Historical Evaluation of the Film Badge Dosimetry Program at the Y-12 Facility in Oak Ridge, Tennessee
Part 1 – Gamma Radiation

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Information contained in this historical evaluation draws heavily on work experience, documented by memoranda, technical reports, and published manuscripts, of C. M. ("Hap") West, a health physicist who was supervisor over the film monitoring program at the Y-12 facility from 1956 until 1985. After retiring from Y-12, Hap worked from 1985 to 2000 in the Hazards Assessments Group of the Center for Epidemiologic Research (CER), Oak Ridge Institute for Science and Education (ORISE). He provided important information and insight into radiological hazards assessment at all of the Oak Ridge facilities, particularly Y-12, and his work is reflected in publications and personal communications. Appendix C contains Hap's resume and copies of his memos that are cited in this report.

The authors wish to thank B. Jolene Jones for typing and editorial assistance in manuscript preparation and to Y-12 personnel who assisted in obtaining background memos and reports. We also express our gratitude to ORAU Team staff and contractors and NIOSH staff who participated in discussions that led to the adoption of the methods for dose reconstruction described herein.

Summary

This report provides background information on the Y-12 external dosimetry program through 1979 and focuses on film badge monitoring of gamma radiation. Information herein should be valuable in verifying that quarterly dose data were used effectively in the development of a process for estimating individual gamma doses for quarters when a worker was employed at Y-12 but not monitored for external radiation exposure. Also included is a summary of the maximum likelihood (ML) methods used to estimate parameters for randomly left censored lognormal data. These parameters were used to determine quarterly lognormal prediction densities required for dose reconstruction as specified by the Energy Employees Occupational Illness Compensation Program Act of 2000. Tables of geometric means (GM) and geometric standard deviations (GSD) defining the prediction densities are supplied for 1947 through 1979 and can be used for sampling individual doses.

Graphical methods were used to evaluate the lognormal assumption for the quarterly dose data. Histograms 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 time period confirmed that these data may not be suitable to use in dose reconstruction.

Alternatively, 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. Although all employees were to be monitored with film badges from 1961 to 1979, before 1961 only workers with greater exposure potential were monitored. Consequently, it is to be expected that estimated doses based on the regression analysis of the subgroup data are claimant favorable.

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

1. Introduction

To use data appropriately it is essential to understand the context in which it was collected. An awareness of the developing dosimetry program is particularly important for proper evaluation of the external dosimetry records of individuals employed at the nuclear facilities of the Department of Energy (DOE) and its predecessors half a century ago. The start up 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. Monitoring policies, recording practices, and dosimeters were repeatedly modified and updated over time as knowledge increased and technology advanced. The motivation for this report is to provide definitive documentation of these changes over time at the Y-12 facility in Oak Ridge, Tennessee, and to furnish the background to allow doses recorded during the film badge period to be used appropriately in dose reconstruction. This report, Part 1, deals with gamma radiation while Part 2 will discuss the skin doses and Part 3 the neutron doses.

Opening in June of 1943, the Y-12 facility was managed by Tennessee Eastman Corporation (TEC) for the Atomic Energy Commission (AEC) and produced enriched uranium by the electromagnetic separation process. The primary hazard from this process was internal exposure from alpha radiation from the dust of natural and enriched uranium (Dupree et al., 1994). Only 6.7% of the TEC workforce continued employment at Y-12 when Union Carbide Corporation-Nuclear Division (UCCND) assumed management in May of 1947, and the mission of the facility changed to nuclear materials fabrication and processing (Watkins et al., 1993, 1997). After a transition period the types of procedures used in UCCND production processes remained relatively constant over time, and the greatest radiation hazard for fabrication and processing was from internal exposure via inhalation or ingestion. Although some clean-up and close-down activities remained, it is likely that workers received only minimal, if any, gamma doses. Y-12 health physicists believed that the primary source of external exposure during transition and throughout the film badge period was beta radiation from U-238 daughters.

2. Y-12 Film Badge Program

2.1 Overview

The Y-12 film badge dosimetry program evolved as improved technology was developed and complex radiation fields encountered in the workplace were better understood (Kerr, 2003). The routine film badge exchange frequency was gradually decreased and corresponded to sequential reductions in the radiation protection standards or guidelines (Morgan, 1961). The radiation protection guidelines used at Y-12 are summarized in Table 1 (Wiley, 2004) and the exchange frequencies of the film badge dosimeters are summarized in Table 2 (Souleyrette, 2003). Table 3 provides information on doses that were to be assigned when film badge readings were less than the minimum detection level (MDL). The film badge period ended in 1980 as film dosimeters at Y-12 were largely replaced by thermoluminescence dosimeters (TLDs) (McLendon, 1980; Howell and Batte, 1982; McMahan, 1991; BWXT Y-12, 2001).

Starting in 1948 external radiation monitoring was performed using pocket ionization chambers (PICs), typically exchanged on a weekly basis. Additional early screening efforts involved using photographic film pads on the uranium workers' palms and fingers for purposes of beta-particle dosimetry (Struxness, 1948b). Attempts were made to correlate the film pad readings with whole-body exposures, which were recorded first with PICs and later with film badge dosimeters. The MDL of the very early measurements with PICs was about 5 mrem (Soulyrette, 2003).

The first film dosimeter used at Y-12 is believed to be the same badge used at the Oak Ridge National Laboratory (ORNL) in 1949 (West, 1993a) and described by Thornton, Davis, and Gupton (1961). This film badge was an AEC Catalog Number PF-1B film badge manufactured by the A. M. Samples Machine Company in Knoxville, Tennessee (Patterson, West, 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. One portion of the film was covered by a one-mm thick cadmium filter to determine the dose from gamma rays. 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). 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). This was also the point in time when monitoring policies changed from selected monitoring on a weekly basis or monthly basis to quarterly monitoring of all workers.

As in the PF-1B, a cadmium filter with a thickness of approximately one mm or mass density of 1000 mg cm^{-2} has been included in all film badge designs used at Y-12 to measure the penetrating whole-body dose from gamma rays. In addition, Y-12 film badges have 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 badge used after 1961. The areas behind 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 (Sherrill and Tucker, 1973).

Film badges were calibrated for beta particles by placing the film badges face down on a slab of natural uranium (Souleyrette, 2003), and for gamma rays by exposing the film badges in air at known distances from a gamma-ray source. A radium source enclosed in 0.5 mm platinum was used initially for the calibration gamma-ray source, and a Co-60 source was used starting in the early 1960s (Souleyrette, 2003). Film badge dosimeters typically exhibited about the same sensitivity to beta and gamma radiation; i.e., a one rem dose of beta particles yielded about the same response in the film as one rem of gamma rays (Auxier, 1967). Thus, the MDLs of the film badge dosimeters were approximate the same for beta particles and gamma rays (see Table 3).

Neutron sensitive films were added to the film badge dosimeters in 1949 for the assessment of neutron exposures to workers, and these films were exchanged on a biweekly schedule (Souleyrette, 2003). Neutron doses were recorded as zero if the neutron film in a worker's film badge (1) was not processed and read, or (2) was read and neutron dose was less than the MDL of the neutron film. The neutron sensitive films were calibrated using neutrons from a polonium-beryllium neutron source starting in 1949 and an americium-beryllium source starting in the early 1960s (Souleyrette, 2003). The MDL of the neutron film is uncertain, but it is believed to be about 50 mrem for all years of usage at Y-12 (Kerr, 2003).

The recorded dose from penetrating radiation was the sum of the doses from gamma rays and neutrons during the exposure period. Recorded dose to the skin was the sum of the dose from beta particles (and low-energy x-rays) and the penetrating dose from both gamma rays and neutrons.

All external monitoring data supplied to ORAU by the Y-12 facility were quarterly data with each record containing a two-digit year and single-digit quarter (see Section 3.1). Continued study of the Y-12 monitoring program over many years has confirmed weekly and monthly exchange schedules during earlier years of plant operation rather than a quarterly schedule as implied by the records themselves (see Table 2). In addition, many of the nominal quarterly results in earlier years appear to be the product of the existing MDL times 13 weeks, which lends evidence for a weekly exchange frequency. Considerable effort has been directed towards acquiring examples of weekly external monitoring data, but with little success. Only a very small number of records appearing to be weekly film badge results for a single week, the week following the June 16, 1958 accident (Y-12 Plant, 1958; Hurst et al., 1959), were discovered. However, the data associated with these records point to the conclusion that this may have been a special monitoring event rather than data for a single week in the external monitoring program. Regardless, no other weekly monitoring records for external exposure have been located for the Y-12 population.

Recorded doses throughout the film badge period reflect not only individual radiation exposure 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 that were recorded for an individual worker.

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

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

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

Table 2. Historical monitoring techniques and routine exchange frequency for external radiation dosimeters at the Y-12 facility (Souleyrette, 2003; Kerr, 2003)

Dates	Monitoring technique	Routine exchange frequency	Comments
1948-1949	Film badges, film pads, pocket ionization chambers	Some daily, some weekly	
1950-1958	Film badges	Weekly	Neutron sensitive films exchanged biweekly
1958-1961	Film badges	Monthly	
1961-1979	Film badges	Quarterly	Nearly all workers monitored
1980-1996	TLD	Some quarterly, some annually, a very limited group on a monthly basis	Quarterly exchange if expected to receive more than 500 mrem; annual exchange if expected to receive less than 500 mrem
1996-Present	TLD	Mostly quarterly, some monthly	Workers monitored only if entering radiological areas.

Table 3. Minimum detection level (MDL) and assigned MDL doses* for film used to measure beta and gamma radiation exposures at the Y-12 Plant (West, 1993a)

Period of time**	MDL	Assigned MDL
January 1948 to January 1950	30	30
January 1950 to January 1952	30	0
January 1952 to September 1952	50	50
September 1952 to January 1953	43	43
January 1953 to July 1954	50	50
July 1954 to July 1956	30	30
July 1956 to July 1961	30	15
July 1961 to October 1980	30	Not Applicable

* Doses in mrem.
** Dates are approximate because the changes did not occur for all employees at the same time (West, 1993a).

2.2 1948-49

An small-scale external dosimetry program was started in 1948 to monitor the external exposures of individuals working in the Assay Laboratories, Radiographic Shop, Spectrographic Shop, and Machine Shops where uranium metals were being handled (Murray, 1948a,b; Struxness, 1948a,b). These workers represented a very small fraction of the Y-12 workforce, and the film badge dosimeters were exchanged on a weekly schedule.

2.3 1950-51

An expanded personnel monitoring program for external radiation exposure was initiated at Y-12 in 1950 (McLendon, 1960). All Y-12 personnel working with (1) depleted uranium, (2) discrete gamma, beta, or neutron sources, (3) x-rays, and (4) materials contaminated with fission products were asked to wear a film badge dosimeter. The film pads were also replaced with so-called film rings to assess the radiation exposure to the hands of uranium metal workers (Struxness, 1951).

Dosimetry practice was to record weekly open window dose to skin from beta particles (and low energy x-rays) or the penetrating doses from gamma rays behind the one-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 from beta particles among monitored workers in both 1950 and 1951.

2.4 1952-mid56

Documented dosimetry policy was to assign the MDL dose for weeks with result less than MDL for either beta or gamma radiation (Table 3). The MDL was 50 mrem for 1952 (weeks 1-38 approximately), all of 1953, and 1954 (weeks 1-30, approximately). In 1952 the MDL was 43 mrem for weeks 39-52. For the remainder of 1954 and all of 1955 and 1956 the MDL was 30 mrem. In practice, however, weekly doses less than the MDL were often left blank.

Beginning in 1953 the assigned MDL dose was recorded as due to either beta or gamma radiation according to a worker’s potential type of exposure as judged by the health physics staff (West, 1981). As a result, the recorded penetrating doses from gamma rays and neutrons were sometimes larger than the skin doses, which are the sum of the gamma, neutron, and the beta-particle (or low-energy x-ray) doses. Health physicists later recommended that these unusual records be modified so that skin doses were always equal to or greater than the penetrating radiation doses (West, 1981; West, 1991).

2.5 mid1956-60

The radiation dosimetry policy to monitor only selected workers (approximately 10-20% of the workforce) continued (Watkins et al., 1993, 1997). Monitored workers were those believed by health physics staff to have potential for external radiation exposures greater than 10% of the radiation protection guidelines in effect at that period of time (Table 1). Weekly doses for readings less than the MDL were recorded as 15 mrem, half the MDL (Table 3), and entered as beta doses. In 1958 monthly monitoring began replacing weekly. A criticality accident at Y-12 facility in 1958 also resulted in extremely high penetrating whole-body doses to eight workers who were not among the monitored group at the time of the accident (Y-12 Plant, 1958; Hurst et al., 1959).

2.6 1961-79

As a result of the 1958 criticality accident, a program was instituted in July 1961 to monitor all Y-12 workers for external radiation exposure using a dosimeter system that was an integral part of the worker's identification badge and contained components for both accident and routine dosimetry (Thornton, Davis, and Gupton, 1961; McLendon, 1963; McRee, West, and McLendon, 1965; Kerr, 2003).

Starting in 1961, the film badge dosimeters were read quarterly, and the quarterly radiation doses were recorded and tabulated at the end of each calendar year. Zero doses for a year were entered for beta and gamma radiation only when, for all quarters, the densitometer (or film reader) showed at least 100% transmission when compared to a blank (or exposed film). Annual neutron doses were recorded as zeros only when neutron doses were less than the MDL of 50 mrem for all quarters of the year.

In 1962 a semiautomatic film reader was developed and installed during the third quarter to measure simultaneously the transmission of light through four film areas, namely an open window and plastic, aluminum, and cadmium filters. Light transmission measurements through each filter area were recorded in volt units on IBM cards (Y-12 Plant, 1963). Factors for converting the volt units to radiation dose were calculated from sets of calibrated films, and the radiation dose was tabulated by computer using the volt units on the IBM cards. The computer tabulated doses appear to have been used as the dose of record for each quarter. The film control program was also reviewed and changed to focus on dose levels of chief interest, i.e., at ranges from 120 mrem to 2500 mrem (Y-12 Plant, 1963; McLendon, 1963). The calibration films were exposed to gamma-ray doses ranging from zero to 5000 mrem, i.e., 0, 30, 120, 240, 480, 720, 960, 1440, 1920, 2880, 3840, and 5000 mrem.

In 1972 a newer automated reading instrument was placed in service. In addition, to better define the calibration curve for film badge dosimeters at higher gamma-ray doses of interest, gamma-ray doses of 1400, 1750, and 3250 mrem were added to the calibration films (Sherrill and Tucker, 1973).

3. Y-12 External Dose Database

3.1 Data Delivered to ORAU/CER

From 1978 through the 1980s the Y-12 site delivered electronic files of worker data to CER as a resource for the Health and Mortality Studies conducted for the DOE and its predecessor agencies. Data in these files had been obtained from hardcopy records and manually transcribed by UCCND personnel beginning in 1965 at the request of the Atomic Energy Commission (Denton and Fore, 1979). Files containing records for more than 17,000 Y-12 workers were received on magnetic tapes and included beta, gamma, and neutron radiation measurements, penetrating dose and skin dose, and additional relevant information. Due to changes over time in record keeping practices and procedures at Y-12, the files were in several different formats that were similar, but not identical. 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 later constructed a carefully linked relational database with a standardized file format. Since 2002 the data have resided in a Microsoft © SQL Server database.

The data set underlying this analysis is composed of over 512,000 records for years 1950 through 1988 with over 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 units of mrem. Although each record has a flag to note an error condition, this flag had all null values before 1980 and so was not relevant for the film badge period of interest.

Database records from the film badge period, through 1979, were put into a text file used for developing methods to provide individual doses for unmonitored quarterly periods of employment. To maintain the confidentiality of worker data, personal identifying information was not included.

3.2 Subgroup Data for Regression Analysis of Gamma Doses

A sub-population of workers who had been monitored both before and after 1961 was identified to investigate whether a time trend was present in dose potential and, if so, to incorporate the trend into the dose assignment methodology. Multiple database queries identified a set of workers satisfying the criteria of four quarters of gamma measurements per year recorded for at least five years during each of the two time periods 1952-60 and 1961-70. Data for 147 workers who met these qualifications supplied a total of 5686 quarterly doses between 1956 and 1965 that were used as the basis for a regression analysis. Results of the regression were used to infer doses for unmonitored quarters before 1956.

4. Statistical Methods

4.1 Maximum Likelihood Estimation for Lognormal Data with Non-Detects

For notational convenience, let the m detected radiation doses d_i be listed first followed by the d_i^* indicating non-detects, so 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 (see Cohen, 1991 and Schmoyer et al., 1996). If a value of zero is recorded for d_i whenever 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

$$L(\beta,\sigma) = \sum_{i=1}^{m} \log\left[g(d_i\,;\,\mu_i,\sigma)\right] + \sum_{i=m+1}^{n} \log\left[G(d_i^*\,;\,\mu_i,\sigma)\right], \quad (1)$$

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, $j = 1,\ldots,p$ and σ. The resulting equations cannot be solved directly so a Newton-Raphson type 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).

4.2 Upper Confidence Limit for pth Percentile with Non-Detects

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 are below this tolerance limit. In small samples without non-detects 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% UCL for D_p, i.e. the estimated $100p$-100γ geometric tolerance limit is

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

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

4.3 Prediction Density with Non-Detects

To estimate the prediction density for an unmonitored quarterly dose z = log(d) at known values of the explanatory variables $\mathbf{x}_f$, we use the "large sample" maximum likelihood prediction density (MLPD) as proposed by Lejeune and Faulkenberry (1982) ,

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

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

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

i.e. the prediction density for d is lognormal.

In particular, $\boldsymbol{\beta} = (\alpha,\beta)$, and $\mathbf{x} = (1, x_f)$, then $\hat{\mu}(\mathbf{x}\hat{\boldsymbol{\beta}}) = \hat{\alpha} + x_f\hat{\beta}$ and

$\text{var}[\hat{\mu}(x_f\hat{\boldsymbol{\beta}})] = \text{var}[\hat{\alpha} + x_f\hat{\beta}]$, then the MLPD is $n(\hat{\alpha} + \hat{\beta}x_f,\ \hat{\sigma}^2 + \text{var}[\hat{\alpha} + x_f\hat{\beta}])$,

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

4.4 Non-Parametric Methods for Samples with Non-Detects

The product limit estimator (PLE) of the cumulative distribution function was first proposed by Kaplan and Meier (1958) for right censored data. For randomly left censored data, Schmoyer et al., (1996) defined the PLE is 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 non-detects or detects that are less than or equal to a_j. Then the PLE is 0 for $0 \le x$

$\leq a_1'$ where a_1' is a_1 or the value of the detection limit for the smallest non-detect if this limit is less than a_1. For $a_1' \leq x < a_L$ 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 $x \geq a_L$. Note that when there are only detects this reduces to the usual definition of the cumulative distribution function. The R function **plend()** can be used to compute the PLE (see 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 $H_j = G^{-1}(\hat{F}_j)$, where G^{-1} is the inverse of the CDF of the standard normal distribution. If the empirical distribution approximates a lognormal, the points on the plot will fall near a straight line. The square of the correlation coefficient $R^2 = cor(log(a_j), H_j)^2$, is an objective evaluation of the lognormal fit. In the complete data case this will closely approximation to the Shapiro-Wilk W statistic used as a test for normality. A formal test for normality of randomly left censored data has not been developed.

4.5 Non-Parametric Upper Tolerance Limit

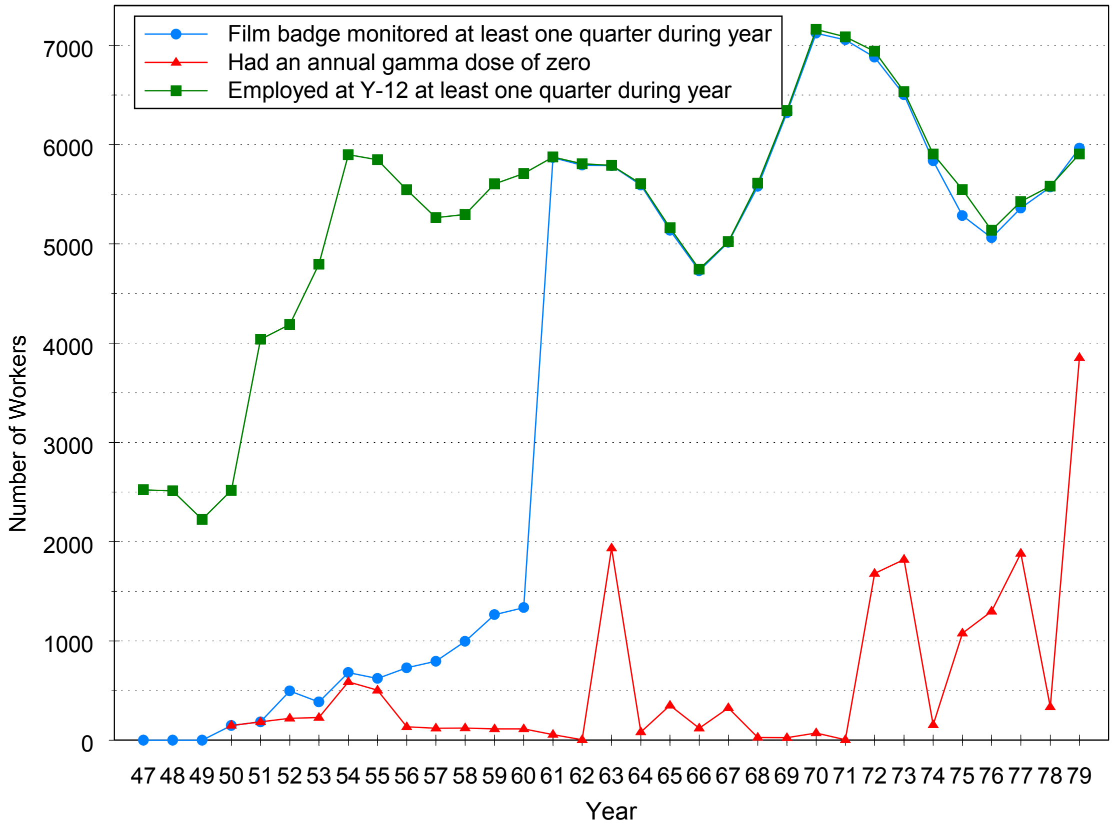
A non-parametric upper tolerance limit can be obtained using the method described by Somerville (1958). Given a random sample of size n from a continuous distribution, with a confidence level of at least γ, 100p% of the population will be below the k^{th} largest value in the sample. The value of k for specific values of n, p, and γ can be obtained from the R function **nptl()** (see 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. Evaluation of Film Badge Doses over Time

5.1 Annual Doses

Figure 1 presents 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 monitored during the year. It confirms that from 1961 nearly all Y-12 workers were monitored for gamma radiation.

Figure 1: Annual Film Badge Monitoring of Y-12 Workers for Gamma Exposure



5.2 Quarterly Doses

As seen in Table 2, film badges were routinely exchanged on a quarterly basis from 1961-1979. Although film badges were read more frequently (generally weekly) in earlier years, only quarterly summations were available. Examining the official policies, it would be expected that there would be no quarterly doses less than 30 mrem except from 1956-61 when the lowest recorded dose could be half the MDL, or 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: 2601). From 1962 to 1979 the number of recorded quarterly doses less than 30 mrem ranged from 2555 in 1979 to 18,090 in 1971 and the number less than 15 mrem ranged from 1749 in 1964 to 8708 in 1971.

Histograms were constructed for exploring the distributions of gamma doses each quarter beginning with 1952, since all quarterly doses in 1951 and all except one dose in 1950 were zero. Recorded doses for 1948-49 were not available. Appendix A contains annual graphs for 1952-79 containing 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. 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, the clustering of quarterly doses around 400 and 600 mrem may be influenced by these dosimetry practices (see Section 2.1). 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 exposure data after 1956, q-q plots and R-square statistics were produced for each quarter (see Section 4.4). These graphs are included in Appendix B. With few exceptions R-square was well above 0.9 for quarters in 1956 and later but was much lower in earlier years.

5.3 Limitations of Doses for Dose Reconstruction

After viewing the quarterly histograms, q-q plots, and R-square statistics and 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 by Kerr and Smith (2004). However, quarterly data before 1956 could not be used justifiably for such estimation.

Certain summary statistics were investigated and further confirmed the suitability after 1956 of using the lognormal model and data from the quarter where the unmonitored dose occurred in the process of estimating the dose. Table 4 presents the summary statistics based on applying 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 doses per quarter corroborates the policy change from monitoring selected workers with higher exposure potential to monitoring all workers. Including workers with lower exposure potential also led to a generally higher percent of non-detectable quarterly doses, although the this percentage varies 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.

As expected, beginning in 1961 the estimates of mean, median, 99th percentile, and upper tolerance limits dropped substantially from earlier years since the population of monitored workers was no longer restricted to individuals with higher exposure potential. During the time period with numerous unmonitored quarters (before 1961) the expected dose derived from the quarterly lognormal model (AM) was generally higher than the mean dose estimated non-parametrically (PLE). Also, beginning with the fourth quarter of 1956 through 1960 upper tolerance limit (UTL) based on the lognormal-model generally exceeded the non-parametric estimate (npUTL). These findings support the use of the model-based approach since it would likely result in estimated doses that were somewhat higher and thus claimant favorable. The upper tolerance limits also demonstrate compliance with the radiation protection guidelines in force during the film badge period (see Section 2.1).

Definitions of the columns in Table 4 are as follows:

Yr	year (1956-1979)
Qt	quarter (1, 2, 3, or 4)
N	number of quarterly doses
%nd	percent of non-detectable quarterly doses (< MDL)
μ	mean of the doses on log scale
σ	standard deviation of doses on log scale
se(μ)	standard error of μ
GM	exp(μ); geometric mean; median of doses on original scale
KM	non-parametric Kaplan-Meier (product-limit) estimate of mean of doses on original scale, adjusted for censoring
AM	$\exp(\mu + \sigma^2/2)$; estimate of arithmetic mean of doses on original scale; expected value of dose based on lognormal model
D99	99th percentile of doses on the original scale
UTL	99-95 geometric upper tolerance limit based on lognormal model
npUTL	non-parametric 99-95 geometric upper tolerance limit

Table 4: Summary Statistics for Y-12 Quarterly Gamma Doses, 1956-1979

Yr	Qt	N	%nd	μ	σ	se(μ)	GM	AM	KM	D99	UTL	npUTL
56	1	448	71	2.296	2.086	0.178	10	87	67	1272	1957	1207
56	2	492	58	3.042	1.220	0.075	21	44	54	358	443	1282
56	3	617	40	3.648	1.264	0.058	38	85	83	726	875	977
56	4	620	20	4.480	1.184	0.049	88	178	155	1387	1631	935
57	1	565	10	4.550	0.747	0.032	95	125	119	538	598	612
57	2	595	29	3.646	1.191	0.052	38	78	78	613	725	756
57	3	668	32	3.563	1.286	0.054	35	81	83	702	835	955
57	4	678	57	3.038	1.002	0.052	21	34	41	215	248	586
58	1	704	25	3.726	0.965	0.038	42	66	67	392	444	484
58	2	694	15	4.385	1.187	0.046	80	162	145	1269	1474	875
58	3	689	13	4.549	1.020	0.039	95	159	149	1015	1155	1056
58	4	788	24	4.116	1.065	0.040	61	108	104	731	833	600
59	1	844	5	4.727	0.870	0.030	113	165	155	854	941	710
59	2	854	44	3.612	1.244	0.049	37	80	70	669	785	595
59	3	909	23	3.793	1.025	0.036	44	75	74	481	540	530
59	4	1053	20	4.174	1.004	0.032	65	107	103	671	745	564
60	1	1148	28	3.569	1.114	0.035	35	66	66	474	530	502
60	2	1104	11	3.961	1.055	0.032	53	92	88	611	678	517
60	3	1055	4	4.216	1.015	0.031	68	113	104	719	794	452
60	4	985	7	4.459	0.937	0.030	86	134	127	764	842	521
61	1	5301	78	2.060	1.238	0.035	8	17	21	140	150	222
61	2	5525	1	3.815	0.598	0.008	45	54	56	183	187	269
61	3	5494	1	3.013	0.853	0.012	20	29	31	148	153	178
61	4	5565	0	3.951	0.530	0.007	52	60	61	178	183	244
62	1	5583	0	2.460	0.940	0.013	12	18	22	104	108	178
62	2	5352	0	3.910	0.584	0.008	50	59	62	194	199	329
62	3	5394	0	3.630	0.795	0.011	38	52	52	240	248	355
62	4	5327	0	3.346	1.079	0.015	28	51	47	350	366	257
63	1	5456	58	2.419	1.217	0.023	11	24	25	190	202	227
63	2	5536	57	2.757	0.882	0.016	16	23	27	123	128	208
63	3	5549	66	1.996	1.581	0.033	7	26	26	291	315	300
63	4	5461	78	2.432	0.903	0.025	11	17	22	93	98	165
64	1	5477	83	2.186	1.300	0.047	9	21	34	183	199	255
64	2	5314	83	2.181	1.266	0.046	9	20	35	168	182	230
64	3	5360	14	3.090	1.207	0.017	22	46	41	364	384	288
64	4	5122	73	2.182	1.336	0.033	9	22	25	198	213	276
65	1	5037	35	2.735	1.044	0.017	15	27	27	175	183	206
65	2	4474	42	2.433	1.158	0.021	11	22	24	168	179	252
65	3	4345	0	2.713	0.935	0.014	15	23	26	133	139	230
65	4	4336	0	3.505	0.529	0.008	33	38	40	114	117	252
66	1	4333	61	1.977	1.436	0.032	7	20	21	204	221	242
66	2	4339	41	2.471	1.284	0.023	12	27	28	235	251	285
66	3	4400	0	2.889	1.416	0.021	18	49	39	484	518	340

Table 4: Summary Statistics for Y-12 Quarterly Gamma Doses, 1956-1979

Yr	Qt	N	%nd	μ	σ	se(μ)	GM	AM	KM	D99	UTL	npUTL
66	4	4485	37	2.767	1.074	0.018	16	28	32	194	204	374
67	1	4515	76	2.112	1.333	0.039	8	20	26	184	199	326
67	2	4613	45	2.457	1.221	0.022	12	25	27	200	213	280
67	3	4753	9	2.532	0.991	0.015	13	21	22	126	132	176
67	4	4797	47	2.307	1.048	0.019	10	17	19	115	121	189
68	1	4884	23	2.027	1.179	0.019	8	15	19	118	125	167
68	2	4974	1	3.971	0.336	0.005	53	56	57	116	118	169
68	3	5212	91	1.612	1.161	0.062	5	10	15	75	80	136
68	4	5293	1	3.468	0.744	0.010	32	42	40	181	187	211
69	1	5398	8	2.993	0.742	0.010	20	26	26	112	116	169
69	2	5466	6	2.947	0.883	0.012	19	28	28	149	154	194
69	3	5935	7	3.191	1.022	0.013	24	41	40	262	274	311
69	4	5882	10	2.839	1.044	0.014	17	29	30	194	203	279
70	1	6024	6	2.938	1.045	0.014	19	33	32	215	224	242
70	2	6002	5	2.333	0.932	0.012	10	16	16	90	94	95
70	3	6509	6	3.268	0.914	0.011	26	40	39	220	228	225
70	4	6672	19	2.983	0.990	0.013	20	32	32	197	205	243
71	1	6759	0	3.230	0.632	0.008	25	31	34	110	113	201
71	2	6757	26	2.012	1.019	0.014	7	13	13	80	83	131
71	3	6629	1	3.225	0.778	0.010	25	34	34	154	158	196
71	4	6556	10	2.651	0.924	0.012	14	22	22	122	126	164
72	1	6525	23	2.561	0.970	0.013	13	21	22	124	129	187
72	2	6400	75	2.069	1.115	0.026	8	15	17	106	112	177
72	3	6403	92	1.566	1.106	0.056	5	9	14	63	67	113
72	4	6194	90	1.723	1.123	0.048	6	11	16	76	81	141
73	1	6311	58	2.059	1.143	0.020	8	15	16	112	118	162
73	2	6062	89	1.762	1.237	0.055	6	13	19	104	111	144
73	3	5880	35	2.225	1.080	0.016	9	17	18	114	120	190
73	4	5398	96	1.005	1.280	0.133	3	6	15	54	59	79
74	1	5298	5	3.277	1.058	0.015	26	46	45	311	325	346
74	2	5359	40	2.203	1.222	0.020	9	19	19	155	164	198
74	3	5364	13	2.630	0.964	0.014	14	22	23	131	136	188
74	4	5214	71	1.997	1.131	0.027	7	14	15	102	109	127
75	1	5168	21	2.209	0.988	0.015	9	15	17	91	95	151
75	2	4917	88	1.678	1.170	0.050	5	11	15	81	87	142
75	3	4483	91	1.537	1.112	0.059	5	9	13	62	66	94
75	4	4540	89	1.610	1.075	0.049	5	9	12	61	65	86
76	1	4618	45	2.390	0.847	0.016	11	16	17	78	82	131
76	2	4605	83	1.869	1.065	0.036	6	11	13	77	82	126
76	3	4572	46	2.445	0.954	0.018	12	18	19	106	111	143
76	4	4694	95	1.669	0.928	0.072	5	8	13	46	49	70
77	1	4933	74	1.825	1.025	0.026	6	10	12	67	71	92
77	2	5021	81	1.869	0.924	0.028	6	10	11	56	59	59
77	3	5058	54	2.325	0.984	0.019	10	17	18	101	106	177

Table 4: Summary Statistics for Y-12 Quarterly Gamma Doses, 1956-1979

Yr	Qt	N	%nd	μ	σ	se(μ)	GM	AM	KM	D99	UTL	npUTL
77	4	4902	72	1.646	1.013	0.025	5	9	9	55	58	81
78	1	5007	61	1.684	1.038	0.022	5	9	10	60	64	75
78	2	5073	50	2.214	0.972	0.018	9	15	16	88	92	114
78	3	5202	8	3.460	0.724	0.010	32	41	41	171	177	189
78	4	5255	77	1.616	1.108	0.030	5	9	10	66	70	83
79	1	5169	77	1.672	1.021	0.027	5	9	10	57	61	87
79	2	5512	83	1.939	0.924	0.029	7	11	12	60	63	80
79	3	5196	86	1.801	1.185	0.044	6	12	18	95	102	236
79	4	5489	88	1.840	1.091	0.043	6	11	16	80	85	142

6. Estimates for Unmonitored Quarterly Doses

6.1 Procedure Used through Third Quarter of 1956

As discussed in Section 5.2, information gathered from the histograms and q-q plots led to the determination that quarterly dose datasets before 1956 may not have been suitable for estimating doses for unmonitored quarters. An alternative approach was developed in which unmonitored doses were estimated from a regression analysis based on the subgroup data of 147 workers described in Section 3.1. 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 2 shows all quarterly doses for the subgroup of 147 from 1956-65, the set of data used for the alternative approach. Since the vertical axis is on a logarithmic scale, for graphing purposes each subgroup member's zero doses during a quarter were replaced by half his minimum non-zero quarterly dose. The smoothing function **supsmu()** in the software package R (R, 2004) produced the (green) curve that begins with a slightly 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 obtained for the 5686 data points by fitting a lognormal model for left censored data with zero doses replaced by 30 mrem, the limit of detection. These plots show a general trend of decreasing dose with increasing time.

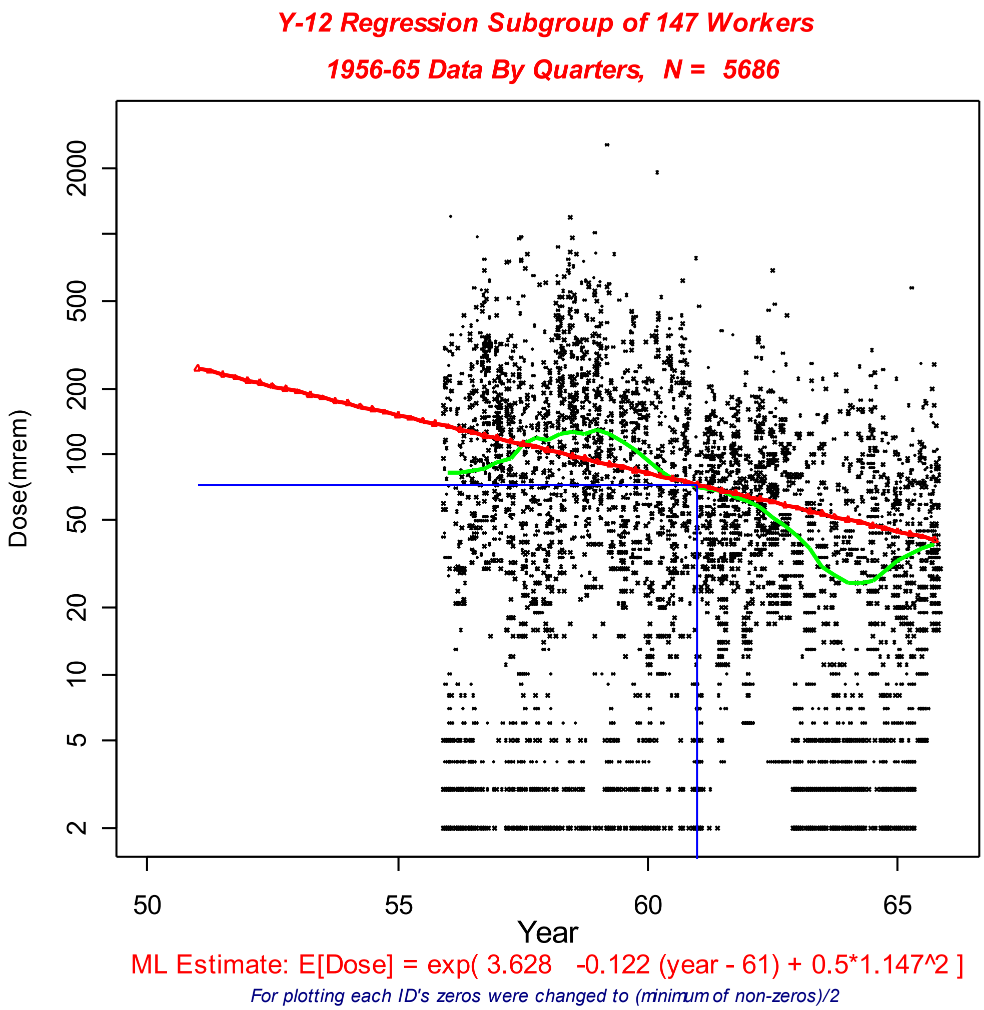
ML estimates were used to obtain parameters for the prediction densities before 1957 using the lognormal model $\mu_i = \alpha + \beta x_i$ where $x_i = t_i - 61$ for t_i the time in years and quarters for the i^{th} observation (see Section 4.3). The expected dose E(log(dose)) = $\alpha + \beta$ *(t-61) and estimates obtained were these: $\hat{\alpha}$ = 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 Eq. (4) to determine the prediction density for each quarter of this time period. As an extra assurance of claimant favorability, $\hat{\sigma}$ was replaced by its upper 95th percent 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 2 indicate that the expected dose from the regression for the first quarter of 1961 was about 70. These ML estimates are equivalent to parameter values obtained from a least squares regression using the logs of the doses with a normal model.

6.2 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 the fourth quarter of 1956 (see Sections 5.2 and 5.3). The period before 1961 was of particular interest since 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 4.1. These parameters were used to determined 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 $\hat{\sigma} = (\hat{\sigma}^2 + \mathrm{var}(\hat{\mu}))^{1/2}$. This is equivalent to equation 4 when there are no predictor variables so that $\hat{\mu} = \hat{\alpha}$ and var($\hat{\mu}$) = var($\hat{\alpha}$). Values of $\hat{\mu}$, $\hat{\sigma}$, and var($\hat{\mu}$) can be determined from columns 5-7 in Table 4. For easier implementation in dose reconstruction, the quantity $(\hat{\sigma}^2 + \mathrm{var}(\hat{\mu}))^{1/2}$ was calculated for each quarter and appears in column 4 of Table 5. The GSD in Table 5 was calculated using the variance of the prediction density.

Figure 2: Regression of Quarterly Data from 1956-65 for a Subgroup of Workers Monitored Before and After 1961



6.3 Parameters for Lognormal Prediction Densities

Columns 5 and 6 in Table 5 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 5 covers years from the take over of Y-12 by UCCND in 1947 to the end of the film badge program in 1979, the GM and GSD for earlier years and later years were obtained in two distinct manners. These values for 1947 through the third quarter of 1956 were calculated using the subgroup regression approach discussed in Section 6.1. In contrast, from the fourth quarter of 1956 through 1979 the GM and GSD for each quarter were determined by applying a lognormal model directly to the doses for that quarter as discussed in Section 6.2.

Table 5. Parameters for Lognormal Prediction Density, 1947-1965

Yr	Qtr	μ	σ	GM(reg)	GSD(reg)	E(dose)
47	3	5.2684	1.1710	194.1093	3.2254	385.3264
47	4	5.2380	1.1710	188.3017	3.2251	373.7602
48	1	5.2077	1.1709	182.6679	3.2248	362.5419
48	2	5.1773	1.1708	177.2026	3.2245	351.6610
48	3	5.1469	1.1707	171.9009	3.2243	341.1072
48	4	5.1165	1.1706	166.7578	3.2240	330.8709
49	1	5.0862	1.1706	161.7685	3.2238	320.9423
49	2	5.0558	1.1705	156.9285	3.2235	311.3123
49	3	5.0254	1.1704	152.2334	3.2233	301.9717
49	4	4.9950	1.1703	147.6787	3.2230	292.9120
50	1	4.9647	1.1703	143.2603	3.2228	284.1247
50	2	4.9343	1.1702	138.9740	3.2226	275.6015
50	3	4.9039	1.1701	134.8161	3.2224	267.3344
50	4	4.8735	1.1701	130.7825	3.2222	259.3159
51	1	4.8432	1.1700	126.8696	3.2220	251.5383
51	2	4.8128	1.1699	123.0738	3.2217	243.9945
51	3	4.7824	1.1699	119.3915	3.2216	236.6773
51	4	4.7520	1.1698	115.8194	3.2214	229.5801
52	1	4.7217	1.1697	112.3542	3.2212	222.6961
52	2	4.6913	1.1697	108.9927	3.2210	216.0189
52	3	4.6609	1.1696	105.7317	3.2208	209.5423
52	4	4.6305	1.1696	102.5683	3.2206	203.2603
53	1	4.6002	1.1695	99.4995	3.2205	197.1670
53	2	4.5698	1.1695	96.5226	3.2203	191.2567
53	3	4.5394	1.1694	93.6347	3.2202	185.5239
53	4	4.5090	1.1694	90.8333	3.2200	179.9633
54	1	4.4786	1.1693	88.1156	3.2199	174.5698
54	2	4.4483	1.1693	85.4793	3.2197	169.3381
54	3	4.4179	1.1693	82.9218	3.2196	164.2636
54	4	4.3875	1.1692	80.4409	3.2195	159.3415
55	1	4.3571	1.1692	78.0341	3.2193	154.5671
55	2	4.3268	1.1691	75.6994	3.2192	149.9361
55	3	4.2964	1.1691	73.4346	3.2191	145.4441
55	4	4.2660	1.1691	71.2375	3.2190	141.0869
56	1	4.2356	1.1690	69.1061	3.2189	136.8606
56	2	4.2053	1.1690	67.0385	3.2188	132.7611
56	3	4.1749	1.1690	65.0328	3.2187	128.7846

Table 5. Parameters for Lognormal Prediction Density, 1947-1965

Yr	Qtr	μ	σ	GM(direct)	GSD(direct)	E(dose)
56	4	4.4804	1.1849	88.2670	3.2705	178.1117
57	1	4.5501	0.7481	94.6429	2.1129	125.1996
57	2	3.6461	1.1926	38.3236	3.2957	78.0411
57	3	3.5629	1.2870	35.2668	3.6219	80.7312
57	4	3.0381	1.0032	20.8654	2.7271	34.5129
58	1	3.7262	0.9659	41.5229	2.6271	66.2019
58	2	4.3848	1.1877	80.2184	3.2794	162.3934
58	3	4.5488	1.0210	94.5197	2.7759	159.1748
58	4	4.1164	1.0660	61.3370	2.9037	108.2611
59	1	4.7269	0.8700	112.9481	2.3870	164.9118
59	2	3.6119	1.2450	37.0373	3.4730	80.3958
59	3	3.7927	1.0253	44.3740	2.7880	75.0609
59	4	4.1739	1.0040	64.9716	2.7293	107.5551
60	1	3.5687	1.1147	35.4690	3.0488	66.0222
60	2	3.9611	1.0556	52.5129	2.8736	91.6675
60	3	4.2164	1.0153	67.7919	2.7602	113.5069
60	4	4.4589	0.9375	86.3962	2.5535	134.0703
61	1	2.0601	1.2387	7.8465	3.4512	16.8995
61	2	3.8154	0.5982	45.3955	1.8188	54.2889
61	3	3.0126	0.8528	20.3409	2.3463	29.2623
61	4	3.9514	0.5300	52.0060	1.6990	59.8494
62	1	2.4602	0.9398	11.7075	2.5595	18.2078
62	2	3.9103	0.5839	49.9146	1.7931	59.1934
62	3	3.6301	0.7948	37.7183	2.2141	51.7299
62	4	3.3465	1.0791	28.4022	2.9419	50.8382
63	1	2.4188	1.2168	11.2322	3.3763	23.5485
63	2	2.7574	0.8825	15.7582	2.4170	23.2612
63	3	1.9958	1.5818	7.3584	4.8636	25.7093
63	4	2.4319	0.9032	11.3810	2.4674	17.1123
64	1	2.1856	1.3008	8.8959	3.6723	20.7314
64	2	2.1811	1.2667	8.8559	3.5490	19.7529
64	3	3.0904	1.2067	21.9863	3.3425	45.5361
64	4	2.1823	1.3366	8.8664	3.8062	21.6621
65	1	2.7352	1.0437	15.4128	2.8396	26.5709
65	2	2.4326	1.1580	11.3883	3.1837	22.2673
65	3	2.7133	0.9351	15.0795	2.5474	23.3482
65	4	3.5052	0.5286	33.2881	1.6965	38.2786
66	1	1.9772	1.4366	7.2223	4.2062	20.2675
66	2	2.4709	1.2845	11.8327	3.6130	27.0013
66	3	2.8886	1.4160	17.9675	4.1208	48.9677
66	4	2.7667	1.0745	15.9067	2.9285	28.3323

67	1	2.1120	1.3340	8.2651	3.7962	20.1221
67	2	2.4571	1.2213	11.6708	3.3917	24.6041
67	3	2.5324	0.9914	12.5839	2.6951	20.5711
67	4	2.3066	1.0483	10.0406	2.8528	17.3936
68	1	2.0275	1.1793	7.5948	3.2521	15.2235
68	2	3.9709	0.3359	53.0336	1.3992	56.1115
68	3	1.6120	1.1632	5.0130	3.2000	9.8600
68	4	3.4677	0.7441	32.0645	2.1046	42.2925
69	1	2.9932	0.7417	19.9487	2.0994	26.2637
69	2	2.9467	0.8831	19.0424	2.4183	28.1224
69	3	3.1905	1.0226	24.3011	2.7803	40.9903
69	4	2.8390	1.0444	17.0981	2.8417	29.4989
70	1	2.9383	1.0453	18.8832	2.8442	32.6087
70	2	2.3328	0.9323	10.3065	2.5403	15.9164
70	3	3.2685	0.9138	26.2714	2.4939	39.8865
70	4	2.9826	0.9899	19.7397	2.6910	32.2203
71	1	3.2304	0.6317	25.2897	1.8808	30.8742
71	2	2.0116	1.0196	7.4756	2.7721	12.5717
71	3	3.2247	0.7777	25.1451	2.1765	34.0246
71	4	2.6512	0.9245	14.1717	2.5207	21.7287
72	1	2.5615	0.9698	12.9550	2.6373	20.7324
72	2	2.0685	1.1157	7.9132	3.0517	14.7452
72	3	1.5660	1.1079	4.7873	3.0280	8.8436
72	4	1.7225	1.1241	5.5986	3.0774	10.5308
73	1	2.0587	1.1435	7.8361	3.1377	15.0673
73	2	1.7620	1.2384	5.8243	3.4501	12.5393
73	3	2.2251	1.0806	9.2547	2.9464	16.5928
73	4	1.0047	1.2874	2.7312	3.6233	6.2552
74	1	3.2767	1.0585	26.4875	2.8820	46.3800
74	2	2.2031	1.2222	9.0535	3.3945	19.1056
74	3	2.6296	0.9638	13.8678	2.6216	22.0654
74	4	1.9974	1.1317	7.3699	3.1009	13.9820
75	1	2.2088	0.9884	9.1049	2.6869	14.8391
75	2	1.6778	1.1706	5.3537	3.2240	10.6224
75	3	1.5370	1.1138	4.6508	3.0459	8.6479
75	4	1.6097	1.0764	5.0012	2.9340	8.9259
76	1	2.3905	0.8472	10.9189	2.3331	15.6328
76	2	1.8695	1.0656	6.4850	2.9025	11.4411
76	3	2.4448	0.9544	11.5278	2.5971	18.1777
76	4	1.6694	0.9306	5.3088	2.5361	8.1857
77	1	1.8246	1.0249	6.2001	2.7868	10.4832
77	2	1.8694	0.9248	6.4843	2.5213	9.9441
77	3	2.3250	0.9847	10.2263	2.6769	16.6056
77	4	1.6465	1.0129	5.1886	2.7535	8.6661

78	1	1.6841	1.0384	5.3875	2.8248	9.2374
78	2	2.2135	0.9717	9.1477	2.6424	14.6669
78	3	3.4596	0.7243	31.8027	2.0632	41.3399
78	4	1.6158	1.1084	5.0318	3.0295	9.3004
79	1	1.6718	1.0216	5.3215	2.7777	8.9676
79	2	1.9389	0.9249	6.9514	2.5216	10.6618
79	3	1.8009	1.1861	6.0554	3.2744	12.2363
79	4	1.8403	1.0917	6.2985	2.9792	11.4291

Discussion

The motivation for this report was to provide useful, comprehensive, and accurate background information on the film badge program through 1979 at the Y-12 site as a resource for dose reconstruction. This closure date was chosen because film badges were replaced by thermoluminescense dosimeters for monitoring external radiation beginning in 1980. Specifically, information in this report should be valuable in assuring that quarterly gamma dose data were used effectively in developing the process for providing prediction densities for sampling individual doses during quarters when a worker was employed but not monitored for external radiation exposure.

Although production was and is, by necessity, a major concern at the Y-12 facility, it was of particularly high priority during earlier years of plant operation because of the dangers brought about by the Cold War. However, worker health also had high priority as evidenced by the complexity of the monitoring program and the large number of monitoring records generated. Radiation monitoring policies and recording procedures and practices were continually upgraded as the knowledge base expanded and technology progressed to allow improved accuracy in monitoring devices and processes. Health physics staff gradually shifted focus from compliance with standards to measuring more accurate doses for individuals. In particular, after the criticality accident in 1958 (Y-12 Plant, 1958; Hurst et al., 1959) additional political and social pressure resulted in larger budgets for the health physics section that provided the resources for monitoring all Y-12 workers for external radiation rather than only workers with potential to be exposed to 10% or more of the radiation protection guidelines. Doses were likely highest during the earliest years when only selected workers were monitored. However, exposure to gamma radiation from the Y-12 production processes was expected only for workers in a limited number of jobs and generally regarded as a lesser concern than exposure to beta-rays.

In the 1970s exposure data were collected and computerized for use in the DOE Health and Mortality Studies of nuclear workers, which further encouraged the accurate assessment of individual worker doses. During this time the atomic bomb survivor study results began to provide initial information on the connection between radiation exposure and human health, sparking further interest in the accuracy of doses.

The statistical methods reported herein were developed for determining prediction densities to estimate doses for unmonitored quarters. These methods were the outcome of a thorough investigation of the available data and were carefully thought out and applied to provide reasonable dose estimates that should be claimant favorable. Prediction densities were derived using different methods before and after 1956. After 1956 the quarterly doses were used to derive parameter estimates by ML methods for quarterly lognormal prediction densities. Before 1956 the parameters for the prediction densities were derived from a ML regression based on data from a subgroup of 147 carefully selected 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 at least five years before 1961. Subgroup members also had recorded 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 claimant favorable, the standard deviation of the doses was replaced by its upper 95th percent confidence limit when calculating the lognormal parameters from the regression model.

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