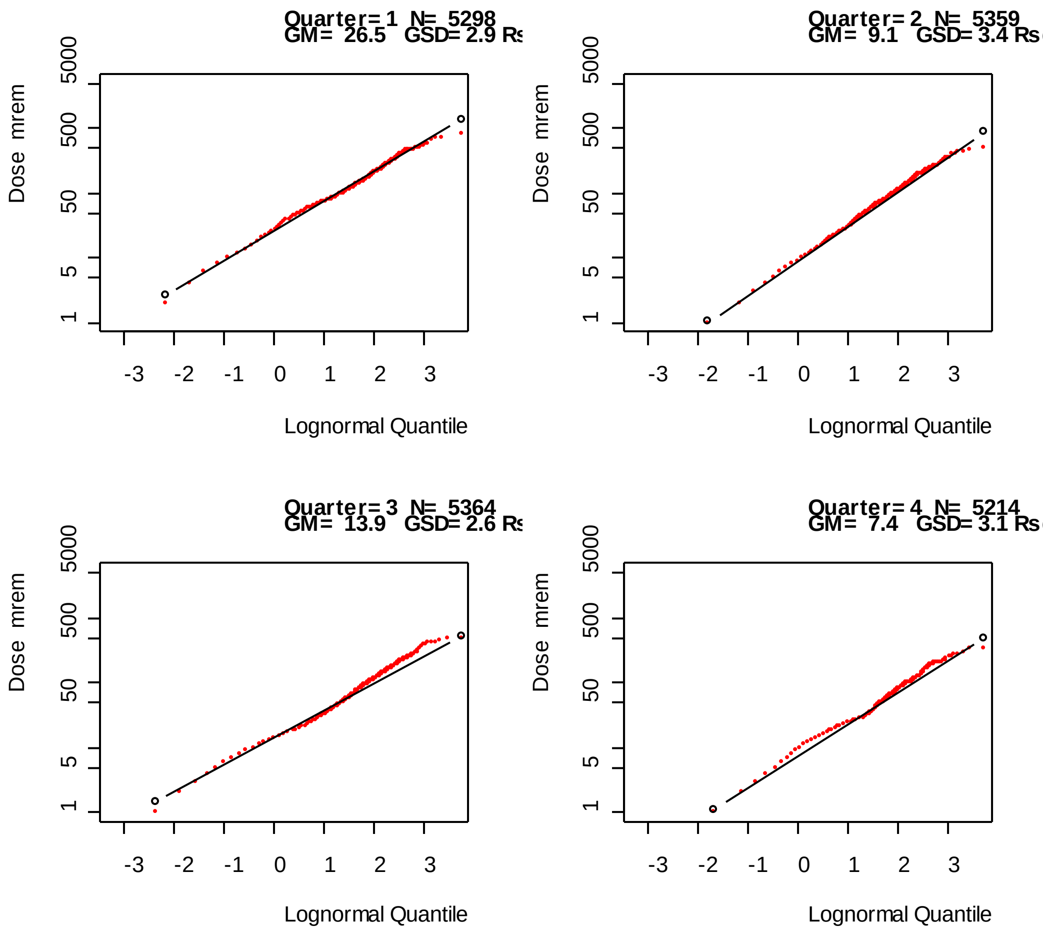

Figure B-23. Quarterly Y-12 film badge gamma dose for 1974.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

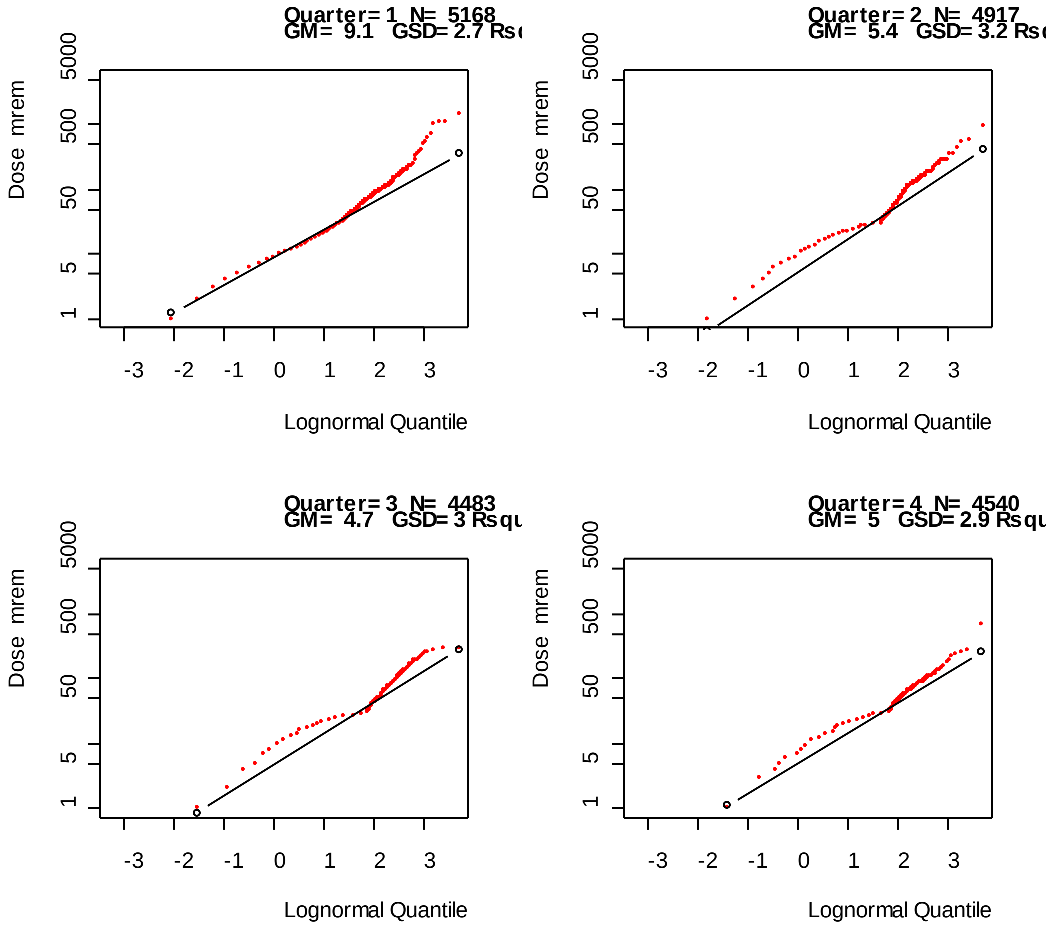

Figure B-24. Quarterly Y-12 film badge gamma dose for 1975.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979
Page 25 of 28

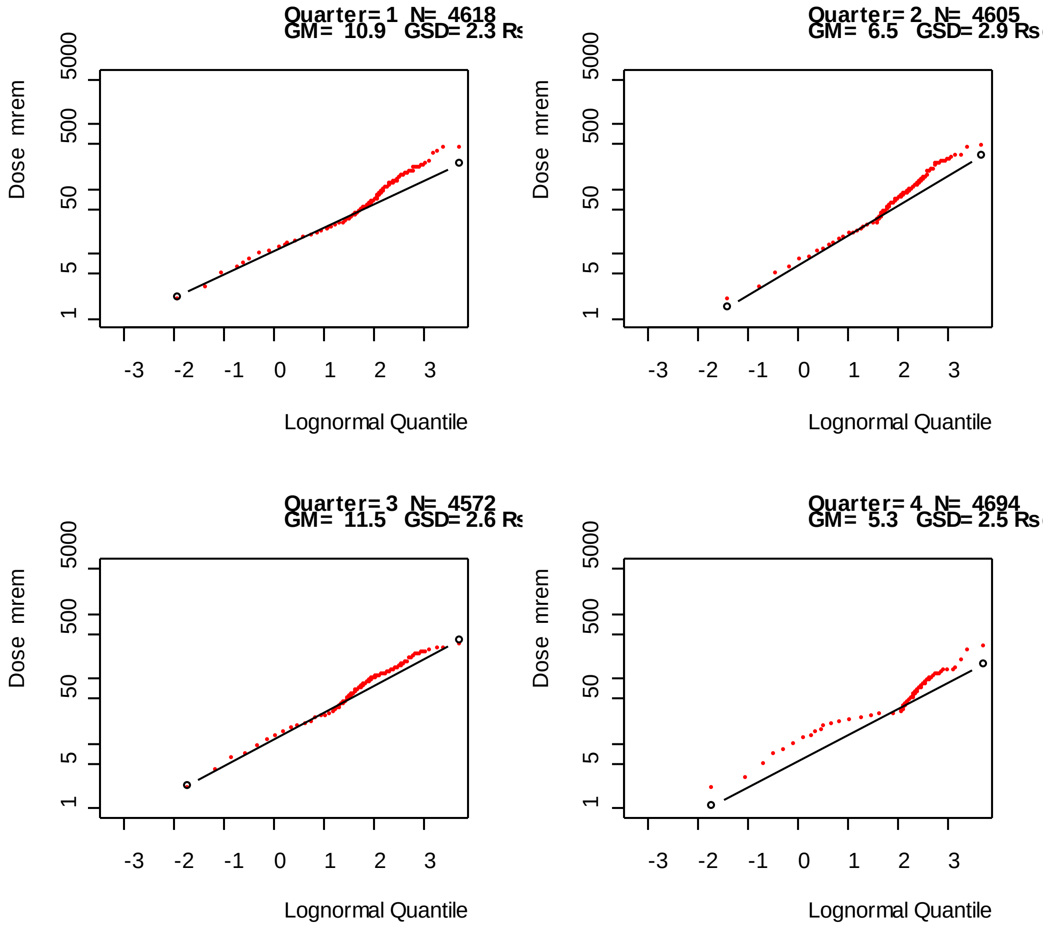

Figure B-25. Quarterly Y-12 film badge gamma dose for 1976.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

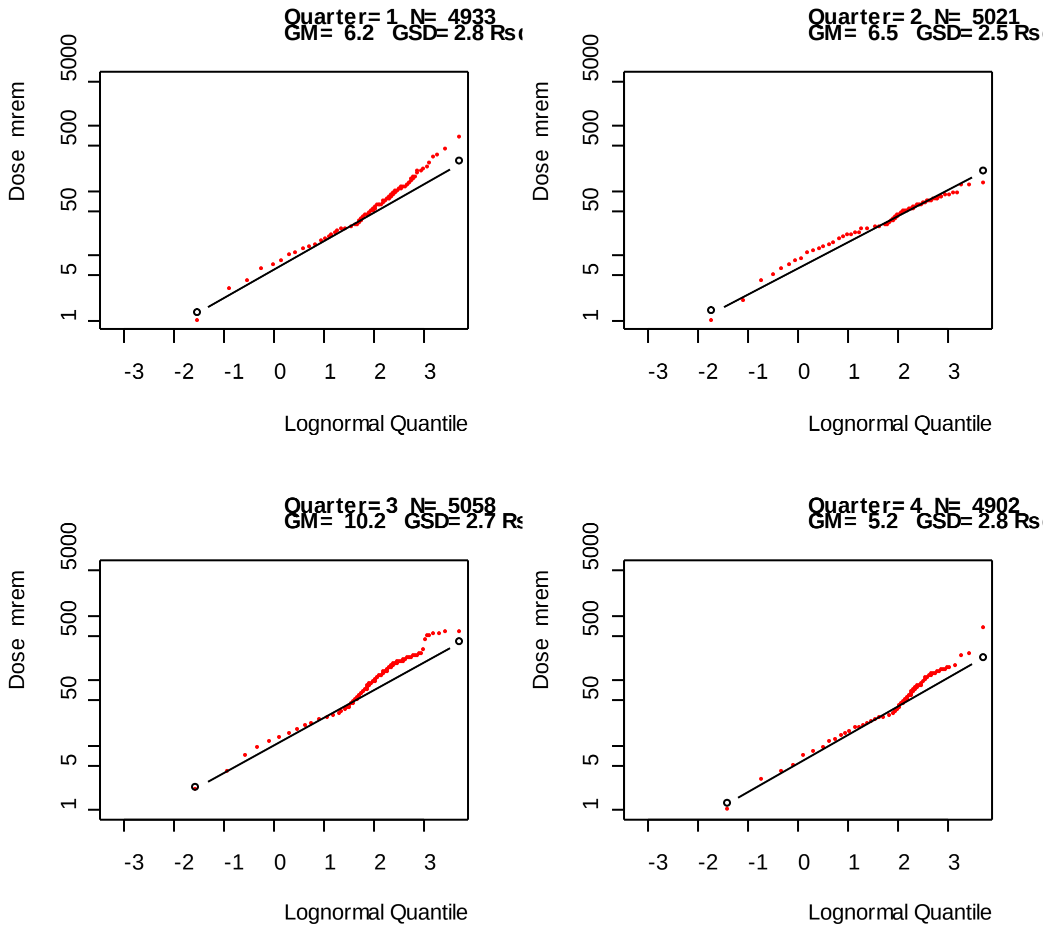

Figure B-26. Quarterly Y-12 film badge gamma dose for 1977.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979

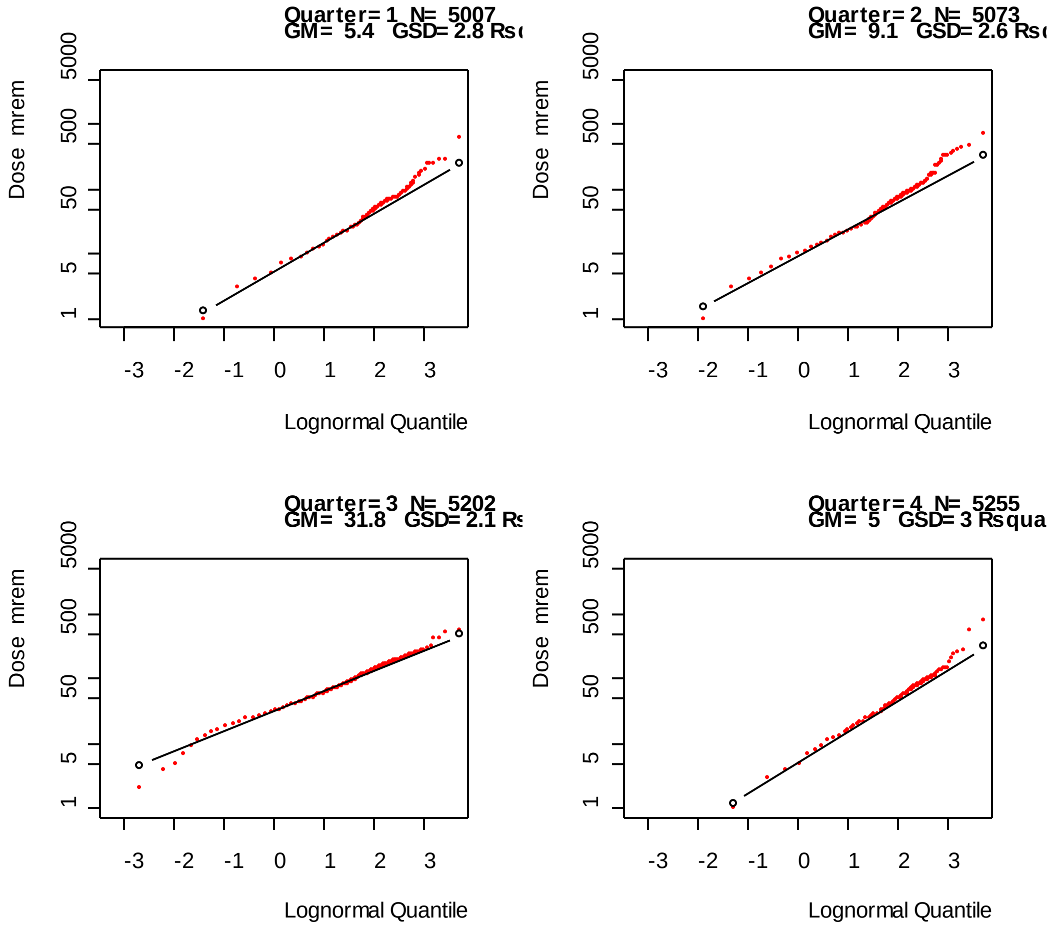

Figure B-27. Quarterly Y-12 film badge gamma dose for 1978.

ATTACHMENT B
QUANTILE-QUANTILE PLOTS OF QUARTERLY DOSES, 1952 TO 1979
Page 28 of 28

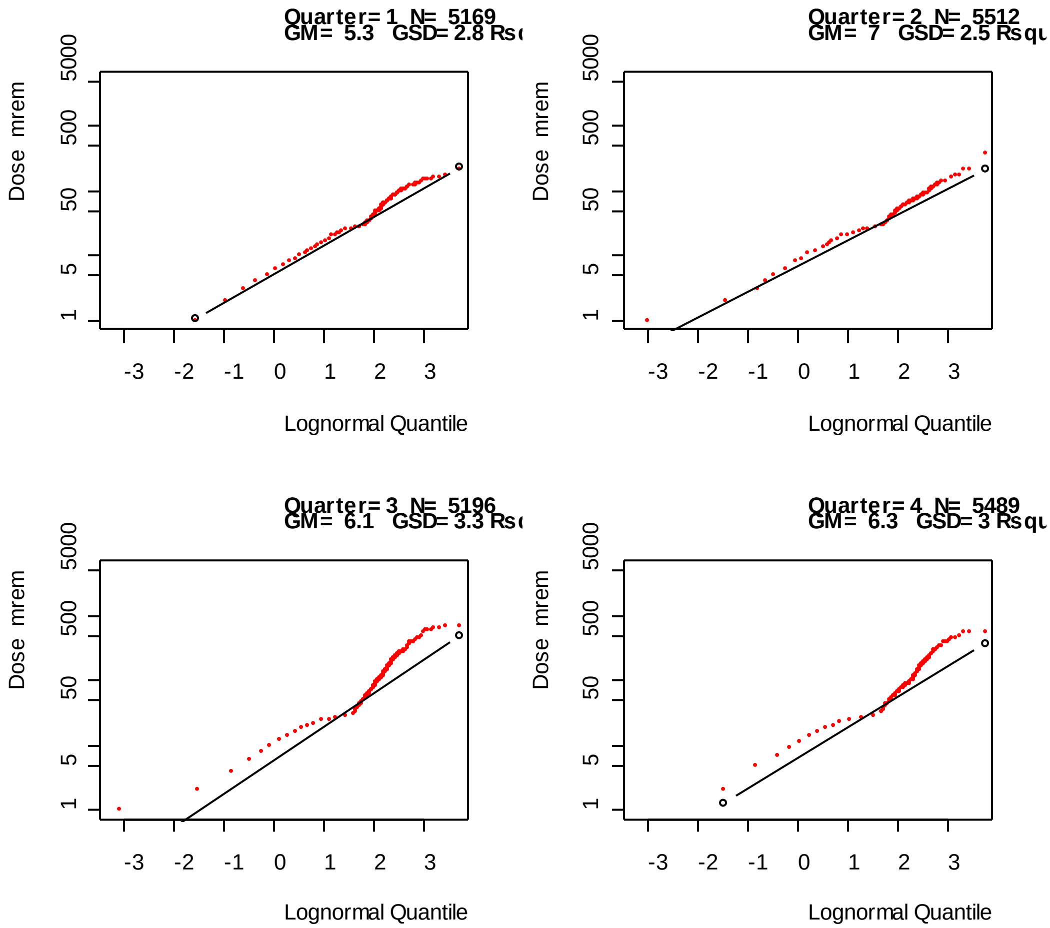

Figure B-28. Quarterly Y-12 film badge gamma dose for 1979.