Technical Basis Document for the
Neutron Dose Reconstruction Project

NEUTRON DOSE RECONSTRUCTION PROTOCOL

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1.0 Purpose

The purpose of the Neutron Dose Reconstruction Project (NDRP) is to provide to current and former radiation workers of the Rocky Flats Environmental Technology Site (hereafter designated as Rocky Flats) the best reasonably achievable assessment of the neutron exposure they received while performing work in the plutonium production facilities from 1952 through 1970.

This protocol describes the methods and technical basis used by the NDRP to reassess these neutron doses, either by rereading neutron films and plates used to monitor workers for neutron exposures or by estimating the neutron doses for periods of time when a worker was not monitored for neutron exposures in a plutonium-related building.

2.0 Background

From 1952 through 1970, neutron doses received by radiation workers at Rocky Flats were measured using neutron track glass plates, supplied and read by Los Alamos National Laboratory (LANL), then called Los Alamos Scientific Laboratory (LASL), or nuclear-emulsion Type A (NTA) films. Neutron radiation dose to these plates and films is evaluated by manually counting, using a microscope, tracks left by recoil protons from neutron interactions with hydrogen atoms in the emulsions on the plates or films. For some radiation workers, no neutron monitoring at all was performed during the period 1952 through 1970. For others, from1967 through 1970, NTA film badges were issued but not evaluated after they were used.

In a pilot study performed in FY1994, selected plutonium worker NTA films from 1959 through 1966 were reevaluated for neutron dose. Neutron track plates and films from 1952 through 1958 were not included in the pilot study because these plates and films were unavailable at the time. Also, in 1967, the neutron monitoring program had been upgraded, and films for 1967 through 1970 were not included in the pilot study. The results of the pilot study indicated that the original evaluations of the films may have contained significant errors and that the resulting neutron doses of record may have been significantly higher or lower than doses actually received.

For some plutonium workers, neutron monitoring was not provided until the early 1960s, and their dose of record may not include significant contributions from neutron exposure received prior to being issued a neutron dosimeter. These workers included most of the employees working in Building 71 (now Building 771). Only a small number (10–18) of these employees were monitored for neutron exposure, and that monitoring was only during the period October 1956 to September 1957.

Operations in Building 71 involved chemical processing of plutonium in acid solutions and resulted in significant neutron fields from the alpha-neutron reaction with light elements, especially from the plutonium tetrafluoride compound. No evidence has been found that neutron shielding was present for these operations until the early to mid 1960s.

Radiation workers associated with these operations may have received a significant, but unrecorded, neutron dose.

Upgrades to the Rocky Flats neutron monitoring program that were initiated in 1967 included (1) implementation of quality assurance oversight, (2) implementation of a system to prioritize films to be evaluated microscopically, and (3) implementation of a program to assign "notional" neutron doses to personnel whose NTA films were not evaluated.

In 1971, Rocky Flats converted its neutron monitoring techniques from using NTA films to using thermoluminescent dosimeters (TLDs) for monitoring exposure to neutrons. The scope of the NDRP does not include reevaluating neutron doses in the TLD era starting in 1971.

3.0 History of Neutron Dosimetry at Rocky Flats

3.1 Neutron Track Glass Plate Dosimetry

The initial neutron sensitive element was known as a neutron track glass plate. These neutron track glass plates were pieces of glass approximately one-sixteenth inch thick and one inch square with an emulsion coating on one side of the glass. Not only were the glass plates more susceptible to breakage, but they also required delicate handling because the emulsion was adhered to the glass through a simple drying process and could be easily dislodged or removed. Following the cutting of the glass squares, each plate was then etched with individual numbers and issue dates. Following this last cutting, cleaning, and etching step, the emulsion was placed on the ultraclean side of the glass (the side opposite the etched numbers and dates) and allowed to dry. These glass plates were then sent to Rocky Flats from Los Alamos for issue to radiation workers. Following the assigned wear period, these glass plates were collected and shipped back to Los Alamos for analysis.

To interpret neutron doses, the dosimetrist used a microscope to see the ionized, developed grains in the emulsion, to identify and count the proton-recoil tracks, and to determine the track length—technically demanding and time-consuming tasks. Interpreting a neutron dose hinged on the dosimetrist's ability to determine track lengths (track lengths were broken into two categories: either short or long tracks) and to assign appropriate conversion factors to the net tracks for each track length or category. Net tracks were determined by subtracting background tracks (determined from a non-occupationally exposed dosimeter) from the total tracks counted for the worker's dosimeter.

For the analysis of the neutron dose, the dosimetrist counted the number of short tracks (10 to 100 µm) and long tracks (= 100 µm) within 35 fields of view (total surface area = 1 mm^2). A calibration factor (CF), ranging from 5.55 to 6.68 mrem/track, was used for short tracks, based on the assumption that all of the neutrons causing the short tracks had an energy of 3.75 MeV. The CF for long tracks ranged from 8.33 to 10.4 mrem/track, assuming an energy equal to 5.0 MeV for all neutrons causing the long tracks.

From 1952 through 1956, the neutron track plates were supplied, processed, and evaluated by LANL. LANL processed the Rocky Flats beta-gamma film through May 1953. Thereafter, Rocky Flats processed all beta-gamma film that was issued to workers at Rocky Flats.

3.2 Neutron Film Dosimetry

NTA film was the neutron sensitive element used at Rocky Flats from 1957–1970. Rocky Flats procured their neutron-sensitive films from two separate vendors at different times based on availability and cost. These two vendors were either the DuPont Chemical Company or the Kodak Company. These films were created, wrapped in a double-sided paper shield (white on the outside to reflect light and black on the inside to absorb light), packaged in film boxes, and supplied to their customers. The Rocky Flats dosimetry group issued these films to workers, collected and accounted for missing dosimeters, developed and dried them in the same manner using the same chemical processing solutions as the beta-gamma films. The only real handling difference was in the manner in which they were evaluated—beta-gamma by optical densitometer and neutron by microscope.

At the end of 1956, Los Alamos Laboratories chose to cease their neutron dosimetry support to Rocky Flats. As a result, Rocky Flats, not being ready to take over the neutron dosimetry program, subcontracted with a commercial vendor. Rocky Flats entered into a contract with Health Physics Services (HPS) to provide neutron dosimetry support to Rocky Flats, using NTA film. During1957, Rocky Flats completed the development and training of their own dosimetry technicians to perform internal (in-house) processing and interpretation of doses from the new NTA film. As part of the training program for the dosimetry staff, Rocky Flats processed NTA film for about 10 workers in parallel with HPS. The intercomparison evaluation training involved workers in Building 771. The practice of segregating long and short tracks was discontinued in Building 771. Instead, the calibration factor was based on whether the worker was classified as a Pu chemistry worker (coded as “fluoride” or “0.75 MeV”) or as a Pu metal worker (coded as “metal” or “3.75 MeV”). For Pu chemistry workers, the value of the CF was 1.2 mrem/track, and, for Pu metal workers, CF was equal to 6.5 mrem/track. The values of the calibration factors were taken from tables provided by Los Alamos. As for the glass plates, 1 mm^2 of surface area of the film was microscopically examined.

Starting in July 1958 through 1970, Rocky Flats purchased, assigned, processed, and interpreted neutron results using the NTA films. The proton-recoil track density (tracks per mm^2) of the neutron films, starting in July 1958, was determined by dosimetry technicians whose primary microscope skills were acquired through on-the-job training. The calibration factor of 40 mrem/track/mm^2 was used through March 1963 for all workers. Through 1958, only 1 mm^2 of film surface area was examined (read). Starting in 1959, the practice was to read 1 mm^2 of film area. If the track count was greater than a multiple (×2 in 1959–1960 and ×1.5 in 1961) of the blank count, two additional mm^2 of film area was read, and the neutron dose was calculated based on the net tracks for the 3 mm^2. Otherwise, a zero neutron dose was assigned to the worker. Starting in March 1962, 10 mm^2 of film area was read. The method of determining the “positive” track count relative to the blank count, as well as the surface area evaluated and the calibration factors, varied over time. Table 3.1 summarizes these changes in the film evaluation methods.

Table 3.1 History of NTA Film Evaluation Methods

	1958–1959	1960	1961	1962	1963	1964	1965	1966	1967–1970
Area	1 mm^2 3 mm^2	1 mm^2 3 mm^2	1 mm^2 3 mm^2	1 mm^2 3 mm^2 10 mm^2	10 mm^2	10 mm^2	10 mm^2	10 mm^2	10 mm^2
Positive	> 2 x Blank	> 2 x Blank	> 1.5 x Blank	> Blank + 1.65 x sqr(Blank)	> Blank + 1.65 x sqr(Blank)	> 2 x Blank	> 2 x Blank All	All	> Blank
CF (mrem/track/mm^2)	40	40	40	40 100	100	100 70	70 40	110	Custom

In 1967 an improved quality assurance program was implemented. Each dosimetry technician was given additional training and was assigned a custom calibration factor based on the technician’s demonstrated film reading proficiency. In the period from 1967–1970 the technicians’ calibration factors ranged from 35 to110 mrem/track/mm^2 and were at the middle part or lower end of the CF range by 1969. In order to allow more time for the technicians to read the films carefully, not all films were read. Instead, neutron doses were assigned to workers if their penetrating gamma doses were less than a predetermined level (based on building and dosimeter exchange frequency) and they were not working in areas with significantly elevated neutron dose rates.

Throughout the NTA film era, blank films were used to estimate the tracks from nonoccupational neutron exposures of the workers’ films. A blank film was issued and processed with each set of workers’ films. The blank reading was subtracted from the readings of the workers’ films to obtain a value of the net tracks. The net tracks per mm^2 multiplied by the CF yielded the neutron dose for positive results (see Table 3.2.1). The location of the blanks during the monitoring period was generally in the vicinity of the entrance to the work areas but is not well-documented or known for all periods and buildings.

The neutron film system was used until full conversion to the Harshaw LiF TLD system could be achieved in 1971. At that time the entire interpretation process changed from microscopes (for neutrons) and optical densitometers (for beta-gamma doses) to Harshaw TLD readers, model 2000A and model 2000B. The model 2000A heated the crystal, causing the release of light that was then captured in a photomultiplier tube. The output signal (electrical current) from the photomultiplier was sent to the model 2000B, a pico-ammeter that integrated the signal via a charge on a capacitor and displayed the readout in digital units calibrated so that 1 unit was equivalent to 1 mrem of ^{137}Cs penetrating photon dose (at 662 keV).

4.0 NDRP Data Foundation

The data foundation of the NDRP included the original dosimetry worksheets, neutron films and plates, plus supplemental documentation that could be located and retrieved for the period from 1952–1970. These documents and films were located, retrieved, and inventoried, and pertinent information and data were entered into a database created for the NDRP. This section describes this aspect of the NDRP.

4.1 Retrieval of Records

Before any neutron dose reevaluations could be performed, the original records had to be located, retrieved, uniquely identified, inventoried, placed under chain-of-custody control, and cross-referenced to the original records storage boxes. The NDRP documented the review of 943 individual records storage boxes that had been recalled from the Denver Federal Records Storage Center for investigation of applicable records. The reasons for such a large recall of records storage boxes was threefold: (1) the cryptic descriptor for each storage box was too limited to adequately identify everything that was in each box, (2) the individual box inventories were not always complete, and (3) when a storage box was only partially filled, records personnel tended to add other records to the box to help fill out the box, maximize available storage capacity, and preclude the boxes from being crushed by heavier boxes placed on top of partially filled boxes. When additional records were added to the partially filled boxes, these records usually were not recorded on the individual box inventory or added to the individual box descriptor.

4.2 Data Collection

When records storage boxes contained only pertinent records for the NDRP (e.g., beta-gamma film, neutron film, beta-gamma worksheets, and neutron worksheets), these boxes were kept by the NDRP. When a records storage box was identified that contained only a few records pertaining to the NDRP, only those records pertinent to the NDRP were extracted from that box. The box was then returned to the Denver Federal Records Storage Center. All neutron films, beta-gamma worksheets, and neutron worksheets (88 boxes of records) were retained in the custody of the NDRP.

4.3 Chain of Custody

All worksheets (beta-gamma and neutron) were individually identified using a unique identifier number based on year, building, and numerical sequence. As each sheet was uniquely identified, it was recorded in a chain-of-custody logbook. Then the sheet was placed in a manila folder that had a building number reflective of the building information on the worksheet. Each manila folder for each month and building was placed in a hanging file folder that was designated by month and year.

The beta-gamma and neutron film boxes were also inventoried, assigned a unique number, and controlled by a chain-of-custody logbook.

4.4 Data Entry

Prior to the data entry of each data set, several things had to occur. First, all versions and formats of the data set were reviewed to discern the variability of the records. Then, data entry screens were developed so that data for all possible combinations of record formats and data fields could be captured and entered into the database. Third, a work guidance document was written to provide instructions to the data entry personnel and to document the data fields in the original records and in the data entry screens.

The NDRP believed that inputting the original data under the philosophy of "exactly as the condition of discovery in the records" was paramount to the ultimate success of the NDRP. So much so, that the level of data entry could be construed by some as perhaps excessive.

4.5 Database

Data for the NDRP are stored, managed, and retrieved using a Microsoft Access© relational database (Access 2000 file format). The data have undergone several conversions in format since the beginning of the NDRP. Much of the original data were entered into Double Helix© and FoxPro© databases and have undergone several Access migrations. The NDRP software, queries, forms, reports, and Visual Basic program modules are in Access 2000 format.

Information from five primary sources of data was entered into the database. These data sources were Neutron Worksheets, Gamma Worksheets, Neutron Film Identification, Neutron Film Reads, and Employee History Cards.

Neutron Worksheets were entered into the system with a linked structure of Header (***tblNeutronDose***) and Detail (***tblNeutronDoseDetail***) records. Header records for each worksheet contain the information that is common to all of the Detail records: Inventory Number, Building, Issued Date, Returned Date, Work Week, Year, Month, TLD Identifier, and Comments. The fields in the Detail records are: Inventory Number, Employee Number, Last Name, First Name, Badge Number, Original Dose, and Comments.

Gamma Worksheets have a similar structure to the Neutron Worksheets with Header (***tblBetaGamma***) and Detail records (***tblBetaGammaDetail***). The fields in the Header records are Inventory Number, Building, Issued Date, Returned Date, Work Week, Year, Month, TLD Identifier, and Comments. The Detail records have the following fields: Inventory Number, Employee Number, Last Name, First Name, Body Badge Number, Wrist Badge Number, Body Dose CD, Body Dose BR, Body Dose OW, Wrist Dose CD, Wrist Dose BR, Wrist Dose OW, and Comments. CD, BR, and OW are designations for different areas of the film that are often times referred to as “fields”. Each of these fields are used to interpret the doses received from differing types of radiation: e.g., CD represents that portion or area of the film that was shielded both on the front and back by a layer of cadmium metal and is referred to as the hard or high energy gamma field, BR represents that area of the film that was shielded on both the front and back by only a thin layer of Brass metal and is referred to as the soft gamma field, and OW represents that portion of the film that was unshielded or often times referred to as the “open window” or the “Beta window”.

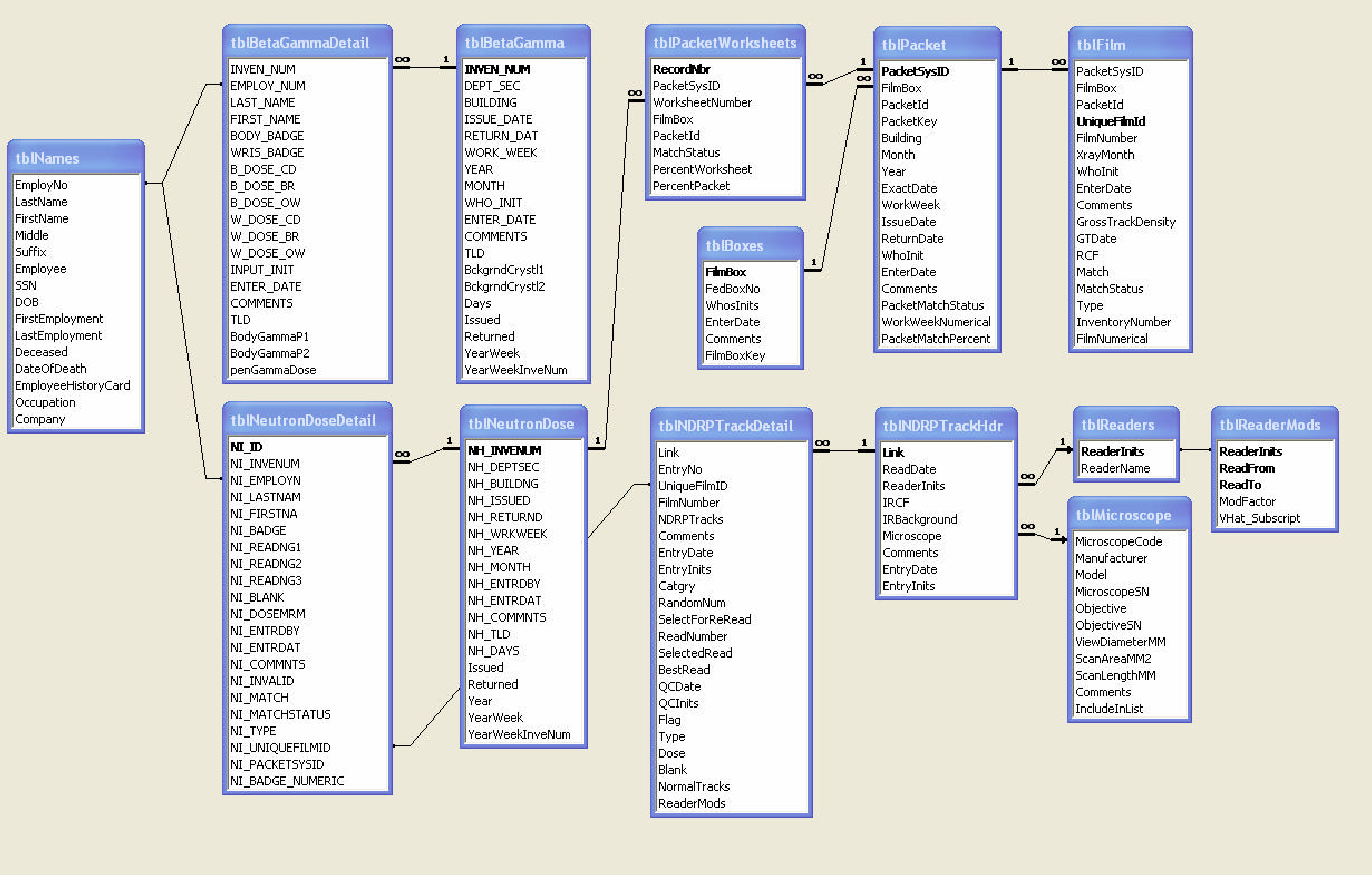
Neutron Film Identification consists of the following cascading structure from highest to lowest: Film Boxes (***tblBoxes***), Packets (***tblPacket***), and Films (***tblFilm***). The following fields are in Film Boxes: Film Box Number and Comments. Data in Packets include Film Box Number, PacketID, Building, Month, Year, Exact Date, Work Week, Issue Date, Return Date, and Comments. The fields in the Films table are Film Box Number, PacketID, UniqueFilmID, X-Ray Month, and Comments. Film Boxes is the Header record for Detail records in Packets. The Packets table is the Header record for Detail records in Films.

Neutron Film Reads also contain a structure of Header (***tblNDRPTrackHdr***) and Detail records (***tblNDRPTrackDetail***). The Header records contain data for all of the films read by a film reader in one day: ReadDate, ReaderInits, IRCF, IRBackground, Microscope, and Comments. The Detail records contain the information about each film that was read by that reader on that date: EntryNo, UniqueFilmID, FilmNumber, NDRPTracks, Type, and Comments. The following fields are entered into the Detail records at various stages in the processing of read films: ReadNumber, BestRead, SelectForReRead, QCDate, QCInits, Dose, NormalTracks, and ReaderMods.

The following data from the Employee History Cards were entered (***tblNames***): EmployNo (four digit employee number, before 1971), Employee (six digit employee number, “50” concatenated with EmployNo, before 1971), LastName, FirstName, Middle, Suffix (e.g., “Jr.”), Employee, SSN, DOB, Deceased, DateoOfDeath, Occupation, FirstEmployment, LastEmployment, Company, and a hyperlink to the scanned image of the EmployeeHistoryCard.

Table 4.1 presents the primary relationships of the NDRP database.

Table 4.1 Primary Relationships of the NDRP Database



4.6 Quality Control of Entered Data

The data entry and daily quality control (QC) process involved a trained data entry person who input data throughout the day, stopped early enough at the end of the day to print out a data entry QC sheet, and performed his/her own initial data entry QC check. If data entry corrections were needed, he/she was to correct those data entries and print out another initial QC check sheet to verify that the initial data entry corrections had been made correctly. The data entry person then dated and initialed this QC sheet and filed the initial correction sheet for the next day's operation. Prior to starting data entry the next day, each data entry person was required to retrieve a QC sheet from a previous day's data entry of another person. (Designated rotations for QC checking were established. A data entry person never did the second QC check of his/her own work.) The original records that had been entered and the data entry QC sheet for those data were then compared to the data in the database. If any errors were identified, the QC data entry person corrected the database, noted in red pencil the error on the first initial QC sheet, printed out a second QC sheet that reflected the correction, stapled the QC sheets together, and initialed and dated the bottom-right hand corner of the corrected QC sheet. If there were no corrections, the data entry person initialed and dated the lower-right hand corner of the initial QC check sheet. Finally, one of the NDRP staff members would randomly select 10% of the final data entry QC sheets from each data entry person and recheck that the data entry had been performed correctly, based on the training, work guidance instruction, and any additional guidance that had been provided by the NDRP team.

5.0 Identification of Affected Workers

There were two primary information sources that were used to identify workers affected by the NDRP. The most directly related source was the neutron dosimetry worksheets. These sheets specifically identified those workers who were assigned neutron-sensitive elements (i.e., neutron films or glass plates). Information on these worksheets usually included the worker's name, employee number, and film badge number. Sometimes only the worker's name was recorded, especially for visitors and workers temporarily assigned to plutonium production areas.

A small portion of the total number of neutron worksheets represent the issuance of neutron dosimeters to a few personnel whose home building assignment was a non-plutonium production building, such as Buildings 21, 22, 23, 34, 44, 81, and 86. These individuals primarily worked in non-neutron buildings but were routinely issued neutron dosimeters because they occasionally performed work activities in plutonium production buildings. Some examples of these job descriptions are guards, radiation monitors, technical researchers, and uranium process operators.

The second source of names was the beta-gamma worksheets for plutonium-related buildings. Only the beta-gamma worksheets from the plutonium production buildings (any building with a number starting with 7) and Buildings 91 and 86, and the combined worksheets for Buildings 21, 22, and 23, were entered into the beta-gamma database. The rosters on the beta-gamma worksheets for these buildings were used to identify workers who would be assigned a notional neutron dose if they were not monitored for neutrons. Beta-gamma worksheets for other buildings were not entered into the database.

6.0 Unique Identification of Glass Plates and NTA films

Glass plates and NTA films were labeled with a generic number through 1960. Starting in 1961, the films were labeled, by X-ray, with the four-digit employee number of the worker. In both eras, many plates and films could share a common number. The NDRP decided that it was essential to label each plate and film with its own unique identification (ID) number. That unique ID number was used to link all pertinent data captured or generated by the NDRP to the worker who was monitored with that plate or film. This section describes the method and process to assign a unique ID number to each plate or film.

6.1 Neutron Track Glass Plates

A total of 757 neutron track glass plates were located that had been stored in three separate storage boxes at LANL. These storage boxes were retrieved from LANL for the purpose of determining whether these neutron track glass plates could be identified, matched, and reevaluated and gathering any other pertinent information or data. Neutron track glass plates, having glass as their substrate, were neither conducive nor amenable to any additional physical methodologies for unique identification, such as perforation or etching.

To minimize damage to the neutron track glass plates, a unique set of bar-code labels was created starting with P0001 through P0757. The “P” designated neutron track glass plates (as compared to the A, B, C, … series that was used for the NTA film), and the numerical numbers were numerically sequenced from 0001 to 0757. These bar-code labels were adhered to the bottom of the paper envelopes in which each of the individual glass plates were stored. Prior to attaching the bar-code labels, the NDRP sorted the plates in the envelopes beginning with the earliest date etched on the glass plates and working forward in time to the most recent dates on the glass plates.

In addition, LANL sent three boxes of original beta-gamma films that had been issued to Rocky Flats workers in 1952 and through February 1953. All six of these dosimeter storage boxes are also currently kept under chain-of-custody control in locked file cabinets at the NDRP’s main office in Arvada, CO.

6.2 NTA Films

Initially, all beta-gamma and NTA neutron films that could be found and identified as personnel films were retrieved from the Denver Federal Records Storage Center for possible use in the NDRP. Based on the initial review of how the beta-gamma and neutron films had been packaged and stored, it became obvious very quickly that a special unique inventorying process had to be developed and documented prior to reviewing, sorting, removing, and documenting the removal of neutron films from the beta-gamma films and beta-gamma films from the neutron films. Beta-gamma films were not used by the NDRP and were returned to the Denver Federal Records Storage Center.

This level of documentation required the recording and documentation of the original federal records storage boxes that had held/contained the film storage boxes while they had been stored at the Denver Federal Records Storage Center. An individual film storage box identification process was created and implemented based on which year had the greatest representation of the films initially stored in that film storage box, the building that had the greatest representation of films initially stored in that box, and whether the films in that box were predominately beta-gamma or neutron. Then each box was numbered and sequenced to a year and building, using a multiple number manual sequencing ink stamp. There were two separate designations implemented, one for beta-gamma film boxes (for example, 6271X001) and one for neutron film boxes (for example, 6271.001). The first two digits represent the year that had the greatest number of packets from that year initially stored in that film storage box (62------). The second two digits represent the building number having the greatest representation of films initially found in that film storage box (--71----). If an individual film storage box was predominately one year but contained multiple buildings, the inventory number would reflect this multiplicity of buildings with a designation of “00” (for ex: --00----), indicating miscellaneous buildings. The two different designators (X) or (.) represent the majority of the types of films initially stored in a film storage box (----X--- or ----.---). For example; if there is an (X) in the middle of the film storage box inventory number, it implies that this particular box contains beta-gamma film, and (.) in the middle of the number implies that this box contains neutron film. Once all of the individual film storage boxes were inventoried (without removing any of the film packets), each box was labeled with the appropriate unique inventory number. The next step was to separate the two types of films (either individual films or packets of similar types of films) from one another. However, it was quickly realized that, prior to the sorting of the films, miscellaneous boxes for each type of film would need to be created to accommodate loose, unlabeled films. These miscellaneous boxes were designated as miscellaneous years and miscellaneous buildings and numerically sequenced. Therefore, the miscellaneous box inventory numbers look like this: 0000X001 for beta-gamma and 0000.001 for the neutron films.

There were three separate efforts initiated by the staff to sort the two types of films from one another. The majority of the time it was somewhat easy, since types of films tended to be in like packets or bundles of one type or the other. There was considerable mixture of films in each of the two types of film storage boxes. As films were removed from an original film storage box (either individually or by packet), they were documented and given a unique additional packet identifier to ensure that they could be traced back to the original film storage box from which they had been extracted. Even though significant effort was exerted to identify and sort each of the two types of film packets, during the film reading process it was discovered that eight individual beta-gamma films had not been identified as beta-gamma films, were uniquely identified, and became a portion of an initial population identified as neutron films (89,984). These eight beta-gamma films were then removed from the neutron film population, thus leaving the final neutron film population at 89,976 neutron films.

A unique film data file was created that contains five levels of detail: (1) the original records storage box in which the films had been located, (2) the number of the original film storage box in which the films were found, (3) the packet number (a group of films typically bound together by tape), (4) the film's X-rayed number along with comments noting any unusual identifying characteristics (marks, chemical processing abnormalities, light leaks, water damage, breaks, and film tears, etc.), and (5) the unique film number that was perforated into the individual film.

The unique film identification numbers always started with an alpha character (A, B, C, etc.) followed by numerical sequencing of numbers (A0001 through A9999). For convenience, the film perforation activity started with the earliest year in which films were found (late 1958) and progressed sequentially through the years until the last films for 1970 were found and uniquely identified. The software was developed so that any film can be traced back to the packet in which it was found, the film storage box in which it had been stored, and the original federal records storage box

The unique film identification process essentially started when the film storage box and the correct packet were identified in the computer and the computer was ready to assign the next numerical sequence of a unique film number. Two basic concepts, embedded in the overall process that helped keep the error rates down, were that the perforator operator could not have more than one packet or group of loose films out of the film storage box at a time and could not end the day with a packet partially perforated.

Once the X-ray number and any additional individual characteristics of that film were input into the computer, the computer software would then generate the next sequential unique film number to be perforated into that film. Before the perforator could perforate the film, the perforator operator first had to perforate a quality control slip of paper and place it between the perforator operator and the computer data entry person, where they were both required to visually verify that the number perforated on the QC slip of paper matched the unique identification number shown in the computer. If they matched, the perforator operator was allowed to perforate the film. Prior to proceeding with the next film, the computer data entry person was required to verify visually that the perforated number on the film matched not only what the computer had generated but also the unique film number reflected on the bar-coded label for that film's individual storage location. The computer data entry person would place the perforated film into the individual storage pouch and prepare the computer for the next film while the perforator operator was manually incrementing the perforator forward to the next unique number. Utilizing a manual incrementing perforator for this NDRP, as opposed to an automatic incrementing perforator, enabled the NDRP to incorporate the level of quality control that was necessary to minimize the loss of data from the perforation process. Also, the automated incrementing perforator machine was not amenable to being reset and to problem resolution.

A very strict quality control process was implemented during the unique film identification process. The purpose for having this process more stringent than any of the other activities was based on the fact that the identification process (perforating an alphanumeric number on the film) removed part of the film. Therefore, any data or information that was removed was gone forever. Only 20 films were misidentified using the initial unique identification process, out of 89,976 neutron films that were uniquely identified. This represented an error rate of 0.022%. Each of these misidentified films was reidentified by using the alternate unique identification method (a bar-code label with the correct alphanumeric number adhered to the film).

7.0 Matching Uniquely Identified Films to Neutron Worksheets

A critical step in the NDRP was to link each film to the worker who was monitored by the film, for the correct year, time period, and building, and to the initial neutron dose evaluated for that film. Since the neutron worksheet generally contained that pertinent information, the neutron worksheet was the obvious focal point to link NDRP film data to the worker. Header information on neutron worksheets included year, building, date issued, date returned, month, week, and miscellaneous annotations. Worker information included name, employee number, and miscellaneous annotations. Film information included film number, number of tracks, background tracks, net tracks, neutron dose, codes, and miscellaneous annotations. Not all worksheets included all of the information. Virtually every combination of items was encountered. All worksheets had been given an inventory number.

The first task was to recreate all of the data on all located neutron worksheets into an electronic database. This task was done with manual data entry instead of by scanning so that data fields could be manipulated digitally for data analysis and quality assurance. Neutron films historically were identified by a number X-rayed onto the film. Prior to 1961, that number was a generic number of the dosimeter holder, which, over time, could have been assigned to numerous workers. Starting in 1961, the worker’s employee number was X-rayed on the film. For those films, the film can be linked to the worker but not necessarily to the worksheet.

Each located neutron film was labeled with a unique ID number. This film ID number was the primary label through which all information concerning that film (e.g., values of the rereads, the person(s) who read the film, the calibration and reader modification factors, the date(s) of the read, and the archival information) were linked.

The archival information for a film included the box number and the packet number. These numbers were assigned by the NDRP. Generally, films were archived each calendar year in boxes labeled with the year plus miscellaneous other information. Within a box, films were clustered in packets secured by rubber bands or tape. Written on the tape or on slips of paper occasionally was information about the building, the group monitored, and the monitoring period. Any information discovered written on the box and packets was captured and entered into the NDRP database, linked to the box number and the packet number. Usually some films in boxes were loose in the box and, therefore, were without supplemental packet information. These films were assigned to a generic packet and could, at least, be matched to the correct year. Since films had the employee number X-rayed on the film starting in 1961, these films also could be linked to the correct worker if the X-rayed number was readable or decipherable.

A software program, named "Match Game," was developed to facilitate the matching of each film to the proper worker in the proper worksheet. Even with this software tool, the matching process involved detective work and attention to detail to discern the proper match for each film. All matching was performed by a senior technical staff member.

Some films could not be matched to an existing worksheet. If the film contained a discernable employee number, the film was assigned to a surrogate worksheet, created for the calendar year. In cases when packets of films were adequately labeled but the worksheets for that period were not found, surrogate worksheets for that period were created for that roster of workers. Films matched to workers on surrogate worksheets allowed the worker to be credited with the reread neutron dose in the proper year. However, the worker also will be credited with the original dose of record for that film, since the NDRP had no means to discern the value of that original neutron dose.

Of the total 89,976 uniquely identified neutron films, 87,943 films (including 657 glass plates) were matched to workers on actual or surrogate worksheets. Of the 87,943 matched films, 2640 were matched to surrogate worksheets of which 1415 films were for year 1970, an ill-behaved-year (see Section 11.5).

The 2033 films that were not matched were an assortment of special study films, calibration films, background films, and films with generic, undecipherable, or missing film numbers.

8.0 Neutron Calibration Film and Sources of Uncertainties

Two sets of films were used to establish the calibration factor (mrem/track/mm^2) for each qualified reader. Each set consists of ten films, eight that received neutron doses of 202 to 491 mrem and two that are blanks. These films originally were used as calibration films in 1967 and 1968. The calibration source was a 210 gram plutonium fluoride (PuF_4) source fabricated in 1962 of Rocky Flats weapons grade plutonium and calibrated at the Los Alamos standard pile. The PuF_4 source was used in two configurations. One configuration was an unmoderated source with an average neutron energy of 1.4 MeV. The other configuration was moderated with seven centimeters of polyethylene (as a shell around the spherical source) with an average neutron energy of 0.15 MeV. The films were exposed in a low-scatter environment at 40 cm from the center of the source. The dose rate for the unmoderated configuration was calculated from the calibrated source strength value and an average neutron energy of 1.4 MeV. The dose rate for the moderated configuration was obtained by measurement, using a 10-inch-sphere rem meter calibrated to the unmoderated PuF_4 source. Each set of calibration films contains four films for the unmoderated configuration and four films for the moderated configuration.

The two sets of films were designated as Calibration sets 1 and 2 (Cal.Set 1 and Cal.Set 2). Films from Cal.Set 1 were used also for training and for the daily QC checks. The calibration factor for each film reader was established from triplicate reads of Cal.Set 1 and duplicate reads of Cal.Set 2. Each film was read over a surface area of a nominal 10 mm^2 using a microscope with a multiplication factor of forty (×40) objective lens and a multiplication factor of ten (×10) eyepiece (40×10=400 magnification). A linear scan of 20 mm was performed for the film read. Depending on the microscope, this read covered a surface area from 9.885 mm^2 to 11.238 mm^2. The calibration factor was then determined for each calibration film by dividing the neutron dose equivalent (mrem, based on a nominal QF = 10) assigned to the film by the net tracks (total tracks – blank tracks) and then multiplying by the surface area evaluated. The units of the calibration factor are mrem per net tracks per mm^2, or (mrem × mm^2)/net tracks. The film reader's calibration factor is the average value for the 40 reads of the non-blank calibration films.

For the film reads for the NDRP, the range of values of the calibration factors was 22.39 to 36.94 (mrem × mm^2)/net tracks with a median value of 30.86 (mrem × mm^2)/net tracks. The percent relative standard deviation ranged from 10.9 to 23.8 with a median value of 18.1. The blank tracks per mm^2 ranged from 1.45 to 3.51 with a median value of 2.01. These values are for a set of 36 reader calibration factors. Several values were excluded from the set because they were not generated according to the established protocol.

The application of the film reader's calibration factor to films worn by workers assumes

- The neutron source used to irradiate the calibration films adequately represents the neutron fields in the work area.
- The film reader reads the tracks on the workers' films in the same manner as the calibration films.
- The characteristics of the tracks on the workers' films are similar to those for the calibration films.
- The readability of the workers' films is similar to those for the calibration films.

The neutron source used for the NDRP study was the PuF_4 source used for film calibrations at Rocky Flats starting in 1962. A mixture of unmoderated and moderated configurations was used. No significant difference in the calibration factors has been observed for the calibration films exposed to the unmoderated spectrum compared to the films exposed to the moderated spectrum. The PuF_4 source is an appropriate source to represent (a,n) neutron sources and also fission spectra neutrons at Rocky Flats. From during the early 1950s, the basis for the calibration factors is not known, but they originated from the nuclear physics group at Los Alamos. For the nuclear track plates supplied by and read by that group at Los Alamos, the calibration factors were 5.55 to

6.68 mrem/track/mm^2 for short (10–100 µm) tracks (related to 3.75 MeV neutrons) and 8.33 to 10.4 mrem/track/mm^2 for long (>100 µm) tracks (related to 5.0 MeV neutrons). When the NTA film program was implemented in 1956 and 1957, the calibration factors were still based on the Los Alamos approach. For workers in plutonium chemistry operations, the calibration factor was 1.2 mrem/track/mm^2 (related to 0.75 MeV neutrons). For workers in plutonium metal operations, the calibration factor was 6.5 mrem/track/mm^2 (related to 3.75 MeV neutrons). In 1958, Rocky Flats started its own calibration, likely using a PoLi neutron source, and established a calibration factor of 40 mrem/track/mm^2, a value similar to the ones obtained for the NDRP.

The calibration factors derived from the NTA films were applied also to the glass plates, since no calibration plates could be located. Factors that could affect the relative sensitivities of the plates versus the NTA films include the emulsion thickness, hydrogen atom density, and emulsion grain size. No information was found that would enable a modifying factor to be quantified and applied to the NTA film calibration factors when used for glass plate readings.

The issue of the film readers reading the workers' films (hereafter called the production films) in the same manner as the calibration films is likely the most significant, and the least quantifiable, source of uncertainty. There are the human factors of fatigue, distractions, and attitudes. There is the natural tendency to read calibration films more carefully than production films, since the given neutron dose is known. There is always a conflict between the need to read films rapidly for timely throughput and the need to read films carefully (and slowly) for quality.

The issue of the characteristics of tracks for calibration films and production films pertains to the freshness of the tracks. For calibration films, the time between irradiation of the film and the development of the film was usually a few days. This means that the tracks appeared fresh and distinct, with minimal fading of the image. Fading of the image resulted when grains of the film emulsion would not fully develop into a dark grain as the time between activation of the grain and the development of the film increased. Production films were typically worn for two-week or monthly periods. Some were worn for three months. Development of production films occurred several days to a week or more following the end of the monitoring period. The tendency was for readers to count the obvious, distinct tracks more thoroughly than partially faded, less distinct tracks, and production films seemed to have a higher prevalence of partially faded, less distinct tracks than calibration films.

The readability of the production films versus calibration films pertains mainly to gamma fogging. Gamma fogging is the darkening of the neutron film primarily from photon (gamma and X-ray) irradiations randomly activating grains in the film emulsion. When the film was developed, dark grains occurred in a random pattern but were frequently the same size as darkened grains in a neutron, proton-recoil track. This fogging tended to make the detection of tracks more and more difficult to the point, in some cases, that the film was not readable at all. Calibration films generally did not have a large amount of gamma fogging.

Another issue is whether an adequate surface area of the film is read. For the NDRP, a nominal 10 mm^2 was read. In the early years at Rocky Flats, only 1 mm^2 was read. Starting in 1962, 10 mm^2 of the film was read. The uncertainties associated with surface area read are mainly counting statistics, assuming a Poisson spatial distribution of tracks.

9.0 Quality Assurance

The objective of the quality assurance (QA) was to ensure that all activities undertaken by this NDRP were performed in a manner commensurate and consistent with the objectives of the Department of Energy – Laboratory Accreditation Program (DOE-LAP) for external dosimetry. Many of the DOE-LAP criteria could not be applied to typical front end dosimetry activities during the NDRP because they could not be duplicated, such as verifying the quality of film purchased, performing intercomparison energy and dose response normalizations, record keeping, dosimeter tracking and documentation, using appropriate and consistent background controls, establishing and retaining annual calibration films, and documenting dosimeter assignments and returns. However, it is important to note that many of the other important parameters of the DOE-LAP program could be implemented, such as QC of data entry of primary data, establishment of standardized film reader training qualifications, development of a standardized approach to establishing individual reader calibration factors, daily QC requirements prior to reading films, establishment of a 10% QC check of films read on a daily basis, and intercomparison of film read results between qualified readers, resulting in reader modification factors to address the human factors issues associated with long-term manual reading of films.

9.1 Film Reader Training and Qualification

Each film reader was initially qualified by establishing his/her own individual reader calibration factor from reading the calibration film sets multiple times and reading blanks and several sets of preselected personnel films that were reevaluated during the pilot study. The important factors involved when establishing individual calibration factors are accuracy, consistency, and the ability to read films that have been darkened from gamma fogging. A lesser factor but an important one that plays into the overall program is the reader's average proficiency. The average proficiency not only takes into account the first three factors but also includes the average time it takes a reader to perform his/her analysis of each film. Time was a variable entity for each film because of track density, gamma fogging, and reader experience.

The training and qualification process, on the average for a full-time reader, took from one to two full months of reading and rereading films. The training time was obviously doubled if the qualifying film reader was only reading films on a half-time basis. The total time for an individual to be considered a qualified film reader was individual-dependent.

Training was conducted either by a senior, qualified film reader, by the NDRP's technical staff, or both. The training focused on teaching the candidate film reader to recognize neutron, proton-recoil tracks and to distinguish those tracks from artifacts (e.g., dust, scratches, cosmic ray "stars," and random emulsion grains exposed by photon radiation). Usually, a dual microscope was used for training so that the trainee and the teacher could jointly examine the field of view and discuss the observations. The trainee would then practice on films, either with a known neutron dose (calibration films) or on production films that had been previously read by qualified readers, to develop consistency and proficiency.

Qualification was typically a four step process: (1) demonstrate an acceptable level of accuracy at reading specific calibration films (relative standard of deviation is less than or equal to ±30%) while developing the reader's calibration factor, (2) demonstrate an acceptable level of consistency during replicate readings of actual personnel films (relative standard of deviation is less than or equal to ±30%), (3) demonstrate an acceptable level of proficiency by reading at least three films per hour, and (4) revalidate the initial reader correction factor by evaluating a final set of calibration films while maintaining the quality and proficiency described within the first three factors.

9.2 Daily Calibration Quality Control Checks

A NDRP staff member identified various groups of films to be read. Prior to initiating the reading of any production films each day, the film reader was required to read and pass an initial qualification test using a calibration film from the first set of calibration films (Cal.Set 1). This daily qualification test was administered, monitored, and reviewed by one of the NDRP staff members. This test verifies and ensures that the reader meets a minimum qualification prior to reading any production films that day. Basically, the reader will have to pass this initial daily test by providing results that are less than or equal to ±30% of the net dose of the preselected random test film for that day before the reader can start reading each day. These results were trended to determine when a qualified reader would need to reestablish his/her reader calibration factor, which could occur within the quality assurance requirement of requalifying every six months. Experience, gained throughout the film reading aspects of the NDRP, reflected that most film readers tended to experience step function changes in their reading ability over very short time periods. Some readers showed a gradual change over time that was identified through the trending process.

9.3 Daily Routine Quality Control Checks

A separate routine quality control program was implemented to reread at least 10% of films that were read the previous day by each reader. The selection of the 10% sample was focused on rereading films with high track counts instead of being a truly random selection. All films with an initial track count of 200 tracks or more were reread. If the 10% sample was not achieved with those films, additional films were randomly selected from films with an initial reading of 50 to 199 tracks. If the 10% sample was still not achieved, additional films were randomly selected from films with an initial reading of less than 50 tracks. The purpose of this focused selection was to ensure that readings of highly dosed films were verified.

To validate the effectiveness of the routine film-reading program, the readings of each of the selected 10% reread films were evaluated statistically to determine whether the initial reading was confirmed by the QC reading. If the reading was not confirmed, one or more additional QC reads were performed until a consensus, or "best," read could be selected. After all matched films had been read, the NDRP decided to replace the approach of selecting the best read for films with multiple readings with the average value of the neutron dose for all reads (see Sections 12.2 and 12.4). Of the 87,723 films that were matched and read, 14,354 films (16.4%) had multiple reads.

10.0 NDRP Neutron Doses from Reread Films

A major focus of the NDRP was to generate a new value of the neutron dose equivalent for each film that could be located and associated with the worker who was monitored for neutrons by that film. Located films were labeled with a unique identification number (see Section 6.0), matched, if possible, to a worker via the neutron dosimetry worksheet (see Section 7.0), and read by qualified film readers to determine the number of proton-recoil tracks/mm^2 of film, evaluated over a nominal total surface area of 10 mm^2. This section describes the method and considerations used to convert the reading of the film (tracks) to the neutron dose equivalent (mrem).

The general equation to calculate the neutron dose equivalent, N, is:

$$N = CF \times RMF \times (T/A - B) \qquad (1)$$

where CF = reader's calibration factor, mrem per net tracks/mm^2
RMF = reader modification factor
T = total tracks read by the film reader
A = area of film microscopically evaluated (mm^2)
B = blank tracks/mm^2

Each film reader established his/her own value of the calibration factor, which was based on multiple readings of two sets of calibration films (see Section 9.1). His/her calibration factors were updated periodically as part of the quality assurance program or following retraining if discontinuities were observed. A reader modification factor (RMF) was applied as a multiplier to the CF to adjust for discontinuities identified by statistical analysis of data for films read by multiple readers (see Section 12.2).

The value of T is the number of tracks counted by the reader during the microscopic evaluation of the area A of the film. Because the fields of view were different for the variety of microscopes used, the areas for a linear scan of 20 mm were also different, ranging from 9.885 to 11.238 mm^2.

For the final analysis of the data, the NDRP decided to normalize T to a virtual reader having CF = 30 mrem x mm^2/track for an $A = 10\ mm^2$. The value of the normalized number of tracks, T_{norm}, is:

$$T_{norm} = CF/30 \times 10/A \times T \qquad (2)$$

The advantage of normalizing the tracks is to facilitate the analysis of the track count data for multiple readers and for the same reader with multiple editions of calibration factors and evaluated areas. The *RMF* was not included in the calculation of the data set of normalized tracks, since the values of the *RMF* were determined from the analysis of that data set. Normalized tracks may be used in Equation 1 to calculate the neutron dose if numerical values of $CF = 30$ and $A = 10$ are also used.

The value of the blank tracks/mm^2 was set equal to zero for the NDRP, since a technically defensible non-zero value could not be determined within the scope of the NDRP. In general, the lower the blank the less likely that a worker will be credited with a neutron dose less than actually received. Conversely, if the selected blank value is greater than the true, but unknown, value, the worker would be credited with a lower neutron dose than actually received. To eliminate the possibility of under-crediting the worker's neutron dose because of an incorrect selection of the blank value, the NDRP decided to set $B = 0$, a worker-favorable condition. Note that, based on normalized tracks, the worker would be over-credited with 30 mrem per film if the true value of B was 1.0 tracks/mm^2.

Many neutron films were read more than one time. Initially, the NDRP was designed to select the best read to use to calculate the neutron dose for that film. After discussion with the consultant statistician, the NDRP decided to use the average of neutron doses obtained for all readings as the best estimate of the neutron dose for that film.

11.0 Notional Neutron Doses

Notional neutron doses are neutron doses that are assigned to a worker who was potentially exposed to neutrons in a plutonium-related building for a period of time but was not credited with a neutron dose in his or her record for that period of time. The lack of a neutron dose of record for a period of time may have been a result of one of the following conditions:

- The worker was not monitored for neutrons but was potentially exposed.
- The worker was monitored for neutrons, but the neutron dose could not be evaluated from the film.
- The worker was not likely to have been exposed to neutrons during that period of time (e.g., on vacation or leave of absence or reassigned to another work area not involving plutonium).

Only for the first two conditions would a notional neutron dose be assigned. The index to identify the first two conditions is the presence of a recorded penetrating gamma dose in a plutonium-related building but no recorded neutron dose for that period of time.

The magnitude of the gamma dose in that period also could be used as an index to estimate the notional neutron dose. The gamma dose multiplied by an appropriate neutron to gamma (N:G) ratio would give an estimate of the notional neutron dose. Another method is to multiply the worker's average monitored neutron dose by the number of days in the period. A weighted combination of these methods was used (see Section 11.3).

11.1 Gaps in the Neutron Dose Timeline

Notional neutron doses are neutron doses that were assigned for periods of time identified as gaps in the worker's neutron dose timeline. The neutron dose timeline was determined from the sequence, by date, of neutron worksheets containing identification of the worker (by name or employee number). The gamma dose timeline, the sequence of gamma worksheets pertaining to the worker for plutonium-related buildings, was also involved in identifying gaps in the worker's neutron dose timeline.

A gap is defined as a period of time when the worker was not monitored for neutrons or has no recorded dose of neutrons but was monitored for gamma doses in a plutonium-related building for that period.

The period of the gap was determined from the neutron work-sheet timeline. If more than one building was involved in the period of the gap, determined from the header information on the gamma worksheets for the period of the gap, the gap was divided into segments based on the dates on the gamma worksheets. A gap may be the entire calendar year or parts of a calendar year. Each calendar year was addressed separately. All gaps were determined according to the logic of the computer software.

11.2 Gamma Doses

Gamma doses, used for the NDRP to establish neutron:gamma ratios and to provide an index for quantifying notional neutron doses, were penetrating (whole body) X-ray and gamma dose equivalents, derived from data on the gamma worksheets. The gamma worksheets did not contain the penetrating gamma doses explicitly. Instead, the worksheets contained the doses assessed for each sector of the film: the cadmium-shielded sector, the brass-shielded sector (when implemented), and the open-window sector. Therefore, it was necessary to convert the film-sector gamma doses to the desired penetrating gamma doses.

The algorithm to convert the film-sector gamma doses depended on the number of sectors (two or three) and on the calibration of the open window sector (plutonium L X-ray or beta calibration). The two-sector dosimeter was the initial dosimeter configuration used at Rocky Flats. The three-sector dosimeter was implemented in Building 71 in the seventh week in 1960 and in all plutonium-related buildings except Building 91 in January 1963. In February 1968, the three-sector dosimeter was implemented in Building 91. The calibration of the open window sector was discerned from a code on the worksheet. Code 1 indicated a beta calibration, typically used for uranium areas and Building 91. Code 2 indicated a plutonium L X-ray calibration, used for plutonium areas. The dose for the cadmium-shielded sector has been labeled on the worksheets as Cd, B2, Gamma B, Shielded B, and Hard ?. The dose for the brass-shielded sector has been labeled on the worksheets as Br and Soft ?. The dose for the open-window sector has been labeled on the worksheets as OW, B1, Open Window B, and X-ray. In the following equations of the algorithms, Cd, Br, and OW were used to designate the cadmium-shielded, brass-shielded, and open-window sector doses, respectively.

Algorithms for the gamma dose (G) are as follows:

- Two-sector dosimeter, Code 1: $G = Cd$
- Two-sector dosimeter, Code 2: $G = Cd + 0.5\ OW$
- Three-sector dosimeter, Code 1: $G = Cd + Br$
- Three-sector dosimeter, Code 2: $G = Cd + Br + 0.35\ OW$

A group of plutonium workers, the plutonium metal (foundry) workers in Building 71, were not monitored for whole body, penetrating gamma and X-ray doses until February 1957. Instead, they were issued only a wrist dosimeter. In order to establish notional neutron doses for these workers, it was necessary first to establish their whole body, penetrating gamma doses. This task was accomplished by determining the ratio of the body to wrist gamma doses from data for the group for February through December 1957, when the workers were monitored for both. The geometric mean of 0.40 of the ratio of body to wrist gamma doses, with a geometric standard deviation of 1.24, was obtained. A reconstructed whole body, penetrating gamma dose was calculated, by multiplying the wrist dose by 0.40, for any monitoring period in which a worker in Building 71 was monitored only with a wrist dosimeter through 1957.

The instrument used for gamma dose interpretation was a densitometer that was “zero” adjusted to the optical density reading of a beta-gamma film that had been identified as a background (nonoccupational) film issued, stored, and processed with the batch of worker films. Based on limited documentation, it appears that the densitometer was zeroed (or set to zero) prior to evaluating production films.

11.3 Method for Determining Notional Neutron Doses for Gaps

The method to determine notional neutron doses for gaps is a weighted combination of notional doses determined from two methods. Method 1 is based on the worker’s average neutron dose per day, obtained from films reevaluated under the NDRP for a given calendar year and building. Method 2 is based on the common neutron-to-gamma ratio for the given building and year. The weighting factors are based on the fraction of the days that each method is operative (defined later). Note: The method can be applied to each gap separately or to the combined gaps per building and year. For the NDRP, the notional doses were assessed separately for each gap.

Method 1:
The notional neutron dose, N_{NOT1}, for method 1 for a gap is given by

$$N_{NOT1} = N_{IBY} \times t_{gap} \tag{3}$$

N_{IBY} is the average neutron dose per day for an individual for a building and calendar year, based on NDRP reread film doses that are paired with monitored gamma doses. The number of days, T_{N1}, used for this average dose rate is equal to the sum of days in the monitoring periods associated with the paired neutron films. The number of days in the gap for that building and year for that individual is equal to t_{gap}.

Method 2:
The notional neutron dose, N_{NOT2}, for method 2 is equal to the common neutron-to-gamma ratio, R_{BY}, for the given building and year multiplied by the penetrating gamma dose, G_{gap}, recorded for the worker for that gap.

$$N_{NOT2} = R_{BY} \times G_{gap} \tag{4}$$

Weighted, Combined Method:
The combined notional neutron dose, N_{NOT}, for a gap is given by

$$N_{NOT} = [T_{N1}/(T_{N1}+ T_{gap})] \times N_{NOT1} + [T_{gap}/(T_{N1}+ T_{gap})] \times N_{NOT2} \tag{5}$$

The sum of the values t_{gap} for all gaps in a given building and year is T_{gap}. If there is only one gap in a building and year, $T_{gap} = t_{gap}$.

If there are gaps for a worker associated with more than one building, this calculation is done separately for each building. Then the combined notional doses for all gaps are summed to get the total notional dose for the year.

Note that, when the worker has only small gaps in the monitored neutron timeline, the notional dose is heavily weighted toward method 1, thus taking advantage of the worker's own NDRP reevaluated neutron dose data. When the worker has no qualified neutron dose data for the building or year, the notional dose is weighted 100% to the N:G ratio method. The method takes advantage of the worker's own quality neutron monitored doses when available, and it works in all cases.

The variance is calculated for the combined notional dose for each building with gaps in a year, assuming that all of the notional dose is based on method 2 (the common N:G ratio method). For cases with some component of method 1, the variance estimated based on method 2 will likely be higher than the actual value. See Section 12.5 for additional information on the selection of the notional dose methodology and variance estimates.

11.4 Neutron:Gamma Building Ratios

Neutron-to-gamma (R_{BY}) ratios were determined for the plutonium-related buildings: Buildings 71, 76, 77, 91, and “All Others.” The neutron part of the ratio is based on NDRP doses from reread neutron film that were paired with gamma doses for the same monitoring period for the building and year. The identification of the building is obtained from the header information on both the neutron and gamma worksheets. Matches of both the building number and the monitoring period for both worksheets were required for the neutron and gamma doses to be considered a paired set and to be included in the determination of the building ratio. For the data set of paired doses, if the gamma dose for a paired set was zero, the gamma dose was set equal to 1 mrem.

The N:G building ratio for a calendar year, R_{BY} is given by

$$R_{BY} = \Sigma \text{ (Neutron doses from paired sets) } / \Sigma \text{ (Gamma doses from paired sets)}$$

for the given building and year (see Section 12.5). The N:G building ratios were determined starting in 1959. For the preceding years (1952–1958), the values for 1959 were used without modification, since no other information was available to justify modifying the values. For periods in the 1960s when few or no workers in a building were monitored for neutrons, the higher of the ratios of the prior or next year was assigned to the intermediate year(s). The ratios for the “All Others” building category were based on the entire set of paired neutron and gamma doses for that calendar year. For some monitoring periods, the workers assigned to Buildings 76, 77, and 78 were combined on a common worksheet. For workers on such worksheets, the notional doses were determined using the higher of the ratios for Buildings 76 and 77 for that year. Also, workers listed on worksheets labeled Building 78 were assigned a notional neutron dose based on the higher of the ratios for Buildings 76 and 77 for that year, since their exposure to neutrons would have been primarily from work in those buildings. The N:G building ratios used for determining notional neutron doses are presented in Table 11.1.

Table 11.1 Common Building Neutron-to-Gamma Ratios

Building	1952–1958(a)	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
71	1.4	1.4	2.8	1.7	2.2	2.3	3.1	1.2	0.6	0.7	1.3	1.5
76	0.6	0.6	0.6	0.6(b)	0.6(b)	0.6(b)	0.6(b)	0.4	0.3	0.4	0.9	2.1
77	1.3	1.3	1.6(b)	1.6(b)	1.6(b)	1.6	1.6	0.8	0.5	0.6	0.9	0.9
76,77,78(d)	1.3	1.3	1.6	1.6	1.6	1.6	1.6	0.8	0.5	0.6	0.9	2.1
91	3.6	3.6	6.8	7.4	10(c)	10(c)	10(c)	3.3	1.2	2.1(b)	2.1	7.3
All Others	1.2	1.2	1.8	1.8	2.3	2.3	3.0	0.9	0.5	0.6	1.2	1.5

(a) Extrapolated from ratio for 1959,

(b) Assigned from the higher of the ratios for the previous or next year with data,

(c) Upper bound value,

(d) Ratios for combined Building designation 76,77,78 or for Building 78 are assigned from the higher of the ratios for the year for Building 76 and Building 77.

Note: The N:G ratio is the ratio of the sum of the NDRP neutron doses divided by the sum of the gamma doses for paired sets of the NDRP neutron dose and the gamma dose of record for that monitoring period.

11.5 Notional Neutron Doses—1970

The year 1970 was very "ill-behaved," in many aspects that caused insurmountable problems to identify gaps and to apply the method to assign a notional neutron dose.

- Most of the neutron films were not archived.
- Many of those films that were archived were not packaged with labels indicating the dates of the monitoring period.
- Not all worksheets were archived.
- Header information, especially issue and return dates, was frequently missing on the neutron worksheets.
- Thermoluminescent dosimeters were implemented for gamma dosimetry.
- Gamma doses could not be consistently or accurately discerned from the data on the gamma TLD worksheets.
- Many plutonium workers, normally assigned to Buildings 776 and 777 that were gutted by the 1969 fire, were still displaced from their normal jobs.
- A strike occurred in the summer of 1970 that introduced a real gap in the neutron and gamma timelines for plutonium workers.

Therefore, the NDRP did not assess notional neutron doses for 1970.

12.0 Statistical Issues in the NDRP - Overview

This section provides an overview of the statistical issues related to the NDRP. The body of the section summarizes the statistical methodology used to estimate worker neutron exposure and to provide approximate error bounds on that exposure. This section also outlines the justifications for the choices made in the selection of statistical methodology. Details of the methodology and the data analyses that support the methodological choices are provided in four appendices: Appendix I, "Statistical Methods Review," dated October 31, 2003, describes the overall plan as it was presented to the Advisory Committee on November 12, 2003; Appendix II, "Reader Modification Factor (RMF) Calculation Documentation," dated March 30, 2004, describes the details of the estimation of the reader modification factors that were used to adjust the neutron film reads for systematic reader overestimation or underestimation; Appendix III, "Neutron Dose Variance Modifications," dated September 15, 2004, describes modifications to the originally proposed neutron variance model; Appendix IV, "Notional Dose Methodology," dated September 19, 2004, describes the methodology for estimation of the "notional" neutron doses (i.e., estimates of the neutron dose received during gap periods for which no neutron film exists). The notation of the mathematical models developed in the appendices has been retained in this section. The connections between the notation used in the mathematical models and the application of the models to the NDRP calculations have been indicated where needed.

The estimated neutron dose for a worker is the sum of two parts: (1) the estimated dose based on neutron film reads and (2) the notional dose, estimated dose for gap periods for which gamma doses but not neutron films are available. Neutron film reads were initially adjusted to account for read area and a calibration factor for each reader. A further modification to the film reads was made to adjust for the long-term tendencies of readers to read too high or too low. These reader modification factors and their variances were estimated using the database of multiple read films and the statistical method, Restricted Maximum Likelihood (REML). Since films with higher doses contribute more to the total dose estimate, they also contribute more to the variance of the dose estimate. To reduce this variance, a program was carried out to assure that films with higher reads received at least one and in many cases two, three, or four additional reads. The estimated dose for each film was the average of those reads. The variance of the neutron dose estimate was approximated using standard statistical methodology that combined the estimated variability of the film reads with the additional variability due to the estimation of the reader modification factors. It is believed that the neutron dose estimates and variances computed this way are on solid scientific and statistical ground.

The notional doses were calculated as a weighted average of two estimates. The formulas for this calculation are given in Section 11.3. The first estimate was based on the worker's average neutron dose for the non-gap periods in a year. The second estimate was formed by multiplying the worker's gamma dose for the gap period by the building average neutron-to-gamma ratio. The notional dose weighted the two estimates according to the ratio of non-gap days to the sum of gap and non-gap days for the worker in that year. Thus, a worker who had neutron reads available for 80% of the year and a gap for

20% of the year would receive a notional dose estimate for the gap period that was 80% derived from his/her neutron read average and 20% derived from his/her gamma value. A worker who had no neutron film in a year would receive a notional dose estimate for the year based entirely on his/her gamma value. The variance estimate for all notional doses was computed as if the entire notional dose had been obtained from the neutron-to-gamma ratios. The notional dose estimates should be considered somewhat speculative, and their variance estimates should be considered quite approximate. However, the actual precision of the estimates is thought to be generally better than the claimed precision, particularly for individuals for whom the notional dose estimate is derived primarily from the neutron average.

12.1 Protocol for Multiple Reads of Neutron Films

Initial QC protocol required an automatic second read of all films having an initial normalized read greater than 200, as well as an automatic second read on a random selection of films having an initial read of 50–200. When the second read was discrepant with the first (as determined by an algorithm based on the greater of Poisson variation and percentage disagreement), a third read was performed. When the third read was discrepant with the first two, a fourth read was done, and so on. Since the largest contribution to estimated total dose comes from the films with the highest true dose, this strategy of requiring multiple reads on the films with high initial reads is highly beneficial in that it reduces the variance of the final estimate of the true dose.

Taking a second read, when the first read exceeds a threshold, induces a negative bias into the combined estimate, because unusually high values will be averaged with a second read, but unusually low values will stand as the only read. This bias was investigated (see Section 1.3 of Appendix I) and estimated to be less than 4%, a small bias relative to other sources of error in the process. Therefore, this bias was ignored.

After review, the initial QC protocol for multiple reads of neutron films was expanded. Since the final estimate of an individual worker's total dose is dominated by the larger reads, the variation in an individual's total dose can be most efficiently reduced by increasing the number of reads on films with high values. By the deadline for production reads, October 31, 2003, at least a second read had been obtained on all films having initial read greater than 120. Additionally, third reads were obtained on all films with an average of the first two reads greater than 250. Approximately 14,500 films (out of the total of approximately 90,000 films) now have multiple reads. The distribution of the number of reads per film (when greater than one) is given in Table 12.1.

Table 12.1 Multiple Reads of Neutron Films

Number Reads	Frequency	Percent
2	10,169	70.00
3	3,553	24.46
4	632	4.35
5	87	0.60
6	20	0.14
7	6	0.04
8	48	0.33
9	12	0.08
12	1	0.01

12.2 Recalibration Methods: The RMF

It became apparent that, over time and under time pressure, the normalized reads tended to be generally lower than would be obtained by best practice. It was observed that reads by some individuals over some time periods appeared to be on average lower or higher than reads by other individuals. The amount by which reads tend to be lower (or higher) depended on the particular reader and the stage of that particular reader's training and production experience.

The tendency for individual readers to read low or high was investigated in a round-robin study, April–June, 2002, for which 60 films were reread by seven readers, including the senior technical staff member. It was found that initial reads (prior to the study) were typically about 30% lower than reads during the study and about 45% lower than a very careful read by the senior technical staff member (taking about twice as much time per read). Subsequent retraining of the readers, followed by a benchmark study in which a balanced 5% of films were reread, indicated that retrained readers raised the average value of their reads by values up to 60%. These results led to the proposed additional adjustment, a reader modification factor (RMF) which adjusted the work of all readers to a standard read based on what is best practice and without time pressure. That best read was done by the senior technical staff member.

12.2.1 Statistical Justification of the RMF

The REML estimates of some RMF values, along with their estimated standard errors and correlations, were computed from the round robin study using the "mixed" procedure in the statistical package SAS. A mixed model was fit to the logarithms of the data. The model used could be described as an "incomplete block" model, where film is the block on which various readers are compared. Using the notation of Appendix I, the log, base 10, of the normalized read (T_{norm}, Section 10.0, Equation 2) for the k^{th} read of the i^{th} film by the j^{th} reader was modeled as follows:

$$Y_{ijk} = M + F_i + R_j + e_{ijk}. \qquad (6)$$

The effects in the model are (in order): a fixed overall mean, a random effect for the film *i*, a fixed effect for reader *j*, and a random error. We assume that (in the $\log_{10}$ scale) the random film effects are approximately normally distributed and the random errors are approximately normally distributed, independent of the film effects. The fixed effects are relative to an authoritative read by the senior technical staff member, whose reader effect during that time period was fixed at zero: $R_{23} = 0$. Additive reader effects in the log scale can be converted to multiplicative reader effects by exponentiation (base 10). The multiplicative effect for authoritative reads is $10^0 = 1$. The multiplicative effects for the other readers are 10^{R_j}.

The RMF factor for each reader is calculated as 10^{-R_j}. Multiplication of each normalized read by the appropriate reader RMF factor cancels the reader's multiplicative effect, thereby standardizing each read to as if it had been read by the senior technical staff member. An approximate covariance matrix for the reader effects, R_j, is obtainable from the standard mixed model formulas. Using a statistical approximation technique called the "delta method," which approximates the exponential function locally by a linear equation, an approximate covariance matrix for the RMF factors can be obtained. The details and results of this analysis are described in Appendix I, Section 2.2. These results establish the potential benefit of such RMF adjustments.

A similar model was fit to the benchmark study data to compare the reads after retraining to the initial reads of the same films. Separate fixed reader effects were estimated for before and after retraining. The data set was too large (about 4,000 films) to allow fitting of the mixed model using SAS Proc Mixed or any other standard mixed model program. Therefore, the model was simplified by omitting the random film effects and fit as a model with just fixed effects. The results of this model are reported in Appendix I, Section 2.3. Although the simplification to the model makes the analysis more approximate than desired, the results generally confirm the benefit of RMF adjustments to the normalized film reads.

Because the round robin study and the benchmark study both supported the benefit of RMF adjustment, a decision was made by the NDRP to proceed with estimation of RMF values and to use these estimates in the subsequent calculations. Since the adjustment are generally upward, the procedure could be termed "worker favorable" in that it is likely to result in a higher estimated neutron dose that would be estimated without such adjustments.

12.2.2 Data Preparation for Estimation of the RMF Values

The computation of the final RMF values and their standard errors is the subject of the document titled "RMF Calculation Documentation," dated March 30, 2004, included as Appendix II. The details of the procedure, along with explicit formulas for the relevant quantities are given there. The stages in the estimation of the final RMF values are described below.

The data set used was the "multiple reads" data set provided to Dr. Chapman, and dated January 9, 2004. This file contained reads of all films that were read two or more times. There were 34,626 reads in the data set, representing approximately 11,000 unique film IDs. All reads were normalized to a standard calibration factor (*CF*) = 30 and read area (*A*) = 10. The most important addition was a set of approximately 220 rereads by the senior technical staff member. These reads were distributed with respect to the other readers, so that there would be a basis for comparison of all readers to these reads by the senior technical staff member, who was treated as authoritative for the purpose of these adjustments. The maximum number of reads on a film was 12.

Time points that represent major changes or retraining events in the history of each reader were identified by the senior technical staff member, based on personal knowledge of the major events in the history of the film reading process. These time points were used to divide the history of each reading into periods for which separate RMF values were estimated (one to three time periods per reader). These time periods for those readers with more than one time period are given in Table 12.2. All other readers had only one period from start to end of their film reading. The authoritative reads by the senior technical staff member are labeled RBF2.

Table 12.2 Reader Time Periods for RMF Estimation

Period 1	Period 2	Period 3
MJD (start–08Jul98)	MJD1 (09Jul98–end)	
IMH (start–02Jul02)	IMH1 (03Jul02–01Sep)	IMH2 (02Sep02–end)
GPW (start–08Jul02)	GPW1 (09Jul02–01Sep02)	GPW2 (02Sep02–end)
BRH (start–16Jul02)	BRH1 (17Jul02–end)	
BAH (start–29Aug02)	BAH1(30Aug02–end)	
DLH (start–01Jan03)	DLH1 (02Jan03–end)	
RBF (start–01Jan96)	RBF1 (02Jan96–01Oct03)	RBF2 (02Oct03–end)

12.2.3 Statistical Programming

The model used for the round robin analysis was also used on the larger "multiple reads" data set to estimate an RMF value for each reader during each period. Due to the size of the data set, the computations could not be done using SAS Proc Mixed, because the estimation procedure involves inverting the approximately 32,000 by 32,000 covariance matrix of the data. SAS Proc Mixed and other mixed model programs attempt to invert this matrix without taking advantage of its special block-diagonal structure and do not run on desktop PCs with normally available amounts of memory. Other special purpose programs exist, primarily on UNIX/LINUX systems, which could have been adapted to the task; however, using these programs would involve a substantial amount of time for installation, testing and learning how to use the program. It was decided that the most efficient path was to program the restricted likelihood function using SAS Proc IML (Interactive Matrix Language). The restricted likelihood function is a relatively straightforward formula. The restricted likelihood and other associated formulas are given in Appendix II. The SAS Proc IML program took advantage of the block-diagonal structure of the covariance matrix. By inverting this matrix in many small pieces, the IML program could run easily on a standard desktop PC with 1GB RAM. The accuracy of the likelihood function was checked using small and moderate size data sets by comparing results of the IML program to results from SAS Proc Mixed.

The program did not include an automated maximization routine. Rather, for a given data set and a fixed set of covariance parameters [film variance, Var(F_i); error variance, Var(e_{ijk})], the program calculated the restricted maximum likelihood value. The program was used to produce a contour map of restricted maximum likelihood values over a grid of covariance parameter values. A small subregion was selected based on the contour map, and the program was rerun over a finer grid representing the subregion. The process was repeated until a close approximation to the maximum was identified.

12.2.4 Modifications to Reduce the Influence of Low Reads on RMF Estimates

Several modifications to the estimation procedure were considered before RMF values and covariance estimates were finalized. These modifications were in response to the perception that RMF estimates were unduly influenced by variation in the low reads. For example, a read of 10 versus a read of 2 on the same film would have little impact on the final dose estimate for an individual, because both numbers are very low. However, a read of 10 versus 2 on the same film would have a very large impact on the RMF estimates for the two readers, because the first number is five times larger than the second number. These effects are the natural result of RMF estimation based on logarithms. The objective of the modification was to decrease the influence of the small numbers on the RMF estimates. Some of the potential modifications that were considered are listed below. A more detailed discussion of the methods and their relative merits is given in Appendix II.

1. Addition of a small constant to all data points prior to computing logarithms
2. Removal of reads with values less than a fixed constant
3. Use of a combination of RMF values from method 2. In this approach, RMF values for each reader were selected from the method 2 analysis in which approximately 90% of the reads for that reader were retained.
4. Removal of a fixed percentage (e.g., 10 %) of the lowest reads for each reader

The final selection of method 4 was a collaborative decision by the NDRP staff and Dr. Chapman. The effect of all three modifications was to reduce the size of the RMF estimates relative to the estimates computed on the full Multiple Reads data set. Method 4 was selected because it was what appeared to be a reasonable compromise between methods 2 and 3. It incorporated the feature of letting the cutoff value for removal vary by reader and also included the estimated covariance matrix calculation that was part of each REML model fit.

12.2.5 Final RMF Estimates

The final estimates are given in Table 12.3. The readers are in alphabetical order, with the exception of SKB, which has been above RBF, RBF1, and RBF2 so that the RBF estimates would be last. All RMF values are relative to RBF2, which has an estimate of 0.0 and RMF 1.0. Note that the standard errors of the RMF values are generally small compared to the amount by which the RMF estimate differs from 1.0. This supports the need for these RMF adjustments, because it indicates that in this data set some readers are clearly reading at higher or lower levels than RBF2. Also note that the cutoff for reads (the lowest number of tracks for a read used for that reader) varies substantially by reader, which supports the choice to remove the lowest 10%, by reader, rather than 10% overall. The number of reads used for each person is also given. The total number of reads is 30,011. This total is slightly lower than 90% of the original data set, because removal of individual reads left some reads as singletons, which then had to be removed. The estimated covariance of the RMF values is not presented here.

Table 12.3 Final RMF Estimates, Standard Errors, and Cutoff Values

Reader	RMF value	Standard error of RMF	Cutoff for reads	Number of reads	Percent of total reads
ADA	0.671	0.019	27.3	1004	3.4
AZA	0.788	0.022	24.3	1149	3.8
BAH	1.282	0.035	10.9	2030	6.8
BAH1	0.910	0.024	18.1	1975	6.6
BES	0.943	0.026	15.3	1452	4.8
BRH	1.195	0.034	11.8	1040	3.5
BRH1	0.815	0.022	18.4	1783	5.9
CEA	1.227	0.035	11.9	911	3.0
CLF	1.050	0.031	18.7	657	2.2
DLH	1.162	0.048	19.8	134	0.5
DLH1	1.202	0.044	16.3	179	0.6
GPW	1.225	0.032	12.3	4034	13.4
GPW1	1.279	0.043	11.5	322	1.1
GPW2	1.117	0.029	15.0	3032	10.1
IMH	1.167	0.031	13.0	4408	14.7
IMH1	1.605	0.055	7.7	282	0.9
IMH2	1.289	0.036	11.9	1029	3.4
JSB	0.553	0.024	22.3	109	0.4
KR	1.069	0.032	15.1	516	1.7
MBR	0.690	0.021	29.9	497	1.7
MJD	0.673	0.022	32.9	341	1.1
MJD1	1.119	0.032	18.5	977	3.3
SKB	1.450	0.040	12.0	1402	4.7
RBF	1.048	0.035	26.8	308	1.0
RBF1	0.828	0.028	22.2	252	0.8
RBF2	1.000	0.000	16.7	188	0.6

12.3 Combining Multiple Neutron Film Reads into a Single Estimate

When there is a single read, that single normalized read as adjusted by the appropriate RMF value, is used as the neutron estimate for that worker during that time period. However, when there are multiple reads, a method is needed to compute the combined estimate from the multiple values. The initial plan for combining multiple estimates is given in the "Work Guidance Document," which described a set of rules by which a best read would be selected. The result of these rules dictated that one of the multiple reads would be selected as the best read. That read may have been the initial read if confirmed by the second read or a middle value out of three or more.

The method described in the "Work Guidance Document" has been replaced with a simple average of available reads (as adjusted by the appropriate RMF value). No formal tests for outliers were employed, and *all* reads were used.

Statistical principles imply that, when the distribution is normal, the variance of the average is smaller than the variance of individual values, even if the individual value is the median. In contrast, when a distribution has heavy tails or is right skewed (e.g. the Poisson distribution), the median has smaller variance than the mean. Investigation of the residuals from the round robin study, reported in Appendix I, indicates that the distribution of the residuals is somewhat right skewed but not unusually heavy tailed. From this, one might conclude that the median of a group of reads from the same film might have slightly smaller variance than the mean of the reads. However, the advantage of a slightly smaller variance must be weighed against the negative bias involved in using the sample median to estimate a population mean. Right skewed distributions have the property that the mean exceeds the median; therefore, the sample median tends to be on average an underestimate of the mean (i.e. negative bias). Since a worker's neutron dose is the sum of many, many films, it was decided that avoidance of bias in each individual film estimate was the primary concern. Therefore, the mean was selected over the median, despite its potential for slightly larger variance.

12.4 Uncertainty Assessment of the Neutron Dose Estimate

12.4.1 Selection of the "Over-dispersion" Model

The uncertainty of the total estimated neutron dose was calculated using standard statistical methods. The basic model and formulas were presented in Section 5 of Appendix I. These formulas assumed that the distribution of individual film reads (before normalization) involved a relationship between the mean and variance that was "over-dispersed" Poisson; that is, the variance was a constant multiple of the mean. For a standard Poisson that multiplier would be 1.

After the individual film reads were modified using the RMF values, the value of the over-dispersion constant was estimated as $k = 4.1$ by a process described in Section 2 of Appendix III. In the estimation process it was discovered that the over-dispersion was better described by a model in which the over-dispersion increases with the size of the read, rather than the initial method, which was based on the assumption of constant over-dispersion.

With the mathematical notation of Appendices I and III for a worker with *n* neutron films, let *N* be the total number of reads on those films ($N = n$). Let $F_i, i = 1,2,...N$ be the normalized track values for read *i*. Note that the symbol F_i is here and in Appendices I and III is the normalized read (called T_{norm} in Section 10.0), not the film effect defined in Section 12.2.1, Equation 6. The new assumed model is

$$Var(F_i) = A_i^{0.5} k f_i^{\,p}, \tag{7}$$

where A_i is the multiplier used to normalize the raw track count ($A_i = CF/30 \text{ x } 10/A$ of Section 10.0), and f_i is the expected value of F_i. Since the value of A_i is near 1.0 and the square root of A_i is even nearer to 1.0, that term was omitted, simplifying the model to

$$Var(F_i) = k f_i^{\,p}. \tag{8}$$

Note that the old model is a special case of the new model, obtained by setting $p = 1.0$. Section 3 of Appendix III describes the process by which the parameters of the new model were estimated as $p = 1.5$ and $k = 0.62$. A graphical comparison of the two models displays how the new model ascribes relatively higher variance to the higher reads, compared to what would be expected of a Poisson distribution.

The new model also seems to be more consistent with informal inspection of the data. For the initial model, the exponent in the over-dispersion model is 1.0, and the standard deviation as a proportion of the mean [i.e., the coefficient of variation (CV)] becomes smaller as the mean increases. For lognormal data, the exponent in the over-dispersion model is approximately 2.0, and the coefficient of variation is approximately constant as the mean increases. Estimation of the exponent *p* as 1.5 places our model about halfway between the over-dispersed Poisson and lognormal models. This result is consistent with the observation that multiple reads on films with high values have variance that is much larger than Poisson variance but not as large as lognormal variance. It appears that the NDRP data lies somewhere between lognormal and Poisson.

The new choice of over-dispersion model could also be described as “worker favorable,” in that a larger estimated variance will increase the upper limit of the confidence bound for individuals with high values.

12.4.2 Description of the Variance Formulas

The formulas estimating the variance of yearly or the sum of yearly doses are developed in Appendix I and modified to accommodate the new over-dispersion model in Appendix III. Let W_i be the weighting applied to the read *i*. Most of the W_i will take the value 1.0, indicating a film that was read once and indicating that the single read is taken as the estimate for that film. However, W_i may be different from 1.0 if an average of multiple reads on the same film is to be used. For example, if i = 2, 3, 4 are multiple reads of the same film, then $W_2 = \frac{1}{3}$, $W_3 = \frac{1}{3}$, $W_4 = \frac{1}{3}$. The W_i values would also incorporate any other fixed multiplicative adjustments. Let M_i be the RMF of the reader that read film i during the time period of the read, and let $\hat{v}_{ij}$ be the estimated covariance between M_i and M_j. Because there are only 26 distinct reader/period combinations, many of the M_i and $\hat{v}_{ij}$ will be repeated in the record of a worker who has many films and multiple reads by the same reader. The estimation of the M_i and $\hat{v}_{ij}$ values is described in Appendix II.

Given the above definitions, the estimated total dose derived from the neutron counts is

$$D = \sum_{i=1}^{N} \left(M_i W_i F_i \right). \qquad (9)$$

An estimator of the variance of D, based on the initial over-dispersion model, is calculated in Section 5 of Appendix I. A revised estimator, based on the new over-dispersion model, is calculated in Section 3 of Appendix III and given below.

$$\hat{V}(D) = \sum_{i=1}^{N} W_i^2 (M_i^2 - \hat{v}_{ii}) A_i^{0.5} k F_i^{1.5} + \sum_{i=1}^{N} \sum_{j=1}^{N} F_i F_j W_i W_j \hat{v}_{ij} \qquad (10)$$

The new formula and the old formula are quite analogous. The only important difference is the power 1.5 on the F_i in the first term. In the original formula the power was 1.0 and the variance estimate was close to unbiased. In the new formula, the use of $F_i^{1.5}$ to estimate the mean of F_i to the 1.5 power involves a positive bias. The size of the positive bias was examined in Section 5 of Appendix III and determined to be relatively small. As previously described, a positive bias in the variance estimate is worker favorable.

The estimation and variance formulas were communicated to the NDRP programmer, who programmed them within the ORISE database. Dr. Chapman wrote SAS Proc IML programs to compute the same estimation and variance formulas. The results of the NDRP's program and Dr. Chapman's program were compared using the data of two different individuals in the database over several different time periods. The two sets of computations agreed to within round-off error.

12.5 Notional Dose Estimates for Missing Periods

The neutron dose methodology, described in Appendices I, II, and III, applies to the estimation of the neutron dose during periods for which neutron films exist. This section describes the estimation of neutron dose during “gaps” for which a neutron dose value does *not* exist but a gamma dose value *does* exist. The notional dose estimates are based on two methodologies: (1) averages of the worker neutron film reads from non-gap periods within the gap year and (2) the neutron-to-gamma ratio for the building/year multiplied by the worker gamma dose during the gap period. Because estimation of neutron doses for gap periods is somewhat speculative, we use the term “notional dose” to distinguish the estimates for gap periods from the estimates for non-gap periods, which are based directly on reread neutron films and have a very solid justification.

12.5.1 The Neutron-to-Gamma Dose Regression Model

We first consider the mathematical model that underlies the neutron-to-gamma methodology. We take a “predictive approach” (which involves a regression of neutron dose on gamma dose) to the estimation of the neutron dose, as opposed to a “calibration approach” (which would involve a regression of gamma dose on neutron dose).

Let *i* refer the i^{th} neutron:gamma pair available for a particular building, year combination. Assume *i* = 1,…, n, where n is the number of pairs. Let N_i be the *true* neutron dose for observation *i.*

Assume that N_i is related to the measured gamma dose, g_i, by the regression equation

$$N_i = bg_i + e_i, \tag{11}$$

where, for fixed g_i, $E(e_i) = 0$ and $Var(e_i) = s^2 g_i$.

The *true neutron value,* N_i, is not observable. In its place the measured neutron dose, Y_i, is recorded. Assume that Y_i has been adjusted with the relevant calibration factor and RMF and that after such adjustment a Poisson, or over-dispersed Poisson, model is appropriate. Assume

$$Y_i = N_i + f_i, \tag{12}$$

where, given N_i, $E(f_i) = 0$ and $Var(f_i) = kN_i$. Putting the models for Y_i and N_i together, we obtain

$$Y_i = bg_i + e_i + f_i. \tag{13}$$

Using this model the weighted least squares estimate of the regression slope is the neutron-to-gamma ratio:

$$\hat{b} = \frac{\sum_{i=1}^{n} Y_i}{\sum_{i=1}^{n} g_i} . \tag{14}$$

A gap period with total gamma dose equal to *G* has predicted neutron dose $G\hat{b}$ with estimated expected mean square prediction error (*MSPE*):

$$MSPE = \hat{s}^2 G + G^2 \frac{\hat{t}^2}{\sum_{i=1}^{n} g_i} , \tag{15}$$

where $\hat{t}^2 = \frac{1}{n-1} \sum_{i=1}^{n} \frac{\left(Y_i - \hat{b} g_i\right)^2}{g_i}$ and $\hat{s}^2 = \hat{t}^2 - k\hat{b}$ are variances estimated from the data.

12.5.2 Simulation Studies to Select Notional Dose Methodology

The notional dose methodology was developed using a “matched pairs” data set in which neutron film dose values were paired with gamma dose values for the same periods. The data set contained approximately 76,000 records. For some analyses neutron and gamma readings are summed by year, yielding one gamma/neutron pair for each individual in each building in each year (approximately 8,700 records).

Two types of simulation studies were run. Details of these studies are reported in Sections I and II of Appendix IV. In the first type of study, prediction of neutron doses for the current year is based on neutron reads from the same building in the previous year. The idea of the study was to mimic the process of estimating annual neutron dose when there is no neutron data from the same year available. In such cases any neutron estimates and neutron-to-gamma ratios would have to come from neighboring years, but gamma information would be available for the current year. In the second type of study, prediction of neutron doses for individual badges was based on data from the same building in the same year. In this type of study the idea was to mimic the situation in which small gaps are being filled in using the most contemporary data. Each study was run with a variety of modifications and adjustments.

The results of the first type of study are reported in Section 1 of Appendix IV. The study clearly indicates that the method with the smallest average absolute error was the “basic” method, in which the neutron dose for an individual is estimated by the neutron dose from the same individual from the previous year, adjusted to the number of days of monitoring. The method with the largest average absolute error is the "individual" method, in which the worker's individual neutron-to-gamma ratio (N:G) from the previous year is used together with the neutron dose for the current year to estimate the neutron dose for the current year. It is clear that individual N:G ratios are far too erratic to use. The performance of the individual ratios improves when the individual ratios are bounded or combined with the common building ratio.

This analysis supports the idea of using an individual's own observed neutron information to estimate neutron dose for missing periods whenever that is possible. There are, however, several factors that constrain the ability to use neutron values in this way. This analysis was performed on Buildings 71, 76, and 77 and only for years in which those buildings were consistently monitored. Also, the analysis was only performed on individuals who worked in the building for both years under consideration. A substantial portion of the missing observations, for which estimates are needed, would not have such neutron data available.

The results of the second type of study, reported in Section 2 of Appendix IV, indicate that the method with the smallest average absolute errors is the method that estimates the individual badge neutron value using the average of the other neutron badge values from the same individual in the same year. The methods that use the N:G ratio did not perform as well, comparatively. The building average N:G ratio works better than the individual N:G ratios, although the performance of the latter improves when the individual ratios are bounded. The method that mixes the building N:G and the individual N:G ratios also shows promise.

The gamma readings in the data set had been adjusted for estimates of the background gamma radiation. The neutron readings in the data set were not so adjusted. As a result of the gamma background adjustment, many individual badges estimate gamma levels of zero. The zeros in the database were replaced with the value 1. The large numbers of very small gamma values inflated the building ratio and led to erratic estimates.

The work of Stanfield (1998) suggested that the variances for estimators based on the N:G ratios would be very high. In Appendix I we speculated that our variances may be proportionally smaller than Stanfield's for two reasons: (1) neutron doses used in the estimation process would be adjusted for reader modification factors and (2) we estimate the variance of the error for prediction of the *true* neutron dose; Stanfield estimated the variance of the error for prediction of the *measured* neutron dose, which is larger. Our studies suggest that the anticipated improvements are minimal.

12.5.3 Selection of the Notional Dose Estimator

The primary conclusion from the data analysis is that for a short gap in the neutron film record the best single estimate of a neutron dose is the average daily neutron dose recorded during the non-gap periods for the worker in the same year. However, for large gaps, comprising a large portion of the year, this method carries substantial risk because the non-gap periods are short and contain relatively few neutron badges and short non-gap periods are likely to be concentrated in a single portion of the year, which may not be representative of the whole year. Due to these risks it was decided not to base the entire notional neutron dose estimate for gap periods on the reread neutrons films. It was decided that the notional neutron dose estimate should be based on a combination of neutron badge values and estimates from N:G ratios.

Estimates based on N:G ratios were generally more accurate when the common building N:G ratio was used rather than individual worker N:G ratios. Some combinations of common and individual ratios were considered; however, these were rejected as too complicated and not consistently better than the common ratio by itself. In the data analysis the individual N:G ratios were highly variable. This variability was aggravated by the adjustment for background, which left many gamma dose values at or near zero and the ratio very large. The modification of stabilizing the gamma values by adding a small constant was considered but was not adopted primarily because it had the property of reducing the highest estimates to values closer to the average. A discussion of this decision is given in Section 4 of Appendix IV. The estimation of individual N:G ratios was improved by bounding the ratio estimate to what were considered by NDRP personnel to be reasonable values. There was no formal analysis investigating which level of bounding would produce the best results. However, bounding was only an issue for three years in Building 91 for which bounds of ten were fixed.

Building N:G ratios were estimated using aggregation methods suggested by the NDRP senior technical staff member, based on knowledge of building process history. Individual estimates were made for Buildings 71, 76, 77, and 91. Years for which no matched N:G pairs were available were extrapolated from neighboring years. Data to estimate N:G ratios for all other buildings were believed insufficient for separate estimation. The N:G ratios for all other buildings were based on the entire paired set, based on the consideration that neutron exposures for workers in secondary and support buildings would most likely result from projects or activities in the major plutonium production buildings. The N:G building ratios are given in Table 11.4.1 of Section 11.4.

The method chosen for the notional dose is a weighted average between an estimate based on the reread neutron films and an estimate based on the N:G ratio. The two estimates are weighted according to the number of days for which neutron films are present relative to the total number of days for which neutron films are present plus the number of days in the gap.

When the gap is small, the notional dose is determined primarily by the reread film values from the same year. When the gap is large, the notional dose is determined primarily by the N:G ratio and the gamma values in the gap periods. Although the idea of the method is reasonable, the choice of proportional weights was somewhat arbitrary. No attempt was made to identify the optimal combination of weights. The equation to implement the method is Equation 5 in section 11.3, reproduced below:

$$N_{NOT} = [T_{N1}/(T_{N1} + T_{gap})] \times N_{NOT1} + [T_{gap}/(T_{N1} + T_{gap})] \times N_{NOT2}$$

Note that the weighting formula defaults to an estimate based entirely on the N:G ratio for building/year combinations in which there were no neutron badge readings ($T_{N1} = 0$). An argument can be made based on the first data analysis, where the neutron dose from an individual in one year was used to estimate the neutron dose for the same individual in the following year, that neutron dose estimates from neighboring years might be a better estimate than the estimate based on the N:G ratios. Although this argument may have some validity, there was a strong preference for basing the notional dose estimates on some measurement (i.e., the gamma value) taken directly during the year in question. The notional dose estimation process sometimes involved estimating neutron doses several years removed from actual neutron readings. It was believed that the N:G ratio would be more stable over a longer period of time than the neutron value. Another reason for using the chosen method was that it did not require making separate subjective adjustments for the many individual worker situations that arise. The method chosen was a fixed rule that can be applied automatically.

12.6 Uncertainty Assessment for the Notional Dose Estimate

In principle, a variance estimate for this weighted sum could be obtained by summing variance estimates for the two individual terms. Summing would be justified because the gamma doses obtained during the gap periods could reasonably be argued as being independent of the reread neutron films obtained during the non-gap periods. A variance estimation method for the right-hand term has already been derived and presented in Section 12.5.1. A variance estimator for the other term is more problematic. If the gap periods were missing at random, a variance estimator could be developed using individual badge simulations much like the ones used in Section 2 of Appendix IV. Such estimates would have to be adjusted for a variety of situations involving the number and configuration of gap periods within the year and also the level of dose values for the non-gap periods. (Individuals at high dose levels would be expected to have larger variances than individuals at lower doses.) The result of such an effort would be complicated and speculative.

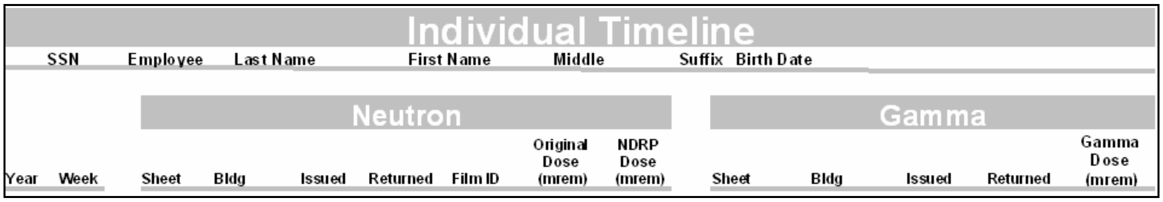
It was decided that the variance estimation method derived for the N:G portion of the estimate would be used and that this method would be applied to the entire estimate as if the weight of the last term in the variance equation (W_G) were 1.0. This decision could be viewed as conservative, because the variance of the portion of the notional dose that was based on reread neutron films has been demonstrated to have lower variance than the portion estimate using the N:G ratios. Therefore, it is likely that the true variance of the estimate would be lower than the estimate based solely on the N:G ratio methodology. This decision also could be viewed as worker favorable, because an overestimate of the variance widens confidence intervals and leads to higher upper confidence limits. An upper confidence limit may be interpreted informally as an upper limit on where the individual's true neutron dose during the gap period is likely to lie. Higher upper confidence limits support the possibility of higher levels of true exposure.

13.0 Application

This section describes the application of the neutron dose assessment and uncertainty methods to reports of the data for a worker. Three types of reports are addressed: individual timeline, neutron dose detail, and neutron dose summary. Also addressed is a variation of the neutron dose summary report, which is the neutron dose summary plus reconstructed gamma dose report.

13.1 Individual Timeline

The Individual Timeline is a report that displays the neutron and gamma monitored data by calendar year and monitoring period found in or derived from the dosimetry worksheets for the worker for 1952–1970. Also presented are the NDRP matched films and the NDRP neutron doses from reread films and notional doses for gaps. Figure 13.1 displays the header and data fields for the individual timeline report.



Individual Timeline

SSN	Employee	Last Name	First Name	Middle	Suffix	Birth Date

		Neutron							Gamma				
Year	Week	Sheet	Bldg	Issued	Returned	Film ID	Original Dose (mrem)	NDRP Dose (mrem)	Sheet	Bldg	Issued	Returned	Gamma Dose (mrem)

Figure 13.1 Individual Timeline Header and Data Fields

The header fields are

- SSN—The social security number of the worker.

- Employee—The four-digit employee number or an alphanumeric sequence for non-employees as found on the dosimetry worksheet(s).

- Last Name, First Name, Middle, Suffix—Fields for the worker’s name. The suffix refers to designations such as Jr., Sr., and II.

- Birth Date—The date of birth of the worker, based on records available to the NDRP.

- Data fields—The data fields are divided into two sections, neutron data and gamma data, which are organized by calendar year and week in the year. If no neutron and gamma data are found for a plutonium-related building for a given year, a report for that year is not generated. Blanks in any data field indicate that no information for that field was found.

- Year—The calendar year of the monitoring period, based on the issue date (i.e., the start of the monitoring period).

- Week—The week in the year, based on the returned date (i.e., the end of the monitoring period).

Sheet—The NDRP inventory number of the dosimetry worksheet (see Section 4.3). (Note: The word "gap" may appear in this column. This condition occurred when a discontinuity in the neutron monitoring timeline was identified that was filled by a notional neutron dose.)

- Building—The number of the building noted on the worksheet, or for the set of worksheets, on which the worker's neutron or gamma dosimetry data were recorded. Some worksheets had more than one building recorded.

- Issued—The date the dosimeter was issued, either recorded on the worksheet or inferred from supplemental information. This date is the start date of the monitoring period. For a gap, the date is the start of the gap.

- Returned—The date the dosimeter was returned, either recorded on the worksheet or inferred from supplemental information. This date is the end date of the monitoring period. For a gap, the date is the end of the gap. (Note: Frequently, the issue and returned dates of associated neutron and gamma worksheets overlapped by one or several days. Some editing was performed to correct discrepancies of two days or less between the issue and returned dates for associated neutron and gamma worksheets.)

- Sheet, Building, Issued, and Returned—Apply to both neutron and gamma worksheet information.

- Film ID—The unique identification number of the neutron film or glass plate that was matched to the worksheet entry for the worker. A blank in this field indicates that no film or plate was matched to this worksheet. (See Section 6.0 for a discussion of the unique identification number and see Section 7.0 for a discussion of the matching process.)

- Original Dose (mrem)—The original neutron dose (mrem) recorded on the neutron worksheet or, for glass plates, calculated from the value of % tolerance. All neutron doses were based on a nominal quality factor of 10. A blank in this field indicates that no neutron dose value was found on the worksheet entry for the worker. (Note: For glass plates, the neutron dose was obtained by multiplying the reported % tolerance by 12. 100% tolerance was 300 mrem/week or 1200 mrem/4 weeks. A monitoring period of 4 weeks was assumed.)

- NDRP Dose (mrem)—The neutron dose (mrem) obtained by the NDRP for reread films or plates (see Section 10.0) or a notional neutron dose calculated for a gap (see Section 11.0). A blank in this field when there is a unique NDRP film number in the "Film" column indicates either that the film was not readable or that the NDRP film result was invalidated. Invalidation resulted as a result of notations on the worksheet that indicated that the film was contaminated by nonoccupational exposure to neutrons or that the film was involved in a special study while the worker was being monitored by the normal neutron dosimeter.

- Gamma Dose (mrem)—The whole body penetrating X-ray and gamma dose (mrem) derived from information on the gamma worksheet (see Section 11.2). An asterisk after the value of the gamma dose indicates that the dose was calculated by multiplying the wrist dose for the monitoring period by 0.4. A blank in this field indicates that no data were available from which to calculate the gamma dose.

The equation used to calculate the notional neutron dose is printed on the line below the information for the gap. The equation is an implementation of Equation 5 in Section11.3 and has the form

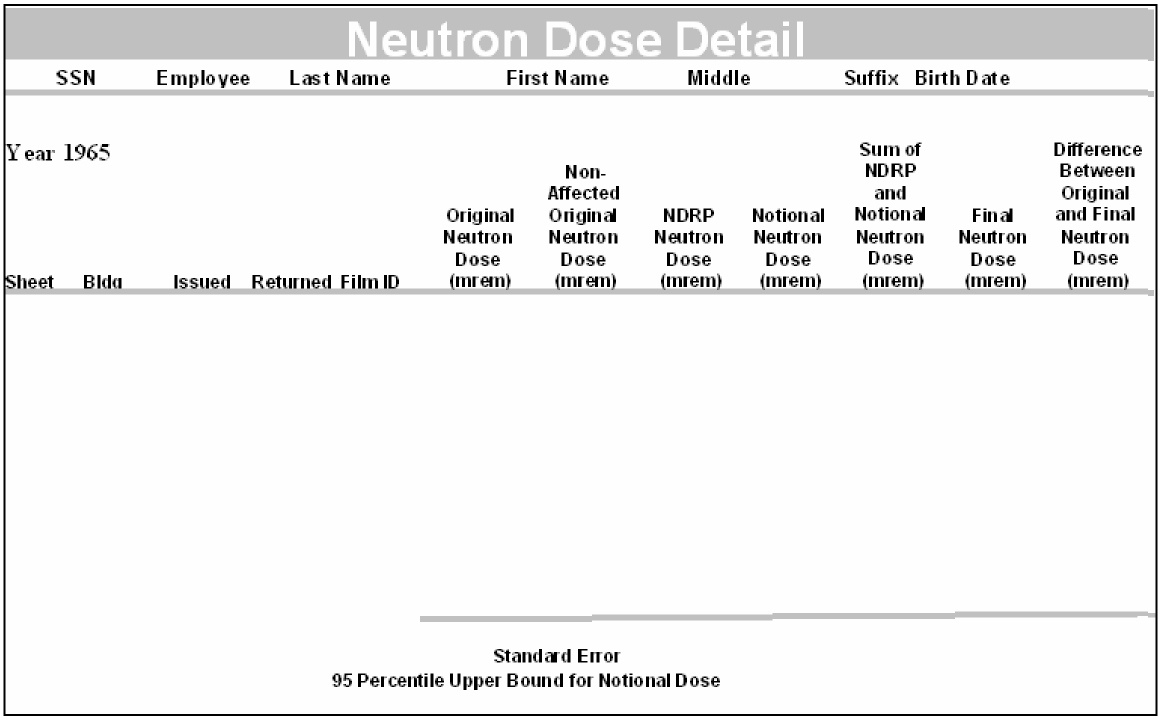
$$\text{CInt(Gap End Date – Gap Start Date)} \times N_{1BY} \times [T_{N1}/(T_{N1}+ T_{gap})] + \mathrm{G_{gap}} \times R_{BY} \times T_{gap} /(T_{N1}+ T_{gap})]$$

The function CInt(Gap End Date – Gap Start Date) calculates the number of days (t_{gap}) in the gap defined by the gap start date and the gap end date. N_{1BY} is the average neutron dose per day and is calculated by dividing the sum of the NDRP neutron doses from film rereads (for films paired with gamma doses) by the sum of days of the monitoring periods for the corresponding neutron films. CInt(Gap End Date – Gap Start Date) × N_{1BY} is the method 1 notional dose, N_{NOT1}. Note that neutron doses for films matched to surrogate worksheets are excluded from the calculation of the average neutron dose per day. The gamma dose G_{gap} is obtained from the "Gamma Dose" column for all gamma monitoring periods contained within, or sometimes overlapping, the gap period for the building of the gap. R_{BY} is the N:G building ratio taken from Table 11.4.1. $G_{gap} \times R_{BY}$ is the method 2 notional dose, N_{NOT2}. The terms $[T_{N1}/(T_{N1}+ T_{gap})]$ and $[\mathrm{T_{gap}} /(T_{N1}+ T_{gap})]$ are the weighting factors for method 1 and method 2, respectively. The value of T_{N1} is the sum of the days for all the neutron monitoring periods with a valid NDRP neutron dose and paired to monitored gamma dose(s) in that building. The value of T_{gap} is the sum of the days for all gaps in that building. Note that when T_{N1} is 0, the weighting factor for method 2 is 1, and all of the notional neutron dose is based on method 2. Incidentally, when T_{N1} is 0, N_{1BY} is also 0 and the method 1 notional neutron dose is 0.

The notional neutron dose for all gaps prior to 1959 are based 100% on method 2 even though there were some NDRP neutron doses for films for December 1958 for Building 71, and there were some NDRP neutron doses for glass plates in Building 91 in1952 through January 1957.

13.2 Neutron Dose Detail

The Neutron Dose Detail report displays the neutron dose timeline and the values for categories of neutron dose as well as the sums for each calendar year for a worker. The standard errors are calculated for the sum for the year for both the NDRP neutron doses and the notional neutron doses. Figure 13.2 displays the header and data fields for the Neutron Dose Detail report.



Neutron Dose Detail

SSN	Employee	Last Name	First Name	Middle	Suffix	Birth Date

Year 1965

Sheet	Bldg	Issued	Returned	Film ID	Original Neutron Dose (mrem)	Non-Affected Original Neutron Dose (mrem)	NDRP Neutron Dose (mrem)	Notional Neutron Dose (mrem)	Sum of NDRP and Notional Neutron Dose (mrem)	Final Neutron Dose (mrem)	Difference Between Original and Final Neutron Dose (mrem)

Standard Error
95 Percentile Upper Bound for Notional Dose

Figure 13.2 Neutron Dose Detail Header and Data Fields

The worker identification fields are the same as those described for the individual timeline. The calendar year is printed under the worker identification fields. Generally, there is one page per calendar year. The page for a calendar year is printed only if there is at least one neutron dose entry for the worker for that year.

The data fields on the left half of the report (Sheet, Bldg, Issued, Returned, and Film ID) are the same as those described for the individual timeline.

Neutron dose fields are

- Original Neutron Dose (mrem)—The neutron dose equivalent in units of millirem. This field corresponds to the original dose in the individual timeline report (see Section 13.1). The sum of the original neutron doses, if any, is printed at the bottom of the column.

- Non-Affected Original Neutron Dose (mrem)—The original neutron dose equivalent that was not affected by an NDRP neutron dose based on a reread film or glass plate. A blank in this field indicates that the original neutron dose was affected or that there was no original neutron dose observed on the worksheet for that monitoring period or gap. The sum of the non-affected original neutron doses, if any, is printed at the bottom of the column.

- NDRP Neutron Dose (mrem)—The neutron dose equivalent, generated by the NDRP from reread films or glass plates. These doses correspond to the NDRP doses on the individual timeline report, not including the notional neutron doses for gaps (see Section 13.1). The sum of the NDRP neutron doses, if any, is printed at the bottom of the column. The standard error of the sum, printed under the value of the sum, is calculated according to the method described in Section 12.5.

- Notional Neutron Dose (mrem)—The neutron dose equivalent, estimated by the NDRP for each gap, if any (see the discussion of gaps in Section 13.1). The sum of the notional neutron doses, if any, is printed at the bottom of the column. The standard error of the sum, printed under the value of the sum, is calculated according to the method described in Section 12.7. The 95 percentile upper bound for the notional dose is equal to the value of the notional dose plus 1.645 times the standard error, and the value is printed under the value of the standard error.

- Sum of NDRP and Notional Neutron Dose (mrem)—The sum of values in columns of the NDRP neutron dose and the notional neutron dose columns. The sum at the bottom of the column is the total neutron dose generated by the NDRP for that worker for that year.

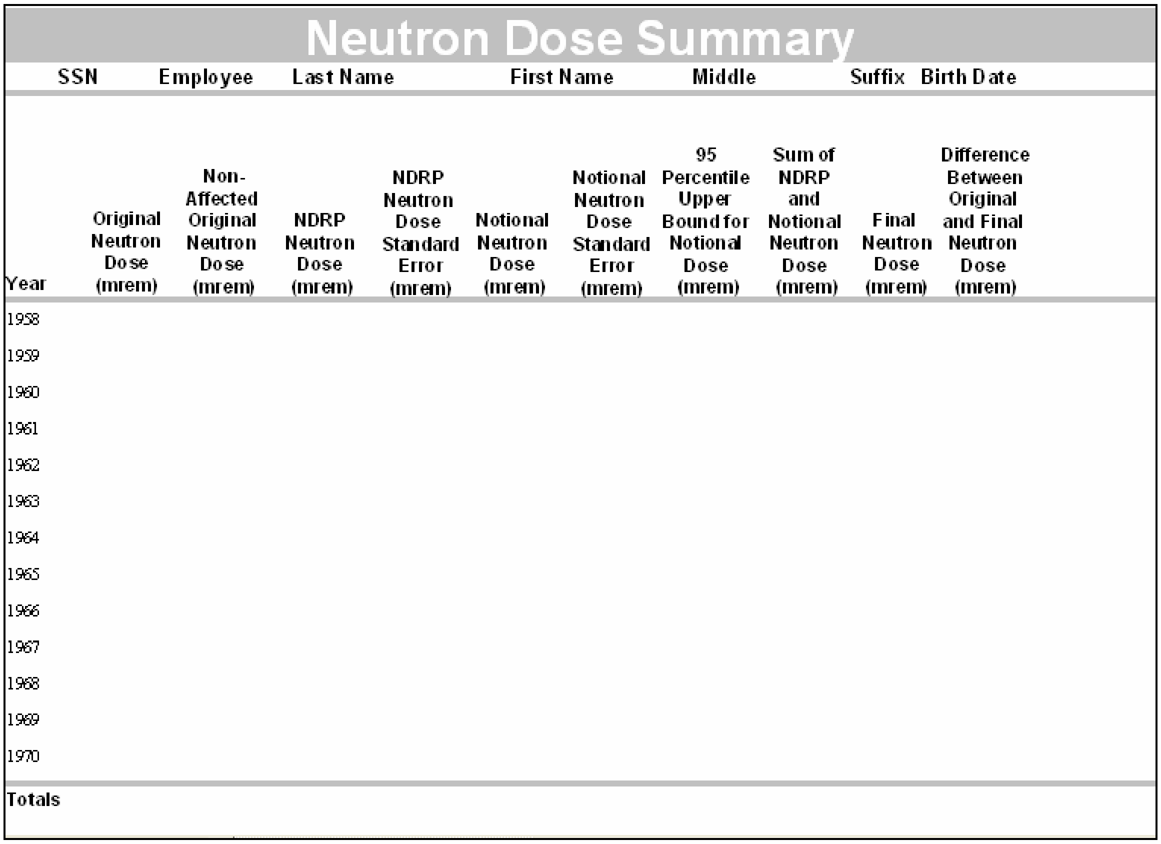
- Final Neutron Dose (mrem)—The sum of the NDRP generated neutron dose (the previous column) and the non-affected original neutron dose. The sum at the bottom of the column is the final neutron dose credited by the NDRP to that worker for that year.

- Difference Between Original and Final Neutron Dose (mrem)—The values of the neutron doses in the final neutron dose column minus the values of the neutron doses in the original neutron dose column.

All neutron doses in this table are dose equivalents, based on a nominal quality factor of 10. The sums on the bottom line are the totals for the calendar year.

13.3 Neutron Dose Summary

The Neutron Dose Summary report displays the sums for categories of neutron dose as well as the standard errors, where appropriate, for each calendar year for a worker. Figure 13.3 displays the header and data fields for the Neutron Dose Summary report.



Neutron Dose Summary

SSN Employee Last Name First Name Middle Suffix Birth Date

Year	Original Neutron Dose (mrem)	Non-Affected Original Neutron Dose (mrem)	NDRP Neutron Dose (mrem)	NDRP Neutron Dose Standard Error (mrem)	Notional Neutron Dose (mrem)	Notional Neutron Dose Standard Error (mrem)	95 Percentile Upper Bound for Notional Dose (mrem)	Sum of NDRP and Notional Neutron Dose (mrem)	Final Neutron Dose (mrem)	Difference Between Original and Final Neutron Dose (mrem)
1958										
1959										
1960										
1961										
1962										
1963										
1964										
1965										
1966										
1967										
1968										
1969										
1970										
Totals										

Figure 13.3 Neutron Dose Summary Header and Data Fields

The worker identification fields and the neutron dose fields are the same as those described for the neutron dose detail report. In addition, the first column is the calendar year, and separate columns are established for the standard errors of the NDRP neutron dose and of the notional neutron dose.

The values for each calendar year are the bottom-line values from the neutron dose detail report. The neutron dose summary report just displays these data on one page and provides a bottom-line total for each column for the worker. The total standard error for the total NDRP neutron dose is calculated from the entire set of NDRP films and their readings for the worker, so that covariances are included (see Section 12.5). Covariances were not an issue for the standard error of the notional neutron doses, so the total standard error is the square root of the sum of the squared standard errors for each year. (Note: The original neutron dose stated either for a year or for the total may not coincide exactly with the worker's neutron dose of record. The NDRP did not capture any administratively assigned doses that may have replaced an original film dose or may have filled a gap unless the administratively assigned doses were on the worksheets.)

A variation of the neutron dose summary report is the neutron dose summary plus reconstructed gamma dose report. This report adds a column, headed with "Reconstructed Gamma Dose* (mrem)," which provided a place to record the gamma doses that were reconstructed from wrist doses for workers in Building 71 through 1957 who were not monitored with a gamma body dosimeter (see Section 11.2). The sum of the reconstructed gamma doses (asterisked) is provided along with the footnote, "This value of the whole body, penetrating gamma dose was calculated by multiplying the wrist dose for the monitoring period by 0.4."

14.0 Transmittal of Reports, Data, and General Information to DOE-Rocky Flats Project Office (DOE-RFPO)

Reports, data, and information will be provided to DOE-RFPO pending final guidance from DOE-RFPO.

The Neutron Dose Summary, Individual Timeline, and Neutron Dose Detail reports will be generated electronically (disc) and organized by last name for inclusion in the NDRP's files.

The neutron dose summary report contains a column headed "Difference Between Original and Final Neutron Dose (mrem)." This difference is the value that would reflect the NDRP's proposed amendment to the worker's neutron dose of record.

All of the neutron films, neutron film storage boxes, beta-gamma worksheets, and neutron dosimetry worksheets will be returned to DOE-RFPO for long-term storage. The numerous NDRP documents, including copies of quarterly reports, comments from the advisory committee, and other general data and program documentation will be archived. It is anticipated that these activities will be completed by the end of March 2005.

15.0 References

Stanfield, S. (1998). Uncertainty analysis of neutron dose estimates for former workers at the Rocky Flats Environmental Technology Site. M. S. Thesis, Dept. of Radiological Health Sciences, Colorado State University, Fort Collins, CO.

Searle, S. R., Casella, G., and McCulloch, C. E. (1992). *Variance Components.* John Wiley & Sons, Inc. New York.

SAS Institute Inc. (2003). *SAS OnlineDoc® 9.1*. SAS Institute Inc. Cary, NC.

Appendix I

Statistical Methods Review

October 31, 2003

Phillip Chapman, Ph.D.

Outline

1.0 Sampling Methods

2.0 Recalibration Methods

3.0 Estimation Methods

4.0 Missing Value Estimation

5.0 Uncertainty Assessment

Summary

1.0 Sampling methods: Protocol for multiple sampling

Quality control protocol requires an automatic second read of all films having normalized initial read greater than 200, as well as a random selection of films having initial reads from 50–200. When the second read was discrepant with the first, additional read(s) were performed. Since the largest contribution to estimated total dose comes from the highest reads, this strategy of requiring multiple reads on the films with high initial reads is highly beneficial in that it reduces total variance. However, taking a second read when the first read exceeds a threshold induces a negative bias into the combined estimate, because unusually high values are averaged with a second read, but unusually low values stand as the only read. This bias was investigated and estimated to be less than 4%, a small bias relative to other sources of error in the process. Recently, the multiple read strategies had been expanded, and a second read has now been obtained on all films with an initial read greater than 120. Additionally, third reads have been obtained on all films with an average of the first two reads greater than 250.

2.0 Recalibration methods: The reader modification factor (RMF)

A reader calibration factor (CF) is used to adjust the work of each reader to a calibrated standard. It has become apparent that; despite this adjustment over time and under time pressure; reads tend to be lower than would be obtained by best practice. In a round robin study, April–June 2002, 60 films were reread by seven readers, including Roger Falk. It was found that initial reads were typically about 30% lower than reads during the study and about 45% lower than a very careful read by Roger (taking about twice as much time per read). Subsequent retraining of the readers, followed by a benchmark study in which a balanced 5% of films were reread, indicated that retrained readers raised the average value of their reads by values up to 60%. These results lead us to propose an additional adjustment, an RMF that will adjust the work of all readers up to the standard read of Roger.

Restricted Maximum Likelihood (REML) estimates of some RMF values, along with their estimated standard errors and correlations, were computed from the round robin study using the mixed procedure in the statistical package (SAS). The mixed model fit to the logarithms of the data included a fixed term for each reader during each time period and a random term for each film. To compute the complete set of RMF values, time periods will be identified for each reader (one to four time periods per reader). The same mixed model will be used to estimate an RMF for each time period for each reader. The mixed model program will produce standard errors and correlations for the RMF estimates. The model will be fit to the entire multiple read database of approximately 32,000 multiple reads. Due to the size of the data set, the computations cannot be done using SAS Proc Mixed. Specialized software will be obtained or constructed for the purpose. The estimation procedure involves inverting the 32,000 by a 32,000 covariance matrix of the data, which is possible due to its block-diagonal structure.

3.0 Estimation methods: Arithmetic averaging of multiple reads

When there is a single read, that single read, as adjusted by the CF and the RMF, will be the estimate for that individual during that time period. However, when there are multiple reads, a method is needed to compute the final estimate from the multiple values. The "Work Guidance Document" describes a set of rules by which a "best read" is selected. The result of these rules is that one of the multiple reads is selected as the best read. That read may be the initial read, if confirmed by the second read, or a middle value out of three or more.

We now believe that a method based on averaging of available reads is superior to a selection of a single best read. Statistical principles imply that, when the distribution is normal, the variance of the average is substantially smaller than the variance of individual values, even if that individual value is the median. When the distribution is somewhat skewed to the right, as is the Poisson distribution, the median tends to be lower than the mean, generating a negative bias in the estimate. The one circumstance in which the median, or trimmed mean, is superior to the mean is a symmetric distribution with very heavy tails (like Cauchy). Investigation of the residuals from the round robin study indicated some right skewness but not unusually heavy tails. Therefore, we believe that the sample average is superior to the best read method. Values that appear to be numerical errors should still be omitted prior to calculating the mean.

4.0 Missing value estimation: Neutron dose from gamma dose

We have proposed a model in which a linear prediction equation is estimated for each building/time period. The model assumes that the *true* neutron dose is a linear function of measured gamma dose, with error variance proportional to the gamma dose. The model then assumes that the *measured* neutron dose is a linear function of the true neutron dose with error variance proportional to the true neutron dose. For this model, the weighted least squares estimate of the true neutron dose is the product of the neutron-to-gamma ratio and the measured gamma value. A prediction variance formula is computed for this model. For an individual subject, predictions and prediction variances from each building/time period are calculated then summed.

The proposed model can be used to construct estimates for missing time periods and compute variance estimates for those estimates. However the work of Stanfield (1998) suggests that the variances for estimator constructed this way will be very high. We expect that our variances may be proportionally smaller than Stanfield's for two reasons: (1) neutron doses used in the estimation process will be adjusted for reader modification factors and (2) we estimate the variance of the error for prediction of the *true* neutron dose; Stanfield estimated the variance of the error for prediction of the *measured* neutron dose, which is larger.

5.0 Uncertainty assessment: Combining uncertainty estimates from multiple sources

The final estimate of the total dose for an individual includes a neutron term plus a gamma term minus a background term. Since these three terms are approximately independent, the variances of the three terms may be added. (We have not yet determined whether the background will be subtracted from individual estimates, whether a total background value will be subtracted at the end, or whether any background will be subtracted.) Approximate one-sided or two-sided confidence intervals may be formed using the estimate plus and minus a value from the normal table times the square root of the total variance estimate. Which intervals are of interest depends on whether the objective is to prove that an individual *was not* exposed above a threshold or to prove that an individual *was* exposed above a threshold.

The total neutron dose estimate is a weighted sum of the individual film values, each film value multiplied by the appropriate RMF. The individual film values are assumed to have an approximately Poisson distribution with a possible “over-dispersion” multiplier. RMF values each have a standard error and a covariance. These variances may be combined using standard statistical techniques to get an approximate variance of the neutron dose. These formulas are described in Section 5.

The gamma term will be a sum of estimates from several predictive equations, and its variance will be a sum of estimated predictive variances. These formulas are described in Section 4.

1.0 Sampling Methods

1.1 Quality Control QC Sampling Protocol

The protocol for taking multiple determinations of a single film is described in the "Work Guidance Document." The protocol specifies that at least 10% of the initial readings (T_1) will be given a second reading (T_2). Films are selected for second readings based on their classification into one of three categories: (1) films with initial readings of 200 normalized tracks or more, (2) films with initial readings of 50 - 199 tracks, and (3) films with initial readings of less than 50. All films in category 1 are selected for review, followed by a random selection from category 2, to achieve the total 10%. If the 10% is not obtained from the first two categories, films are randomly selected from category 3 until the 10% figure is achieved.

When a second reading is discrepant with the first reading, as defined by the "Work Guidance Document", a third reading is taken. For values greater than 80 normalized tracts, a second reading is discrepant if it differs from the initial reading by more than a factor of 1.4 (multiply or divide). For smaller values the discrepancy criterion is based on 1.96 standard errors of the difference, where the standard error of the difference is computed using a Poisson variance formula. If the third value is discrepant with both of the first two, then a fourth reading is taken.

Additional QC reads are taken for various special purposes (e.g., training and comparison of readers). These reads will be included in the estimation process.

1.2 Benefits of Automatic Second Read When the Initial Reads Are High

Random variability includes Poisson sampling variability plus other sources. The variability in a reading is at least the Poisson variance, which equals the true dose value of the film. Therefore, variance of the estimate of a total cumulative dose for an individual will be reduced more by rereads of the larger values than rereads of randomly selected films, which are likely to have smaller values. The initial protocol involved an automatic reread if the first reading is above 200. There is benefit to lowering the threshold at which an automatic second reading is taken. The threshold of 100 was proposed but was adjusted to approximately 120 so that the work could be completed by the end of October 2003.

If the simplest Poisson model is assumed, and two films have true mean values $f_a = 150$ and $f_b = 50$, with initial reads T_{1a} and T_{1b}, then a second read on the first film implies total variance

$$Var[(T_{1a} + T_{2a})/2] + Var(T_{1b}) = (150/2) + 50 = 125.$$

If instead, the second reading is taken on the second film, then

$$Var(T_{1a}) + Var[(T_{1b} + T_{2b})/2] = 150 + (50/2) = 175 .$$

This clearly illustrates the benefit of taking multiple reads primarily on the larger values. Using the same logic, a third read is advisable when the mean for the first film is much larger than the mean of the second film. Assume two films have true mean values $f_a = 450$ and $f_b = 100$, with two reads on the first and one read on the second. If a third read is taken on the first film the variance of the estimated total would be

$$Var[(T_{1a} + T_{2a} + T_{3a})/3] + Var(T_{1b}) = (450/3) + 100 = 250 .$$

If instead, a second read is taken on the second film, then

$$Var[(T_{1a} + T_{2a})/2] + Var[(T_{1b} + T_{2b})/2] = (450/2) + (100/2) = 275 .$$

Therefore, it would be more beneficial, in terms of variance reduction, to take a third read on a high value, rather than take a second read on an intermediate value.

The above discussion assumes that the objective is to reduce the variance of estimates on all the workers. It is possible that films with high values are predominantly from workers that have clearly received a high dose. Should some consideration be given to trying to reduce variance for reads on workers that are near some claim threshold? In principle, this could be done, but it would require another round of readings for such workers after an initial round of estimates had determined that they are near the threshold.

1.3 Bias Due to Taking a Second Reading When the First Reading Exceeds a Threshold

If a rule is followed that requires a second reading for films with first reading greater than or equal to a threshold, then a small bias is created by that rule. This bias is largest for films with true values near the threshold. The bias occurs because random results greater than or equal to the threshold require a second reading, which is averaged with the first; whereas, random results less than threshold stand without further testing. Thus, high values are reexamined but low values are not.

Let μ be the true value of the film. Let T_1 and T_2 be the two readings, respectively, and let the threshold initially be 200. Assume that T_1 and T_2 is distributed according to the Poisson distribution with mean μ and are independent. The value reported (T) is T_1, if $T_1 < 200$, or $(T_1 + T_2)/2$, if $T_1 \geq 200$.

Let E(.) be statistical expectation, or average. Let P(.) be probability, and Po(k) be the probability that a Poisson variable with mean μ will be less than or equal to k. The "|" symbol denotes conditioning and is read "given." Then the expected value of T is

$$E(T) = E(T \mid T_1 < 200)\, P(T_1 < 200) + E(T \mid T_1 \geq 200)\, P(T_1 \geq 200)$$

$$= E(T_1 \mid T_1 < 200)\, P(T_1 < 200) + E[(T_1 + T_2)/2 \mid T_1 \geq 200]\, P(T_1 \geq 200)$$

$$= E(T_1 \mid T_1 < 200)\, Po(199) + E[(T_1 + T_2)/2 \mid T_1 \geq 200]\, [1 - Po(199)]$$

$$= E(T_1 \mid T_1 < 200)\, Po(199) + ½\, [E(T_1 \mid T_1 \geq 200) + E(T_2 \mid T_1 \geq 200)]\, [1 - Po(199)].$$

Since T_1 and T_2 are independent, then $E(T_2 \mid T_1 \geq 200) = E(T_2) = \mu$. Therefore

$$E(T) = E(T_1 \mid T_1 < 200)\, Po(199) + ½\, [E(T_1 \mid T_1 \geq 200) + \mu]\, [1 - Po(199)].$$

The Poisson probabilities and the conditional expectations can be calculated using the function "Poisson" in the statistical computing package SAS. Figure 1.1 is a graph of E(T) versus μ, for values of $\mu = 150, .. 250$. The "bias" in the procedure is the amount by which the diagonal line E(T) line (solid) is below the diagonal line (dashed). The bias appears to be minimal (no more than 2%), which I believe to be acceptable, given the other uncertainties that are built into the methodology.

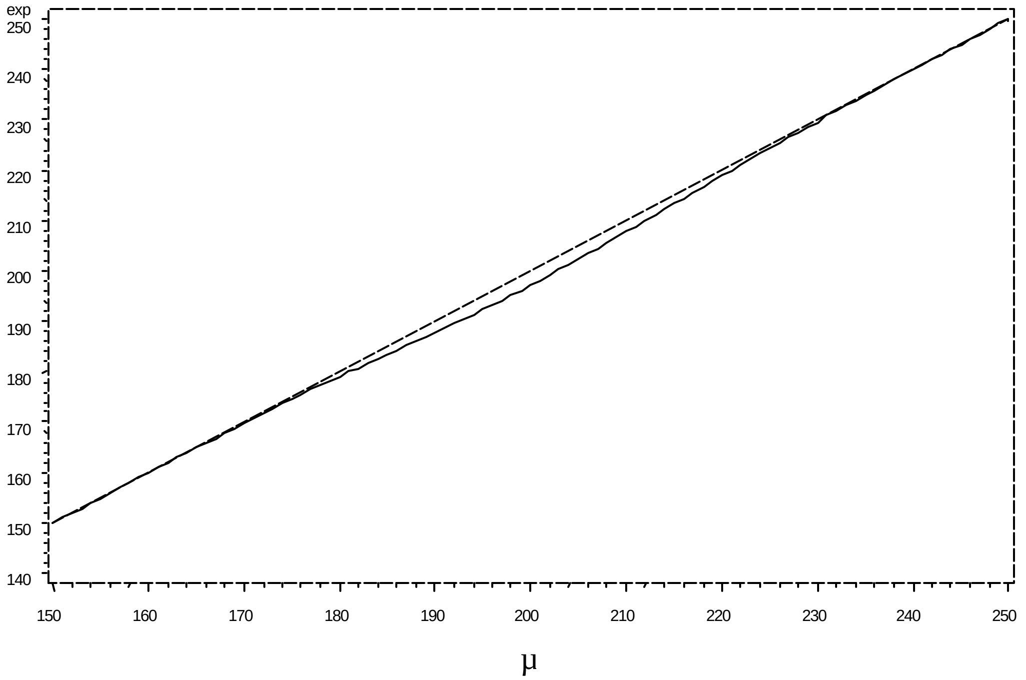


Figure 1.1 Decision to resample when values over 200 are observed: E(T) (solid line) versus μ, for values of $\mu = 150, .., 250$, compared to μ versus μ (dashed line), the reference line of zero bias.

Assuming a threshold of 100 rather than 200 will increase the bias somewhat (Figure 1.2). The bias is a maximum at the value 100 but nowhere exceeds 3%. The conclusion is that the bias induced by the rule that chooses a second read when the first read is high, is small compared to other likely sources of error.

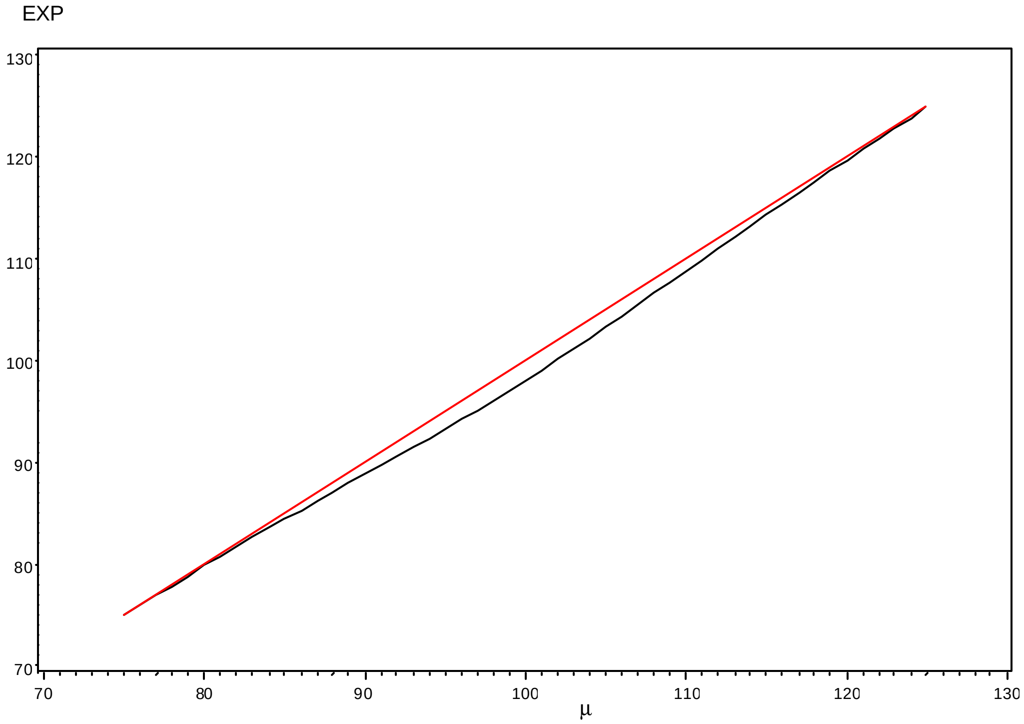


Figure 1.2 Decision to resample when values over 100 are observed: E(T) (bottom line) versus μ, for values of μ= 75, .., 125, compared to μ versus μ (top line), the reference line of zero bias.

2.0 Recalibration Methods

2.1 Reader Modification Factor (RMF)

Initial calibrations of the raw track counts involved adjustments for the reader's performance on a set of QC films. The reader's raw counts are adjusted to a virtual reader with a calibration factor, CF_{QC}, equal to 30 mrem×mm^2/track for an area, $Area_{QC}$, of 10 mm^2.

$$T_{norm} = \frac{CF_{reader}}{CF_{QC}} \times \frac{Area_{QC}}{Area_{reader}} \; T_{reader}$$

Over time it became apparent that time constraints, degree of training, and degree of effort were contributing to readings that were, on average, lower than the best reading practice. The film reading process involves time constraints and periods before and after retraining. It also involves reading film that is perhaps fogged or scratched. To adjust film reads to the best practice, a RMF was proposed. Each reader would have a table, such as the following:

Time Period	**1**	**2**	**3**	**4**
RMF	1.2	1.6	1.1	1.1

The RMF is an estimate of the multiplier that would be needed to get the average readings for that time period up to the average of best practice. In the example above, the first time period may be a period just after training, the second period a time when the reader was influence by complacency or time pressure. Period 3 is a period after re-training, when the reader was brought close to best practice. Each reader would have a set of periods (not necessarily the same in length or number) and an RMF for each period.

The decision whether to use RMF recalibration factors is very important. Evidence in the data indicates that, without such factors, the average read over the project is substantially below best practice (as determined by Roger Falk). With such modifications the results will be generally higher but also more variable. Results will be more variable for two reasons: (1) multiplying results by any number greater than 1.0 increases variability of the results (in an absolute scale, but not in a relative scale) and (2) the RMF values must be estimated, and the variability in those estimates must be included in the estimate of overall variability.

Adjustment by RMF values will increase the estimate of total dose and increase the estimate of the variability applied to that dose. However, the increase in the estimate could be termed "worker favorable." If confidence intervals are formed in the usual way: estimate ± z-value × s.e.(estimate), then an increase in the estimate will move the entire interval up. Whether the increase in the *estimated variability* is also worker favorable may depend on whether the burden of proof is on the employer or the worker. If the burden of proof is on the employer to show that the worker's total dose was *not above a threshold*, then the adjustment is worker favorable, because the upper confidence limit would be adjusted upward by the RMF adjustment. If the burden of proof is on the worker to show that his/her total dose *is above a threshold*, then the adjustment will not be worker friendly if the lower confidence limit is reduced by the adjustment. It is hard to tell at this point whether the increase in the center of the distribution will be more than offset by the increase in the width of the interval.

Estimation of the RMF numbers will be largely based on data but will necessarily contain some subjective components.

2.2 Round Robin Study: Estimation of RMF Values by Mixed Model Analysis of Variance

The Round Robin Study involved six batches of 10 films each, which had been initially read by readers BAH (Beverly, two batches), BRH (Ben), GPW (Griff), IMH (Irene), and KR (Kat). The batches were reread by seven readers: Ben, Carol, Kathleen, Iris, Griffin, Beverly, and Roger. Some of the initial readers were included in the second group; however, separate parameters are estimated for the initial read and the round robin read for the same person. Roger was the "gold standard" or best practice to which all other readers were calibrated. Roger has far more experience and a far higher level of training and took approximately twice as much time per film to do his readings. All readings were normalized to a standard CF = 30 and read area = 10. The responses were modeled in the log10 scale, so that the RMF estimates would have a multiplicative interpretation (although the log scale somewhat overcorrects for the increasing variance). The log10 of the normalized read for the k^{th} read of the i^{th} film by the j^{th} reader was modeled as follows:

$$Y_{ijk} = M + F_i + R_j + e_{ijk}. \tag{2.1}$$

The effects in the model are (in order): a fixed overall mean, a random effect for the film i, a fixed effect for reader j, and a random error. We assume that (in the log scale) the random film effects are approximately normally distributed and the random errors are approximately normally distributed, independent of the film effects. The fixed effects are relative to Roger, whose effect was fixed at zero. The model could be described as an "incomplete block" model, where film is the "block" on which the various readers are compared. The design is complete with respect to the readers in the round robin study but incomplete with respect to the initial readers, who only read 10 of the 360 films.

Table 2.1 gives estimates produced by SAS using the restricted maximum likelihood (REML) method along with their standard errors. The RMF is the estimate, exponentiated, base 10. The s.e.(RMF) is the standard error of the RMF based on the "delta method" which involves a one-term Taylor series estimate of the function $f(x) = 10^x$. The accuracy of the delta method applied here depends on how close to linear the function $f(x)$ is in the vicinity of the estimate plus or minus two standard errors. A graph of f(x) is given in Figure 2.1. The graph demonstrates that f(x) is fairly close to linear for over the necessary regions.

Table 2.1 SAS REML estimates of RMF.

Reader	Estimate	s.e.(Estimate)	RMF	s.e.(RMF)
Ben	0.12	0.019	1.31	0.056
Carol	0.17	0.019	1.49	0.065
Kat	0.16	0.019	1.45	0.063
Griff	0.12	0.019	1.33	0.057
Iris	0.16	0.019	1.44	0.062
Bev	0.14	0.019	1.39	0.060
BAH	0.23	0.027	1.71	0.108
BRH	0.25	0.037	1.78	0.151
GPW	0.31	0.037	2.03	0.172
IMH	0.32	0.037	2.10	0.178
KR	0.15	0.037	1.42	0.120

The initial reads are far below the reads of Roger. The RMF values for the readers during the round robin study period range from 1.31 to 1.49. The RMF values for the initial reads are much larger, ranging from 1.42 to 2.10. The RMF values calculated by these methods would be inserted into the RMF table, representing the appropriate time periods. Note that the standard errors for the initial readers are somewhat larger than the standard errors for the second readers. This is because the initial readers read only 10 films (except 20 for BAH), and the second readers read 60. The initial readers were significantly different from each other, as were the second readers.

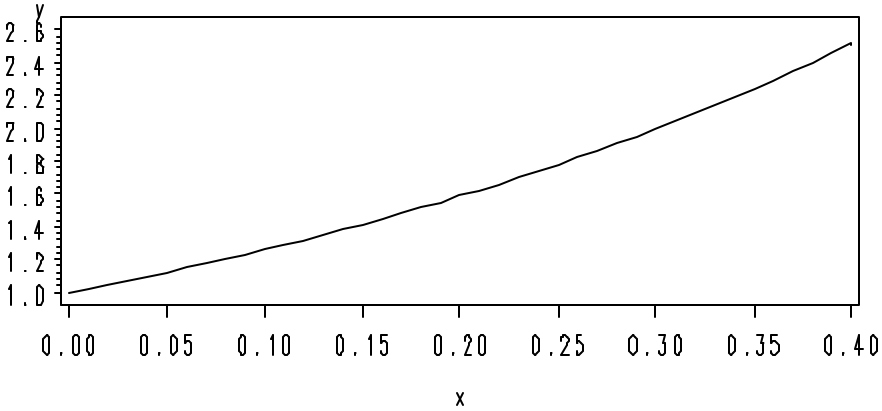


Figure 2.1 Plot of $y = f(x) = 10^x$.

The program can output a correlation matrix that can be used in the uncertainty calculations. Such a matrix is given in Table 2.2. Note that the estimates are all positively correlated. This is because all readers are being adjusted to the same group of reads by Roger.

Use of these factors will result in a dramatic upward adjustment to the readings, effectively modifying all results to the read average of Roger. If Roger is indeed the "gold standard," then a substantial amount of bias will be removed but some variability will be added due to the imprecision in the estimates. Use of these factors will also reduce the relative differences between multiple reads on the same film by adjusting out some of the reader bias.

Table 2.2 Correlation Matrix for RMF estimates

Reader	Ben	Carol	Kat	Griff	Iris	Bev	BAH	BRH	GPW	IMH	KR
Ben	1	0.50	0.50	0.50	0.50	0.50	0.34	0.25	0.25	0.25	0.25
Carol	0.50	1	0.50	0.50	0.50	0.50	0.34	0.25	0.25	0.25	0.25
Kat	0.50	0.50	1	0.50	0.50	0.50	0.34	0.25	0.25	0.25	0.25
Griff	0.50	0.50	0.50	1	0.50	0.50	0.34	0.25	0.25	0.25	0.25
Iris	0.50	0.50	0.50	0.50	1	0.50	0.34	0.25	0.25	0.25	0.25
Bev	0.50	0.50	0.50	0.50	0.50	1	0.34	0.25	0.25	0.25	0.25
BAH	0.34	0.34	0.34	0.34	0.34	0.34	1	0.15	0.15	0.15	0.15
BRH	0.25	0.25	0.25	0.25	0.25	0.25	0.15	1	0.11	0.11	0.11
GPW	0.25	0.25	0.25	0.25	0.25	0.25	0.15	0.11	1	0.11	0.11
IMH	0.25	0.25	0.25	0.25	0.25	0.25	0.15	0.11	0.11	1	0.11
KR	0.25	0.25	0.25	0.25	0.25	0.25	0.15	0.11	0.11	0.11	1

2.3 The 5% Benchmark Study: Estimation of RMF Values by Mixed Model Analysis of Variance

Another set of data that can be used to establish the importance of the RMF is the 5% benchmark study. A 5% subset of the films was selected approximately randomly, with the requirement that it be approximately balanced over the timeline. Four readers had substantial numbers of reads during the benchmark. The analysis below was restricted to the benchmark reads from those four readers and the initial reads by one of the four readers on the *same film*. Table 2.3 gives the numbers of benchmark and initial reads by each of the four readers.

Table 2.3 Benchmark and Initial Reads by Each of Four Readers

Reader	5% Benchmark	Initial Reads	Total
BAH	810	401	1211
BRH	827	278	1105
GPW	809	886	1695
IMH	823	1069	1892
Total	3269	2634	5903

The responses were converted to the log base 10 scale. A mixed model was fit to the responses:

$$T_{ijk} = M + B_i + R_j + (BR)_{ij} + F_k + e_{ijk} .$$

The terms in the model are (in order): fixed overall mean, fixed effect for whether the read was a benchmark (0 = no, 1 = yes), fixed effect for reader, fixed interaction between reader and benchmark, random effect for film, and random error.
The results are given in Table 2.4.

Table 2.4 RMF Estimates and Standard Errors by Reader

Reader	Benchmark	Estimate	s.e.(Estimate)
BAH	N	1.56	0.009
BAH	Y	1.74	0.006
BRH	N	1.55	0.011
BRH	Y	1.76	0.006
GPW	N	1.61	0.006
GPW	Y	1.65	0.006
IMH	N	1.64	0.006
IMH	Y	1.61	0.006

For two of the four readers, there is a substantial difference between the benchmark and non-benchmark data. For example, BAH estimates increase from 1.5617 to 1.7417, a difference of 0.1797. Therefore the BAH benchmark adjustment is a multiplier of $10^{0.1797}$=1.51. For BRH the multiplier is 1.62. This analysis demonstrates the magnitude of the difference between the benchmark and other data on the same reader. For some readers, during some time periods, the RMF factor will be substantial.

2.4 Conclusions About RMF Estimation

Based on the preliminary analyses, it appears to be very important to estimate and use the RMF to further adjust the data. To accomplish this I propose the following:

- Since all values are to be calibrated to the read by Roger, *Roger will have to read many more films if the calibration is to be accurate.* Some care should be given to picking the films that Roger reads. Roger should read at least 10 films from each of the newer readers, so that there will be film on which they have a direct comparison to Roger. Roger should also read a subset of the benchmark films. These films have been read by at least two other people, so that at least two direct comparisons to Roger can be made for each of Roger's reads.
- The work of each reader will have to be divided into phases, so that RMF values can be estimated for each phase. This take is somewhat subjective. The most accurate results will be obtained if Roger has some calibration reads for films read

by each phase of each reader. The current database of multiple reads contains approximately 31,800 reads on 13,700 unique film ID's. There are 15 readers that have more than a trivial number of reads. (See Table 2.5). If the time on the job for each of these readers is divided into one to four phases, there will be 30 to 50 RMF values to estimate. This should be doable.

- Some readers have few reads in the database of multiple reads. In the absence of other information, perhaps their RMF values can be estimated using an average value for other readers.

Table 2.5 Distribution of Reads by Reader Initials

Reader Initials	Frequency	Percent	Cumulative Frequency	Cumulative Percent
ADA	982	3.1	982	3.1
AZA	1237	3.9	2219	7
BAH	4603	14.5	6822	21.5
BES	1394	4.4	8216	25.9
BRH	3278	10.3	11494	36.2
CEA	1049	3.3	12543	39.5
CLF	525	1.7	13068	41.2
DLH	125	0.4	13193	41.6
GPW	8018	25.3	21226	66.9
IMH	6373	20.1	27599	87.0
JSB	112	0.4	27711	87.4
KR	586	1.9	28297	89.2
MBR	541	1.7	28838	90.9
MJD	1308	4.1	30146	95.0
RBF	178	0.6	30325	95.6
SKB	1394	4.4	31719	100.0

The model proposed is the model used for the round robin analysis (Equation 2.1):

$$T_{ijk} = M + B_i + F_j + e_{ijk},$$

in which the terms are (in order): fixed grand mean, fixed effect that has separate levels for each reader in each phase, and random film effect. Thus the reader effect will have 30 - 50 levels, and the random film effect will have 13,800 levels.

I propose the REML estimation method for this model when fit to the complete data set. I was able to fit this model to the round robin data without difficulty, using SAS. The algorithm that SAS uses to fit the model involves writing and inverting the full covariance matrix of the data. In the round robin study, there were 480 data points and the estimation was quick. In the benchmark study, with about 6,000 data points, the program took about 1 hour to run. For the full multiple read database, the program must store and invert a 31,800 by 31,800 matrix. This is unlikely to run on any computer using standard software. Specialized software packages are available [e.g., DFREML (Animal

Genetics and Breeding Unit of the University of New England, Australia) or the Animal Breeder's Toolkit (Department of Animal Science, CSU)] that handle the analysis in a more efficient manner. Because these programs require substantial set-up time, I will look for other software packages that are easier to use. If such a program cannot be found, the estimation procedure can be programmed in SAS Proc IML, because the 31,800 by 31,800 matrix that must be inverted has a block diagonal form, with no block larger than 12 by 12. These blocks and their inverses have a very simple form. I have worked out most of these formulas, but they are not presented here.

3.0 Estimation Methods

3.1 Average Read Compared to "Best Read"

When *only one reading* is taken on a given film, the dose estimate will be based on that single reading, as adjusted by the RMF. When more than one reading is taken, a rule is needed to combine the multiple values. The "Work Guidance Document" describes a set of rules in by which a "best read" is selected. The result of these rules is that one of the multiple reads is selected as the best read. That read may be the initial read, if confirmed by the second read, or a middle value out of three or more. We now believe that a method based on averaging of available reads is superior to a selection of best read. Since high values contribute proportionally more variance to the variance of the final estimate, there is much to be gained by reducing the variance using averaging.

In the simplest case, when there are two reads, the averaging method estimate would be an average of the two adjusted reads. The variance of the average of two values is equal to half the variance of a single value. The same principle applies when there are more than two reads: the average of three reads has variance equal to one third of the variance of a single read. In this case, however, the best read is not equivalent to a single read, because which one is best, depends on the value of the other two. The best read out of three is usually the median of the three but not always. This complicates explicit comparison of the average method to the best read method.

Another argument in favor of taking the average of the multiple reads is that the average is an *unbiased* estimate of the true value for that film. The median is not unbiased, unless the distribution is symmetric. The Poisson assumption, as well the available data, implies that the distribution of reads is right skewed.

3.2 Investigation of Residuals from the Round Robin Study

The relative benefits of a simple average, compared to a weight average or trimmed mean (in which outlying values are discarded) depend on whether the tails of the distribution reads are much heavier than the tails of a normal distribution. For symmetric distributions with heavy tails the methods that down-weight outlying values are preferable to the simple average. Empirical evaluation of the tails of the distribution is limited, because few films have enough observations to estimate the shape of the distribution. An additional complication is that the distribution of interest is the distribution of reads, adjusted by the RMF, not the distribution of raw reads.

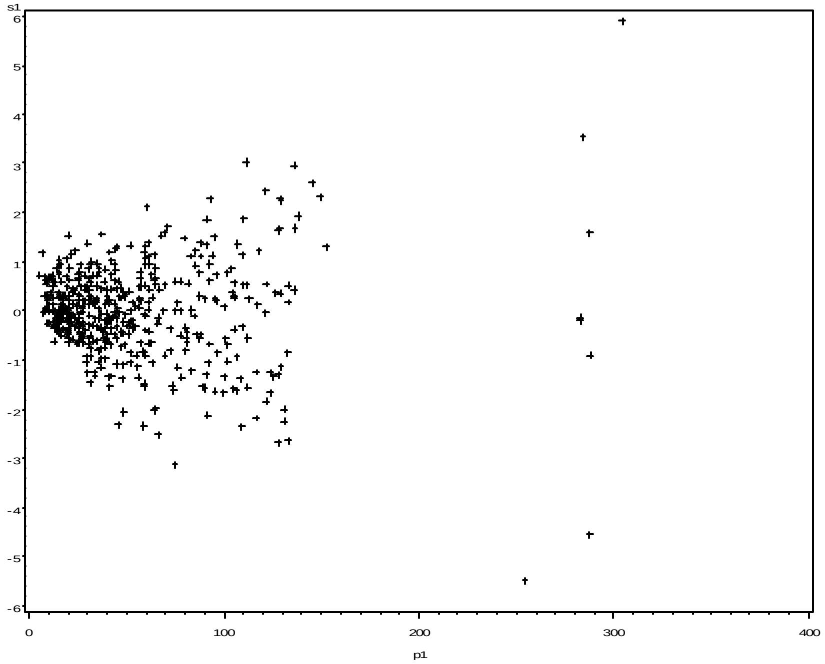


Figure 3.1 Residuals versus Predicted Values in the Original Scale

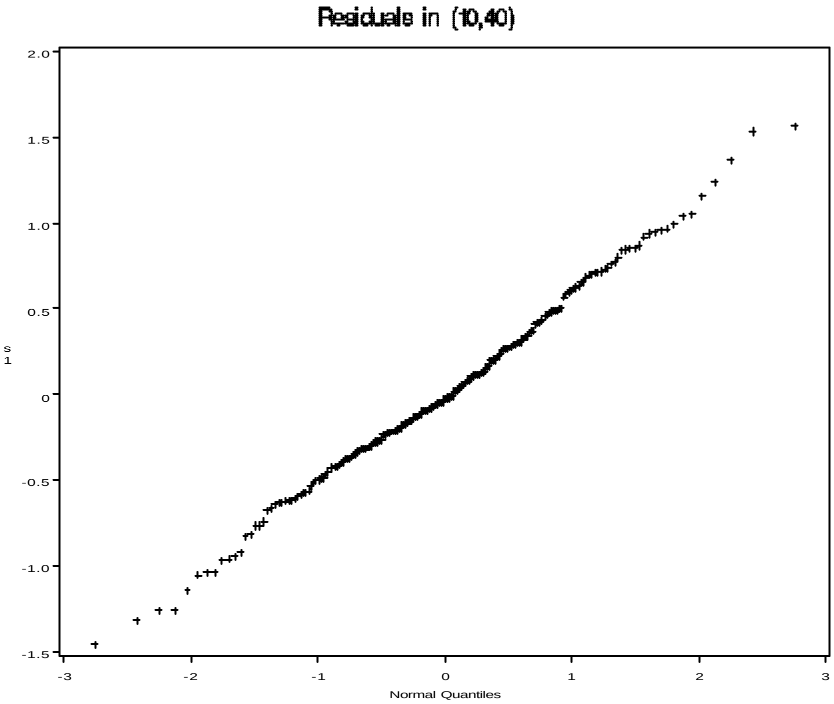


Figure 3.2 Residuals versus Normal Scores for Group 1

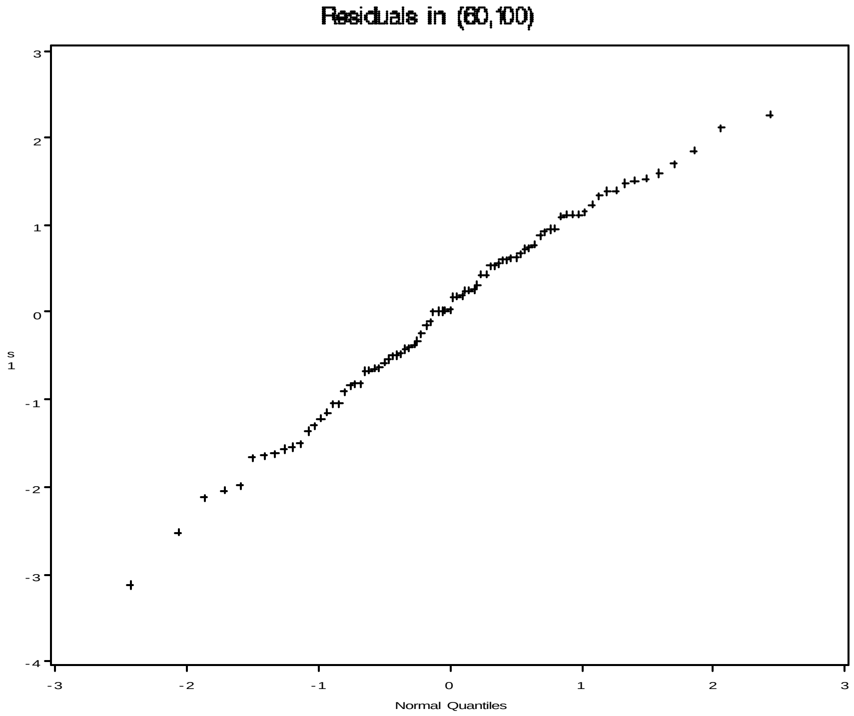


Figure 3.3 Residuals versus Normal Scores for Group 2

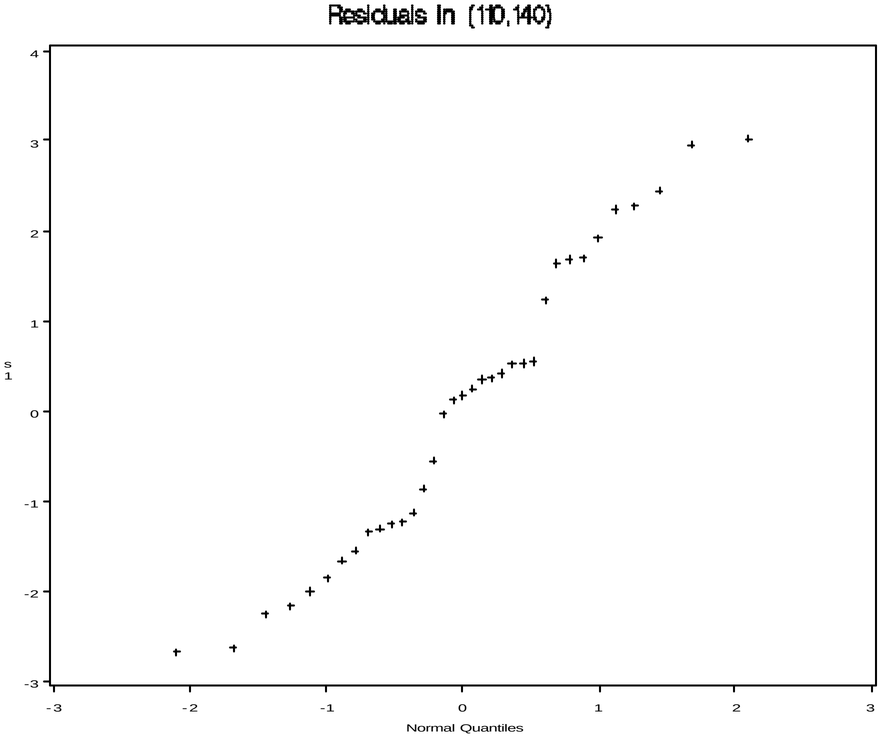


Figure 3.4 Residuals versus Normal Scores for Group 3

Since the round robin study involved seven secondary readers, each reading the same set of sixty films, the data can be adjusted for approximate RMFs and the distribution of the residuals examined. Figure 3.1 is the plot of residuals versus predicted values for the model *in the original scale*. The variance of the mean clearly increases with predicted values. (In section 5.3, the variance is seen to be consistent with the Poisson distribution.) Residuals were grouped by predicted values so that, within a group, the variance would be approximately equal. The predicted values of the three groups are (10, 40), (60,100), and (110,140). The plot of residuals versus normal scores for groups 1, 2, and 3 are given in Figures 3.2, 3.3, and 3.4, respectively

The assumption of approximate normality is supported by a linear appearance in these plots. Figure 3.2 shows a slight bow shape, indicating a slightly right-skewed distribution, consistent with a Poisson distribution. It shows no extreme outliers. Figures 3.3 and 3.4 are straighter, consistent with a distribution that is approximately normal, as would be expected of Poisson distributions with higher means. Outliers would show up as points far above the line at the right side or far below the line at the left side. There are none of these. At least for the round robin data, there is no evidence that the estimation procedure would be improved by using trimmed means or medians.

3.3 Multiple Read Data

There may yet be some opportunity to get shape information about the adjusted reads using the multiple read data. Those values are not reader adjusted, and the number of reads per film is generally small enough that it is hard to get shape information.

3.4 Conclusion

Evidence so far indicates that the adjusted reads will follow distributions that support simple averaging rather than weighted or trimmed averages. When the values are small, trimming should not be done, because the distributions are skewed. Trimming would induce a negative bias. When the values are larger, the distribution appears closer to normal, which would also support a simple average. An effort should be made to exclude values that are wrong due to transcription or counting errors. Such films might be indicated by a very large discrepancy between multiple reads or reads that appear to make no sense.

4.0 Missing Value Estimation: Neutron Dose from Gamma Dose

4.1 Discussion

Prediction of neutron counts based on gamma values was examined by Stanfield (1998). Data from 1971 involved two-week intervals. There were 56 complete annual records with paired neutron/gamma values, as well as additional pairs from incomplete records, comprising a total of 1344 pairs. Stanfield compared eight methods for estimating the predictive relationship between neutron dose and gamma dose. Even for the best methods, relative error size for predicting two-week values was extremely large, with 5 and 95 percentiles of -100% to 1500%, respectively. These results are very discouraging of the use of neutron predictions based on gamma values to fill in missing neutron records over short time periods. Stanfield's results for predicting annual dose are somewhat more encouraging, with 5 and 95 percentiles for the relative errors of –50% and 160%, respectively, roughly a factor of two. Such estimates may be usable when longer periods of neutron data are missing.

Stanfield showed relatively good behavior of the estimation method based on the ratio of averages. The ratio of averages estimator is in fact the *weighted* least squares estimator in the linear regression through the origin, when error with variance is assumed to be *non-constant and proportional to the gamma value.* An advantage of this model is that the same model that produces the estimate also produces a variance to assign to that estimate.

Stanfield also found good performance in his segmented regression model in which he fit a relatively steep line to low gamma values and a relatively flat line to high gamma values. This suggests that we might get good performance in a nonlinear model that transition gradually from a positively sloped line to a flat line. This line can be fit using a nonlinear regression program that accepts weights (e.g., SAS Proc NLIN). Such a program will output estimated prediction errors that are a function of the gamma values. Each prediction would come with an associated error estimate that could be used in the uncertainty calculation. If this nonlinearity is associated with gamma exposure at high levels that is not linked to corresponding neutron activity, then a preferred approach would be to identify such situations and eliminate them, then fit the single straight line.

We do not expect estimates based on the neutron-to-gamma ratio to be very accurate. However, such estimates can be used when no other data are available. In some situations it may be preferable to use adjacent neutron measurements rather than the gamma estimates. This would be the case if there is a missing reading in a sequence of neutron data.

4.2 Proposed Methods

The details of the neutron from gamma prediction methods have not been fully fixed; however, the following plan is being considered:

- Identify building/year combinations that should have similar relationships between neutron and gamma activity. Identify buildings that were subject to high gamma activity not linked to corresponding neutron activity. Eliminate such high gamma values from the data set.
- For the building/year combinations identified, estimate separate prediction equations using the ratio of averages method. Neutron doses adjusted by the RMF values will be used to compute the prediction equations. (Perhaps our predictions will be better than Stanfield's, if some of the variability due to reader is removed by the RMF adjustment.)
- *For each subject* compute the total gamma value for each of building/year combinations in which that subject worked. Use the building/year prediction equations to estimate neutron dose for that subject in each of the building/year combinations. Sum the predictions.
- For each subject in each building/year combination, estimate the prediction variance using the model given below. Sum the prediction variances over the building/year combinations.

4.3 Proposed Model

We take a "predictive approach" to the estimation of the neutron dose (as opposed to a "calibration approach").

Let *i* refer to the i^{th} neutron/gamma pair available for a particular building/year combination. Assume $i = 1,.., n$, where *n* is the number of pairs. Let N_i be the *true* neutron dose for observation *i.* Assume that N_i is related to the measured gamma dose g_i by the regression equation:

$$N_i = bg_i + e_i ,$$

where, for fixed g_i, $E(e_i) = 0$ and $Var(e_i) = s^2 g_i$.

The *true neutron value,* N_i, is not observable. In its place the measured neutron dose Y_i is recorded. Assume that Y_i has been adjusted with the relevant CF and RMF and that after such adjustment a Poisson or overdispersed Poisson model is appropriate. Assume:

$$Y_i = N_i + f_i ,$$

where, given N_i, $E(f_i) = 0$ and $Var(f_i) = kN_i$. The value *k*, is the overdispersion parameter; *k* = 1 implies a standard Poisson.

Putting the models for Y_i and N_i together, we obtain

$$Y_i = bg_i + e_i + f_i .$$

The combined error $(e_i + f_i)$ has mean

$$\begin{aligned} E(e_i + f)_i &= E(e_i) + E(f_i) \\ &= 0 + E[E(f_i \mid N_i)] \\ &= 0 + E(0) \\ &= 0 . \end{aligned}$$

The variance of f_i depends on N_i, which depends on e_i; therefore, e_i and f_i *are not independent*. Using a standard statistical formula

$$Var(e_i + f_i) = E(Var[(e_i + f_i) \mid N_i]) + Var(E[(e_i + f_i) \mid N_i]) .$$

Given N_i, e_i is fixed [i.e., $Var(e_i \mid N_i) = 0$ and $Cov(e_i, f_i \mid N_i) = 0$]. Also $Var(f_i \mid N_i) = kN_i$, $E(e_i \mid N_i) = e_i$, and $E(f_i \mid N_i) = 0$. Therefore:

$$\begin{aligned} Var(e_i + f_i) &= E(0 + kN_i) + Var(e_i + 0) \\ &= kbg_i + s^2 g_i \\ &= (kb + s^2) g_i . \end{aligned}$$

For simplicity of notation, we define

$$t^2 =: kb + s^2 .$$

The weighted least squares estimators of b and t^2 are

$$\hat{b} = \frac{\sum_{i=1}^{n} Y_i}{\sum_{i=1}^{n} g_i}, \text{ (the neutron-to-gamma ratio)}$$

and

$$\hat{t}^2 = \frac{1}{n-1} \sum_{i=1}^{n} \frac{\left(Y_i - \hat{b} g_i\right)^2}{g_i} .$$

From these unbiased estimators, we construct an unbiased estimator of s^2:

$$\hat{s}^2 = \hat{t}^2 - k\hat{b}\ .$$

Using standard statistical principles, we compute the variance of $\hat{b}$.

$$Var(\hat{b}) = \frac{Var\left(\sum_{i=1}^{n} Y_i\right)}{\left(\sum_{i=1}^{n} g_i\right)^2} = \frac{\left(\sum_{i=1}^{n} Var(Y_i)\right)}{\left(\sum_{i=1}^{n} g_i\right)^2} = \frac{t^2\left(\sum_{i=1}^{n} g_i\right)}{\left(\sum_{i=1}^{n} g_i\right)^2}$$

$$= \frac{t^2}{\sum_{i=1}^{n} g_i}$$

Using the above model, we let G be the accumulated gamma dose for an individual during a year in a building and let N be the *true unknown* neutron dose for the same period. The value N is estimated by $\hat{b}G$.

The prediction error is

$$N - \hat{b}G\ ,$$

The prediction error has mean zero and prediction error variance:

$$Var\left(N - \hat{b}G\right) = Var(N) + G^2 Var(\hat{b})$$

$$= s^2 G + G^2 \frac{t^2}{\sum_{i=1}^{n} g_i}\ ,$$

which can be estimated by:

$$\hat{s}^2 G + G^2 \frac{\hat{t}^2}{\sum_{i=1}^{n} g_i}\ .$$

The format of the above variance formula has an intuitive interpretation. The second term is the added variance because the slope of the regression line is estimated, not known. The first term is the variance due to the fact that the true N will vary about the true regression line. Note that the variance of the true N is determined by s^2, which is smaller than the variance of a measured Y, which is determined by t^2.

5.0 Uncertainty Assessment

5.1 Neutron Dose Estimate Uncertainty Model

For an individual with *n* films, let *N* be the number of film reads (*N* = *n*). Let the normalized track values for read *i* be $F_i,\ i = 1,2,...,N$. Let *F* be the vector of normalized reads.

$$F = \begin{pmatrix} F_1 \\ F_2 \\ . \\ . \\ . \\ F_N \end{pmatrix}$$

Each film was read by a reader, who has an RMF value estimated for the period of time during which the read was done. Let the vector of modifying factors for the film reads be

$$M = \begin{pmatrix} M_1 \\ M_2 \\ . \\ . \\ . \\ M_N \end{pmatrix}.$$

The modified read is then

$$M * F = \begin{pmatrix} M_1 F_1 \\ M_2 F_2 \\ . \\ . \\ . \\ M_N F_N \end{pmatrix},$$

where the operator (*) represents element-wise multiplication of the vectors.

The reads will be combined using a weighting vector

$$W = \begin{pmatrix} W_1 \\ W_2 \\ \cdot \\ \cdot \\ \cdot \\ W_N \end{pmatrix}.$$

Most of the W_i will take the value 1.0, indicating a film that was read once, and that single reading is taken to be the estimate. However, W_i may be different from 1.0 if an average of multiple reads on the same film is to be used. For example, if i = 2, 3, 4 are multiple reads of the same film, then $W_2 = \frac{1}{3}, W_3 = \frac{1}{3}, W_4 = \frac{1}{3}$. Also, if two neutron reads, i = 2 and 3, are being used to estimate an intermediate missing value in a sequence, then $W_2 = 1.5,\ W_3 = 1.5$. The W-values would also incorporate any other fixed multiplicative adjustments, such as the adjustment from counts to dose level.

Given the above definitions, the estimated total dose derived from the neutron counts would be

$$D = \sum_{i=1}^{N} \left(W_i M_i F_i \right)$$

The order of multiplication doesn't matter, so we re-order the factors within each term in the summation:

$$D = \sum_{i=1}^{N} \left(M_i W_i F_i \right).$$

One of the following models will be adopted for the distribution of F_i:

1. If F_i is assumed to follow a Poisson distribution with mean f_i, then the variance of F_i is f_i.
2. If F_i is assumed to be an "overdispersed" Poisson with mean f_i, then its variance is assumed to be kf_i, where k is greater than 1.0, thus allowing for the reads to have variation greater than Poisson variation.
3. F_i was adjusted by a reader calibration factor and a relative film area. If we take the adjustment multiplier to be a *fixed value*, A_i (an approximation), then the raw count, before multiplication by A_i, was (F_i / A_i). If the raw count (F_i / A_i), is assumed to be an overdispersed Poisson with mean f_i / A_i, then its variance would be kf_i / A_i, and the variance of $F_i = A_i (F_i / A_i)$ would be $A_i^2 \mathrm{Var}(F_i / A_i) = A_i^2 k f_i / A_i = A_i k f_i$.

The most general case is assumption (3). The simpler cases (1) and (2) may be obtained by setting $A_i = 1.0$ and/or $k = 1.0$. For the purposes of the uncertainty calculation below, we will assume model (3). All of the models assume that the F_i are independent.

5.2 Neutron Dose Estimate Uncertainty Calculation

The values W_i, A_i, and k are constants, and the individual F_i reads are independent random variables. Because the modifying factors are estimated, they are random. The M_i are approximately uncorrelated with the F_i but correlated with each other. The correlation comes from two sources: (1) two films read by the same reader during the same time period will likely have the same M_i value, hence have correlation equal to 1.0 and (2) the M_i values are all estimated from the same data and have positive correlations, estimated as part of the REML estimation procedure.

An estimate of the variance of a product involving both M_i and F_i must take into account that both the M_i and the F_i are random, as well as the correlations between the M_i's. To estimate the variance of $D = \sum_{i=1}^{N} \left(M_i W_i F_i \right)$ we use the standard statistical formula

$$Var(D) = Var[E(D \mid F)] + E[Var(D \mid F)],$$

where the vertical bar denotes conditioning and is read "given," and the "E" denotes averaging, or "expectation." Assume that $E(M_i) = m_i$ and that the covariance between M_i and M_j is v_{ij}. Further assume that $E(F_i) = f_i$ and that $Var(F_i) = A_i k f_i$.

First, compute the left-hand term in the expression for $Var(D)$.

$$E(D \mid F) = E\left[\sum_{i=1}^{N} \left(M_i W_i F_i \right) \mid F \right] = \sum_{i=1}^{N} F_i W_i E\left(M_i \right) = \sum_{i=1}^{N} F_i W_i m_i = \sum_{i=1}^{N} W_i m_i F_i$$

$$Var[E(D \mid F)] = Var\left(\sum_{i=1}^{N} W_i m_i F_i \right) = \sum_{i=1}^{N} W_i^2 m_i^2 \operatorname{var}(F_i) = \sum_{i=1}^{N} W_i^2 m_i^2 A_i k f_i$$

Next, compute the right-hand term in the expression for $Var(T)$.

$$Var(D \mid F) = Var\left[\sum_{i=1}^{N} \left(M_i W_i F_i \right) \mid F \right] = \sum_{i=1}^{N} \sum_{j=1}^{N} F_i F_j W_i W_j Cov\left(M_i, M_j \right) = \sum_{i=1}^{N} \sum_{j=1}^{N} F_i F_j W_i W_j v_{ij}$$

$$
\begin{aligned}
E(Var(D|F)) &= E\left(\sum_{i=1}^{N}\sum_{j=1}^{N} F_i F_j W_i W_j v_{ij} \right) = \sum_{i=1}^{N}\sum_{j=1}^{N} E\left(F_i F_j\right) W_i W_j v_{ij} \\
&= \sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} E(F_i)E(F_j) W_i W_j v_{ij} + \sum_{i=1}^{N} E(F_i^2)\ W_i^2 v_{ij} \\
&= \sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} f_i f_j W_i W_j v_{ij} + \sum_{i=1}^{N} \left[Var(F_i) + E(F_i)^2 \right] W_i^2 v_{ii} \\
&= \sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} f_i f_j W_i W_j v_{ij} + \sum_{i=1}^{N} \left(A_i k f_i + f_i^2 \right) W_i^2 v_{ii}
\end{aligned}
$$

Combining the left-hand side and right-hand side expressions, we obtain

$$
Var(D) = \sum_{i=1}^{N} W_i^2 m_i^2 A_i k f_i + \sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} f_i f_j W_i W_j v_{ij} + \sum_{i=1}^{N} \left(A_i k f_i + f_i^2 \right) W_i^2 v_{ii} .
$$

To estimate the above variance, we need estimators of the unknown components:

1. Assume that we have $\hat{v}_{ij}$, estimates of v_{ij}, based on the REML analysis from which we computed the M_i's.
2. F_i is an unbiased estimate of f_i, except in the expression in which f_i is squared.
3. In the expression containing f_i^2, we note that
$$
\begin{aligned}
E(F_i^2) &= Var(F_i) + E(F_i)^2 \\
&= A_i k f_i + f_i^2 .
\end{aligned}
$$
This implies
$$
E(F_i^2 - A_i k F_i) = f_i^2 .
$$
Therefore ($F_i^2 - A_i k F_i$) is an unbiased estimator of f_i^2.
4. To obtain an estimator for m_i^2 we note that:
$$
E(M_i^2) = v_{ii} + m_i^2 .
$$
This implies:
$$
E(M_i^2 - v_{ii}) = m_i^2 .
$$
Therefore $(M_i^2 - v_{ii})$ is unbiased for m_i^2. Substituting $\hat{v}_{ii}$ for v_{ii} we use $(M_i^2 - \hat{v}_{ii})$ as an estimator for m_i^2.

Substituting these estimates into the variance formula, we obtain

$$\hat{V}(D) = \sum_{i=1}^{N} W_i^{\,2}(M_i^{\,2} - \hat{v}_{ii})A_i k F_i + \sum_{i=1}^{N}\ \sum_{j=1,\, j\neq i}^{N} F_i F_j W_i W_j \hat{v}_{ij} + \sum_{i=1}^{N}\left(A_i k f_i + F_i^2 - A_i k F_i\right)\, W_i^{\,2}\hat{v}_{ii}\ .$$

Simplifying the last term, we rewrite the above

$$\hat{V}(D) = \sum_{i=1}^{N} W_i^{\,2}(M_i^{\,2} - \hat{v}_{ii})A_i k F_i + \sum_{i=1}^{N}\ \sum_{j=1,\, j\neq i}^{N} F_i F_j W_i W_j \hat{v}_{ij} + \sum_{i=1}^{N}\left(F_i^{\,2}\right)\, W_i^{\,2}\hat{v}_{ii}\ .$$

The last two terms can now be combined.

$$\hat{V}(D) = \sum_{i=1}^{N} W_i^{\,2}(M_i^{\,2} - \hat{v}_{ii})A_i k F_i + \sum_{i=1}^{N}\sum_{j=1}^{N} F_i F_j W_i W_j \hat{v}_{ij}$$

5.3 An Examination of the Poisson Variance Assumption Using the Round Robin Study

Since the round robin study was a balanced and controlled experiment, we use these data to estimate the relationship between the mean and variance of the values adjusted by the estimated RMFs to see how closely that relationship conforms to the usual Poisson variance assumption. The two-way analysis of variance is done on the data in the original scale. The residuals from the two-way model represent the deviations of the individual measurements, after removal of film and reader effects. The predicted value from this analysis estimates the true value for each film.

Let Y_{ij} be the normalized dose for the film *i* and reader j. The analysis of variance (ANOVA) model is

$$Y_{ij} = f_i + r_j + e_{ij},$$

where f_i is the film effect, r_i is the reader effect (deviations from the average reader effect), and e_{ij} is the random reading error. Assume that the standard deviation of the residuals for film *i* is s_i and that s_i has a power relationship with the film value f_i:

$$s_i = k\left(f_i\right)^c .$$

If the data display Poisson variance relationships, then $k=1$ and $c=0.5$.

The residuals from the ANOVA model estimate the random reading errors, and the average of the predicted values (averaged over readers) estimates the film mean. Let s_i be the sample standard deviation of residuals for film *i*, and let p_i be the average of the predicted values for film *i*. Then the sample values should have approximately the relationship

$$s_i = k\left(p_i\right)^c .$$

Taking logarithms:

$$\log(s_i) = \log(k) + c\log\left(p_i\right).$$

The regression of $\log(s_i)$ versus $\log\left(p_i\right)$ gives the following results from SAS Proc Reg:

```
                          Parameter       Standard
Variable      DF          Estimate          Error    t Value    Pr > |t|
Intercept      1           0.03818        0.09908       0.39      0.7014
lgpmean        1           0.56960        0.06008       9.48      <.0001
```

The estimate of *c* is 0.57, which is less than one standard error from the Poisson value of 0.5. The estimate of log(*k*) is 0.038, which is less than one standard error from the Poisson value of zero. The estimate of k is therefore $10^{0.038}$=1.09, which is not significantly different from the Poisson value of 1.0

The conclusion from the above calculations is that the best estimate of the relationship between the mean and variance involves an exponent that is only slightly greater than the exponent from Poisson sampling and a constant that is only slightly greater than the Poisson multiplier. However, neither the estimated exponent nor the estimated constant is significantly different from corresponding Poisson value.

5.4 Uncertainty in Neutron Dose Estimated by Gamma Dose

If the neutron dose estimate is based on the model discussed in Section 4.3, then the variances of the prediction errors will be estimated by the formulas derived in that section. The prediction variances are added to get a total variance from predictions sources.

5.5 Combining Neutron Dose Uncertainty with Gamma Dose Uncertainty

The estimated dose from neutron reading is *D*, with estimated variance $\hat{V}(D)$. Let the total estimated neutron dose based on gamma readings be C, with estimated variance $\hat{V}(C)$, then the total dose estimate for an individual is the sum of the two: $D + C$. Since the two estimates are independent, their variances may be added: $\hat{V}(D) + \hat{V}(C)$.

Each of the individual reads or estimates included in the total dose estimate has a distribution that is skewed to the right. However, given the large number of independent components involved in a single total dose estimate, the “Central Limit Theorem” (CLT) implies that the distribution of the total dose is nearly normal. The degree of non-normality depends on the following:

- The number of films in the individual’s record. The more records, the closer the distribution of the estimated total dose is too normal.

- The extent to which the individual's record is dominated by a few large values. The more consistent the reads, the more normal the distribution of the estimated result.
- The size of the correlations between the RMFs. The more highly correlated the RMF values, the less normal the distribution of the dose estimate.
- The number of different readers. If many readers are involved in the reading of the subject's films, then the distribution of the estimated total dose will be closer to normal.

Without data, it is hard to make judgments about the conditions that increase the normality of the estimated total dose. However, it is my opinion that for an employee with moderate or long employment records the distribution of the estimated total will be adequately approximated by the normal distribution. A 95% confidence interval for the total dose for an individual is

$$D + C \pm 1.96\sqrt{\hat{V}(D) + \hat{V}(C)}\ .$$

If the burden is on the employer to demonstrate with 95% confidence that the total dose was below some fixed value, then a one-sided 95% Upper Confidence Limit (*UCL*) is

$$UCL = D + C + 1.645\sqrt{\hat{V}(D) + \hat{V}(C)}\ .$$

We have 95% confidence that the total dose was below the upper UCL.

Appendix II

Reader Modification Factor (RMF) Calculation Documentation

March 30, 2004

Phillip Chapman, Ph.D.

Outline

Summary

This report is provided as a technical supplement to Appendix I, Statistical Methods Review, dated October 31, 2003. In the Statistical Methods Review the idea of reader modification factors (RMFs) was described, several exploratory and preliminary analyses were presented, and a plan to estimate the final RMF values and their covariance matrix was proposed. The RMF discussion is summarized in Section 2.4 of the Statistical Methods Review. The purpose of this document is not to repeat that information; rather, this document details the completion of the RMF estimation process, describes the methodological decisions made in computation of the final RMF values and reports the final values.

Data Set Description

1.0 Data Set Manipulation

The data set used was the "Multiple Reads" data set dated January 9, 2004. This file contained reads of all films that were read two or more times. There were 34,626 reads in the data set, representing approximately 11,000 unique film IDs. All reads were normalized to a standard calibration factor (CF) = 30 and read area = 10. The data set was a slightly augmented version of the data set analyzed for Appendix I: Statistical Methods Review. One improvement to the project's overall statistical capability was the project's ability to provide a second read to all films whose initial track count was greater than 120 tracks. (Originally this goal was to reread all films whose initial track count was 200 or greater.) The most important addition, for the purposes of Reader Modification Factor (RMF) estimation, was the addition of approximately 220 rereads by Roger Falk. These reads were distributed with respect to the other readers so that there would be a basis for comparison of all readers to these reads by Roger, who will be treated as authoritative for the purpose of these adjustments.

Reads greater than 2500 were removed from the data set. Such reads might be unduly influential in the estimation process, and some of such reads were suspected to be errors. A very small number of values that were zero were reset to 1. A very small number of reads associated with initials DU1, DU2, DU3, and NMD were removed; these initials had too few reads to allow estimation of RMF values. Whenever removal of a read left a film with only one read, that single read was also removed; therefore, all films in the final data set had at least two reads. The maximum number of reads on a film was 12.

1.2 Justification for Not Using Films with Single Reads

In principle, films having only one read do carry some information about the tendency of a reader to read high or low; that is, single reads do carry some information about the RMF values. An alternative to using the multiple reads data set would have been to use the entire data set of over 90,000 reads to estimate the RMF values. That approach was not chosen for the following reasons:

- Quantity of information about the RMF in a single read is very low due to the very large variance between films.
- The use of the single reads for estimating RMF values depends greatly on the assumption that the films are randomly distributed among the readers. That assumption is not reasonable in this application, because readers were employed during different time periods and read films from different buildings and eras. This time effect is clearly evident in plots of normalized reads versus time. Any reader who worked primarily when films with high true values were being read would have an unexplained high read average and a *negative* estimated RMF value, erroneously adjusting the high values downward toward the mean. Adjustment for such biases might be possible, but it would be speculative. It is my

opinion that the disadvantage of the biases in that analysis would outweigh the advantage of the variance reduction due to the larger sample size.

- The limiting factor in the accuracy of the RMF estimation is primarily the number of film reads performed by Roger during his last period (RBF2).

1.3 Construction of the Reader Effects

It was clear from the history of the process that some readers were not consistent during their entire tenure. The product of individual readers was divided into up to three time periods, for which separate RMF values were estimated. The earliest time period was denoted with the original initials. Subsequent time periods were denoted by adding a 1 or a 2 after the initials. The break points for the periods were determined primarily by Roger Falk, based primarily on known dates of retraining or recertification. The time periods for readers having multiple time periods are given in Table 1.1. For all other readers a single RMF value was estimated based on their complete timeline. There were 26 RMF values estimated, including RMF2, which was set to zero.

Table 1.1 Time Period for Readers with Multiple Time Periods

MJD (start–08Jul98)	MJD1 (09Jul98–end)	
IMH (start–02Jul02)	IMH1 (03Jul02–01Sep)	IMH2 (02Sep02–end)
GPW (start–08Jul02)	GPW1 (09Jul02–01Sep02)	GPW2 (02Sep02–end)
BRH (start–16Jul02)	BRH1 (17Jul02–end)	
BAH (start–29Aug02)	DLH1 (30Aug02–end)	
DLH (start–01Jan03)	BAH1 (02Jan03–end)	
RBF (start–01Jan96)	RBF1 (02Jan96–01Oct03)	RBF2 (02Oct03–end)

2.0 The Statistical Model and Computations

2.1 Computational Method

The responses were modeled in the logarithmic (base 10) scale so that the RMF estimates would have a multiplicative interpretation (although the log scale somewhat overcorrects for the increasing variance). The log, base10, of the normalized read for the kth read of the i^{th} film by the j^{th} reader was modeled as using the following additive model.

$$Y_{ijk} = M + F_i + R_j + e_{ijk}. \tag{2.1}$$

The effects in the model are (in order): fixed overall mean, random effect for film *i*, fixed effect for reader *j*, and a random error. We assume that (in the log scale) the random film effects are approximately normally distributed with mean zero and variance s_f^2, and the random errors are approximately normally distributed with zero mean and variance to s_e^2. Random film effects and errors are all assumed to be independent. The fixed effects are relative to Roger's last group of readings (RMF2). The model could be described as an "incomplete block" model, where film is the "block" on which the various readers are compared.

The estimation of parameters was done using the restricted maximum likelihood (REML) estimation method. This method is well studied, commonly used, and had been generally found to have good statistical properties. Many statistical packages are available that compute REML estimates. General statistical packages, such as the SAS Mixed Procedure, fit this model without difficulty; however, these programs are written for very general forms of mixed models. The formulas are written in general form that involves writing and inverting the full covariance matrix of the data. On a desktop computer with 1 gigabyte of memory, the size of the data set that can be analyzed is limited to about 3500 reads. Specialized software packages are available [e.g., DFREML (Animal Genetics and Breeding Unit of the University of New England, Australia) or the Animal Breeder's Toolkit (Department of Animal Science, CSU)] that handle the analysis in a more efficient manner, but these programs require substantial setup time. I investigated the use of these programs and searched for other software packages that could be adapted to this project. I was unable to find a program that I was confident that I could adapt in a reasonable period of time.

I wrote a special purpose program for the RMF estimation using the interactive matrix language (IML) procedure in SAS. Because the 34K by 34K matrix that must be inverted has a block diagonal form, with no blocks larger than 12 by 12, the required matrix inversion can be done well within the computer's memory constraints. All of the required calculations can be done without writing a matrix larger than 26 by 34K (where 26 is the number of fixed effects in the model and 34K is the number of reads). Because the objective was to use this program only for this particular application, very little effort was put into extensive documentation within the program.

2.2 Computational Formulas for the Log Likelihood

The model in matrix form is

$$Y = Xb + Zf + e, \tag{1.2}$$

where Y is an n by 1 vector of logarithms (base 10) of the reads, b is a p by 1 vector of fixed effect parameters corresponding to the intercept and all readers except RBF2. X is an n by p matrix having 1's in the first column and the entry for row s column i equal to 1 if read s was read by reader i, 0 otherwise; f is a k by 1 vector of random film effects. Z is an n by k matrix having the entry for row s column j equal to 1 if read s involved film j, 0 otherwise. The vector e is an n by 1 vector of random errors. The elements of f are independent with variance s_f^2, and the elements of e are independent with variance s_e^2.

Given the above definitions, the covariance matrix of the vector Y is the n by n matrix

$$V = ZZ^T s_f^2 + I s_e^2,$$

where I is the n by n identity matrix.

For fixed values of the parameters and data, the restricted likelihood function is given in Searle (1992), page 325.

$$\begin{aligned} L(b, V \,|\, Y) = {} & \frac{(2p)^{1/2}\,|X^T V^{-1} X|^{-1/2}}{(2p)^{(1/2)n}\,|V|^{1/2}} \\ & \times \exp\left\{-\tfrac{1}{2} Y^T \left[V^{-1} - V^{-1}X\,(X^T V^{-1} X)^{-1} X^T V^{-1}\right] Y\right\} \end{aligned}$$

where the |.| function is the determinant of the matrix. The maximization of the likelihood is usually done in the natural log scale. The natural logarithm of the restricted likelihood function is

$$\begin{aligned} l(b, V \,|\, Y) = {} & \tfrac{1}{2}\log(2p) - \tfrac{1}{2}\log\left(\left|X^T V^{-1} X\right|\right) - \tfrac{1}{2} n \log(2p) - \tfrac{1}{2}\log(|V|) \\ & - \tfrac{1}{2} Y^T \left[V^{-1} - V^{-1}X\,(X^T V^{-1} X)^{-1} X^T V^{-1}\right] Y. \end{aligned} \tag{1.3}$$

For ease of programming the rows of the data file are sorted, first by the number of reads on each film (from smallest to largest) then by the film ID. The minimum number of reads for a film was two, and the maximum number was 12.

The key to the calculations is that, after sorting of the data file, the V matrix is block-diagonal, where the dimension of the largest block is 12 by 12, the largest number of reads per film, and the number of blocks is equal to the number of films. Once in block-diagonal form, the determinant of V can be computed as the product of the determinants of the blocks, and matrix products involving *V*. Its inverse can also be computed without actually writing *V*.

To simplify the notation, the formulas are described assuming two films, the first having two reads and the second having three reads. The pattern of the formulas will be clear.

$$Z = \begin{bmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 1 \\ 0 & 1 \end{bmatrix}$$

$$ZZ^T = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix}$$

$$V = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix} s_f^2 + \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} s_e^2$$

Define the resulting matrix

$$V = \begin{bmatrix} V_1 & 0 \\ 0 & V_2 \end{bmatrix},$$

where V_1 is 2 by 2 and V_2 is 3 by 3. The inverse of V is

$$V^{-1} = \begin{bmatrix} V_1^{-1} & 0 \\ 0 & V_2^{-1} \end{bmatrix}$$

and the determinant of V is

$$|V| = |V_1| + |V_2|.$$

Assume that the fixed effects design matrix, *X*, and the response vector *Y* are partitioned in the same fashion as *Z*:

$$X = \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \qquad Y = \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix}.$$

X_1 and X_2 identify the readers of films 1 and 2 and have 2 and 3 rows, respectively. Y_1 and Y_2 contain the log reads for films 1 and 2. The other quantities in the log likelihood can be computed in pieces without writing matrices of the size n by n. We may write

$$\begin{aligned} X^T V^{-1} X &= \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} \mathrm{V}_1^{-1} & 0 \\ 0 & V_2^{-1} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \\ &= \begin{bmatrix} X_1^T V_1^{-1} & X_2^{-1} V_2^{-1} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \\ &= \begin{bmatrix} X_1^T V_1^{-1} X_1 + X_2^{-1} V_2^{-1} X_2 \end{bmatrix} \\ &= \begin{bmatrix} X_1^T V_1^{-1} X_1 \end{bmatrix} + \begin{bmatrix} X_2^{-1} V_2^{-1} X_2 \end{bmatrix}. \end{aligned}$$

The dimension of these matrices is p by p (where $p=26$, the number of readers). Therefore, matrix $X^T V^{-1} X$ can be computed in pieces, with no individual piece being larger than 26 by 26.

Similarly, other quantities needed to compute the log likelihood function can be computed without writing large matrices. The quantity

$$\begin{aligned} V^{-1} Y &= \begin{bmatrix} V_1^{-1} & 0 \\ 0 & V_2^{-1} \end{bmatrix} \begin{bmatrix} \mathrm{Y}_1 \\ \mathrm{Y}_2 \end{bmatrix} \\ &= \begin{bmatrix} V_1^{-1} Y_1 \\ V_2^{-1} Y_2 \end{bmatrix}, \end{aligned}$$

which has dimension n by 1. The quantity

$$\begin{aligned} X^T V^{-1} Y &= \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} V_1^{-1} & 0 \\ 0 & V_2^{-1} \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} \\ &= \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} V_1^{-1} Y_1 \\ V_2^{-1} Y_2 \end{bmatrix} \\ &= \begin{bmatrix} X_1^T V_1^{-1} Y_1 + X_2^T V_2^{-1} Y_2 \end{bmatrix} \\ &= \begin{bmatrix} X_1^T V_1^{-1} Y_1 \end{bmatrix} + \begin{bmatrix} X_2^T V_2^{-1} Y_2 \end{bmatrix}. \end{aligned}$$

Each of the matrices in the in the above equation has dimension p by 1.

For ease of exposition, the formulas have been given for the case of two films. The RMF data set involves approximately 11,000 films. The formulas for the full data sets are the same, except summations are taken from 1 to 11,000 rather than 1 to 2. Because the strategy described allows the log likelihood function to be computed without explicitly writing any *n* by *n* matrices, the resulting program has very modest memory requirements and can run on any moderate-sized desktop PC, on which SAS Proc IML is installed. The program was written, and the results were compared to the results of the SAS Proc Mixed program using several small data sets of similar construction. The results of our program were also compared to the results of SAS Proc Mixed for several subsets of the multiple reads data set, up to 3500 cases (the maximum for Proc Mixed). In all cases the results of our program were identical to the result using Proc Mixed, up to at least six significant digits.

2.3 Minimization of the Likelihood Function and Estimation of the RMF Values

For fixed values of the variance parameters, the log likelihood was computed using the program described in the previous section. The desired parameter values are those that maximize the log likelihood. General purpose statistical packages include optimization routines that find the maximum of the log likelihood, usually using a Newton-Raphson-type method. Since our program was to be run only a few times for this specific problem, an optimization routine was not written into the program. The program computed the log likelihood values over a 10 by 10 grid and generated a contour plot using SAS. With four to five runs of the program with smaller and smaller scale grids, a maximum can be identified. Computation of each log-likelihood value took approximately 0.6 sec., so the grid computation took approximately 1 minute.

For REML estimates of the film to film variance $\hat{s}_f^2$ and the within film variance $\hat{s}_e^2$, the estimated covariance matrix $\hat{V}$ is given by

$$\hat{V} = ZZ^T\hat{s}_f^2 + I\hat{s}_e^2 .$$

Then, the REML estimates of the reader effects values can be computed using the following formula from Searle (1992), p. 325:

$$\hat{b} = X(X^T\hat{V}^{-1}X)^{-1}X^T\hat{V}^{-1}Y .$$

Using the techniques described above, these quantities can be calculated by the program without having to explicitly write the very large matrix $\hat{V}$.

Since the data analysis is in the logarithmic scale (base 10), the RMFs are calculated by exponentiation (base 10) of the individual components of the negative of the $\hat{b}$ vector.

2.4 Calculation of RMF Standard Errors and Covariances

The estimated covariance matrix of $\hat{b}$ is given by the formula

$$Var(\hat{b}) = (X^T \hat{V}^{-1} X)^{-1}.$$

The RMF values are computed by exponentiation (base 10) of the elements of $-\hat{b}$. We note first that $Var(\hat{b}) = Var(-\hat{b})$. An approximation to the covariance matrix of the RMF values can be computed using the "delta method," which involves approximating the exponential function by a linear one-term Taylor series approximation. If the exponential function is adequately approximated by a straight line over the region approximately plus and minus two standard deviations from $\hat{b}$, then the delta method will be adequate. This issue was addressed in Appendix I, Section 2.2. Figure 2.1 of that document indicated the linearity assumption was approximately satisfied.

Let RMF be a vector function of $\hat{b}$ as follows:

$$RMF(\hat{b}) = 10^{-\hat{b}},$$

where the exponential of a vector is defined to be a vector of exponentials. Then the estimated covariance matrix of the RMF vector is given by

$$Var(RMF) \cong \left[\frac{\partial 10^{-\hat{b}}}{\partial \hat{b}}\right] Var(\hat{b}) \left[\frac{\partial 10^{-\hat{b}}}{\partial \hat{b}}\right],$$

where the vector derivative is a diagonal matrix with diagonal component *i* equal to the derivative of the exponential function 10^x with respect to *x*, evaluated at $x = -\hat{b}_i$.

$$\frac{d\left(10^x\right)}{dx} = \frac{d\left(\exp[\log(10)x]\right)}{dx} = \exp[\log(10)x]\log(10) = 10^x \log(10)$$

In the above equation the logarithms are natural logarithms (base *e*). The estimated covariance matrix of the RMF estimates is

$$Var(RMF) \cong \left(\log(10)\right)^2 diag\left(10^{-\hat{b}}\right)(X^T V^{-1} X)^{-1} diag\left(10^{-\hat{b}}\right),$$

where $diag\left(10^{-\hat{b}}\right)$ is a square matrix with $10^{-\hat{b}_i}$ as the i^{th} diagonal element and zero is off the diagonal.

3.0 Selection of the Final RMF Values

3.1 Modifications to Reduce the Influence of Low Reads on RMF Estimates

Several modifications to the estimation procedure were considered before RMF values and covariance estimates were finalized. These modifications were in response to the perception that RMF estimates were unduly influenced by variation in the small reads. A read of 10 versus a read of 2 would have little impact on the final dose estimate for an individual, because both numbers are very low. However, a read of 10 versus 2 would have a very large impact on the RMF estimation, because the first number is five times larger than the second. The objective in these modifications was to decrease the influence of the small numbers on the RMF estimates. The following modifications were considered:

1. *Prior to computing logarithms, addition of a small constant to all data points.* The addition of a constant value to all points greatly reduces the relative discrepancy between low reads on a film but leaves the relative discrepancy of high read nearly unchanged. For example, adding a constant of 10 to the values 10 and 2 yields revised values 20 and 12. The ratio of the original numbers was five; the ratio of the revised numbers is less than two. Adding the same constant to two high reads, say 200 and 100, yields 210 and 110, and the ratio of the two numbers is changed very little. Addition of a constant is a mechanism to reduce the influence of the small values in the RMF estimation process relative to the influence of the large values, while still using the entire data set. Constants considered were 0 (i.e., no modification), 5, 10, and 14.

2. *Removal of reads with values less than a fixed constant*. This is another way to reduce the influence of low reads on the RMF estimates. The influence of values below the selected threshold is removed entirely. However, this procedure uses only part of the data. Thresholds considered were 0 (i.e., no modification), 5, 10, 15, 20, 25, and 30. When removal of reads left any film with only one read, that remaining read was also removed.

3. *Use of a combination of RMF values from modification (2).* This approach was considered in response to a problem noted in modification (2), above. When a fixed threshold was used, some readers had a far greater percentage of their reads removed than others. In this approach, RMF values for each reader were selected from the modification (2) analysis in which approximately 90% of the reads for that reader were retained.

4. *Removal of a fixed percentage of the reads for each reader.* This approach was considered to achieve a similar objective to the one in modification (3). Percentage removal was fixed at 10% by *reader*. Other percentages were not considered based on the preliminary findings from modification (2).

The final selection of the method was a collaborative effort between Joe Aldrich, Roger Falk, Jerry Follmer, and Phillip Chapman. The effect of all three modifications was to reduce the size of the RMF estimates relative to the estimates computed on the full multiple reads data set. This occurred because the relative discrepancies associated with larger or higher track count numbers were much smaller than the larger relative discrepancies associated with the much smaller or lower track count numbers. Modification (1) was not selected because the size of the constant that was needed to reduce the influence of the small numbers (10 or 14) had a noticeable effect on the large and moderate numbers, dampening the RMF adjustment too much. Also, the interpretation of the results is more difficult for this method. Modification (2) was not selected due to the large imbalance in the percentage of reads removed for each reader, leaving some readers with an unreasonably small number of reads. Modification (3) was not selected because the RMF values for different readers were selected from different analyses, leaving no easy way to estimate the covariance matrix of the RMF estimates. The estimated covariance matrix is crucial to the calculation of uncertainty, as described in Appendix I, Section 5. Modification (4) was selected because it was what appeared to be a reasonable compromise between (2) and (3). It incorporated the feature of letting the cutoff value for removal vary by reader, and it also included the estimated covariance matrix calculation that was part of each REML model fit.

3.2 Final RMF Estimates

The final estimates are given in Table 3.1, below. The readers are in alphabetical order, with the exception of SKB, who is above RBF, RBF1, and RBF2 so that the RBF estimates would be last. All RMF values are relative to RBF2, which has an estimate 0.0 and RMF 1.0. Note that the standard errors of the RMF values are generally small compared to the amount by which the RMF estimate differs from 1.0. This supports the need for these RMF adjustments, because it indicates that in this data set some readers are clearly reading at higher, or lower, levels than RBF2. Also note that the cutoff for reads (the lowest number used for that reader) varies substantially by reader, which supports the choice to remove the lowest 10%, by reader rather than 10% overall. The number of reads used for each person is also given. The total number of reads is 30,011. This total is slightly lower than 90% of the original data set, because removal of individual reads left some reads as singletons, which had to be removed. The estimated covariance of the RMF values is not presented here. It will be transmitted separately as an Excel file, which will be used in the uncertainty calculation described in Appendix I, Section 5.

Table 3.1 Final RMF Estimates, Standard Errors and Cutoff Values

Reader	Est.	S.E.(Est.)	RMF	S.E.(RMF)	Cutoff	Number reads	Pct. total reads
ADA	0.173	0.012	0.671	0.019	27.3	1004	3.4
AZA	0.103	0.012	0.788	0.022	24.3	1149	3.8
BAH	-0.108	0.012	1.282	0.035	10.9	2030	6.8
BAH1	0.041	0.012	0.910	0.024	18.1	1975	6.6
BES	0.025	0.012	0.943	0.026	15.3	1452	4.8
BRH	-0.077	0.012	1.195	0.034	11.8	1040	3.5
BRH1	0.089	0.012	0.815	0.022	18.4	1783	5.9
CEA	-0.089	0.012	1.227	0.035	11.9	911	3.0
CLF	-0.021	0.013	1.050	0.031	18.7	657	2.2
DLH	-0.065	0.018	1.162	0.048	19.8	134	0.5
DLH1	-0.080	0.016	1.202	0.044	16.3	179	0.6
GPW	-0.088	0.011	1.225	0.032	12.3	4034	13.4
GPW1	-0.107	0.015	1.279	0.043	11.5	322	1.1
GPW2	-0.048	0.011	1.117	0.029	15.0	3032	10.1
IMH	-0.067	0.011	1.167	0.031	13.0	4408	14.7
IMH1	-0.206	0.015	1.605	0.055	7.7	282	0.9
IMH2	-0.110	0.012	1.289	0.036	11.9	1029	3.4
JSB	0.258	0.019	0.553	0.024	22.3	109	0.4
KR	-0.029	0.013	1.069	0.032	15.1	516	1.7
MBR	0.161	0.013	0.690	0.021	29.9	497	1.7
MJD	0.172	0.014	0.673	0.022	32.9	341	1.1
MJD1	-0.049	0.012	1.119	0.032	18.5	977	3.3
SKB	-0.161	0.012	1.450	0.040	12.0	1402	4.7
RBF	-0.020	0.014	1.048	0.035	26.8	308	1.0
RBF1	0.082	0.015	0.828	0.028	22.2	252	0.8
RBF2	0.000	0.000	1.000	0.000	16.7	188	0.6

Appendix III

Neutron Dose Variance Modification

September 15, 2004

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Outline

Summary

In the "Statistical Methods Review" (Appendix I), dated October 31, 2004, methods were proposed for estimating the variance of neutron dose estimates. Those methods were based on the assumption that the film reads would display a relationship between the mean and the variance that is much like that of the Poisson distribution for which the variance equals the mean. To allow for the possibility that the variance would exceed the mean a proportionality constant was added to model, thereby allowing the variance to be a constant multiple *(k)* of the mean. This document describes the methods by which that constant was estimated as $k = 4.1$. This document also describes an alternative model that appears to be better supported by the data. In the new model the variance is k times the mean to the p^{th} power, where k and p are estimated to be 0.6 and 1.5, respectively. In this document the variance formulas of Appendix I are modified to allow for the new variance model. The effect of the modification on the variance estimates is to increase the estimated variance of films that have high readings relative to films that have low readings. The new formulas generally assign greater uncertainty to the neutron dose estimates, particularly for individuals that have high estimated doses.

1.0 The Statistical Model for Extra-Poisson Variation

Section 5.2 of Appendix I (Statistical Methods Review) addressed the issue of estimating the uncertainty of the neutron dose estimate. In that document it was assumed that film reads would have a variance given by the Poisson distribution, possibly with extra-Poisson variation. In that discussion, F_i was a normalized film read and A_i was the constant by which it had been normalized. The model assumed that the un-normalized film read, F_i / A_i, had a distribution with mean f_i / A_i, and variance $k\left(f_i / A_i \right)$. A value of k = 1.0 would imply a Poisson distribution (for which the mean equals the variance) for the un-normalized film reads. Values of k greater than 1.0 allow extra-Poisson variation. Values of k less than 1.0 are not considered reasonable, because the actual number of tracks in a fixed area of film can be reasonably modeled as Poisson. Variability due to reading error will add, not subtract, from the Poisson variability. Analysis of the round robin study data did not indicate a need for extra-Poisson variation; however, the round robin study involved relatively few films that were read in a relatively short period of time. The size of the extra-Poisson variation is expected to be an important factor influencing the size of the variance estimate.

The normalized film read F_i was assumed to have mean f_i. The variance of F_i is then

$$Var(F_i) = Var[A_i (F_i / A_i)] = \left(A_i\right)^2 k f_i / A_i = A_i k f_i \,.$$

A dose D for an individual is estimated using a combination of the normalized reads.

$$D = \sum_{i=1}^{N} \left(M_i W_i F_i \right),$$

where M_i is the RMF value for read number i, and W_i is the weight applied to that particular read (e.g., two reads on the same film would have W_i values equal to ½, indicating that they are to be averaged). The details of that discussion are not reproduced here (see Appendix I). Based on the above assumptions, an estimator of the variance for a dose estimate was given in Appendix I by

$$\hat{V}(D) = \sum_{i=1}^{N} W_i^{\,2} (M_i^{\,2} - \hat{v}_{ii}) A_i k F_i + \sum_{i=1}^{N} \sum_{j=1}^{N} F_i F_j W_i W_j \hat{v}_{ij} \,.$$

2.0 Estimation of Extra-Poisson Variation Using the Multiple Reads Data Set

Extra-Poisson variation was estimated using the Multiple Reads data set (the one from which the RMF values were estimated). The estimation process was as follows:

- The data were analyzed in the original (not log transformed scale). This scale was used because the final dose estimation was also in the original scale and variance estimates produced would also apply to this scale.

- The normalized film reads were modified using the RMF values estimated previously. This was done because it was believed that some of the apparent extra-Poisson variation was really just a systematic inconsistency between readers, which could be removed by the RMF adjustment. The objective was to model extra-Poisson variance that remained after this adjustment.

- The normalized film reads were used for estimation rather than the un-normalized reads. This was done so that the two films reads would be adjusted to the same read area. In principle, we might like to adjust for film area but not reader calibration factor, but these two terms were combined into one term in the data set. In any event, these adjustments are very small because the normalization constants are fairly close to 1.0. The normalization factor in the new formula contains a square root, which further diminishes the influence of the normalization. (The square root of a number close to 1.0 is even closer to 1.0.)

- Normalized reads with values greater than 2500 were omitted so that data errors would not contribute instability to the estimates.

- Only the first two reads (by date) of each film were used. This choice was made because many of the third, fourth, or fifth reads were taken as the result of a discrepancy between the first two reads. Inclusion of the later reads may negatively bias the variance estimates by diluting the effect of the more discrepant observations.

- The sample variance of each pair (s_i) of reads on the same film was plotted and regressed (through the origin) on the mean (m_i) for each pair: $s_i = km_i + e_i$. Since the variance of the individual observations increased with the size of the measurement, the least squares regression was weighted inversely proportionally to the square of m_i.

The extra-Poisson variation estimated by this process was k = 4.1. The interpretation of this result is that the standard deviation of the normalized RMF-adjusted film reads is approximately twice [=sqrt(4.1)] what one would expect from a Poisson distribution.

3.0 Dependence of the Extra-Poisson Variation Estimate on the Size of the Measurement

A sequence of regressions of sample variance s_i versus sample mean m_i for the paired reads indicated that restriction of the sample mean to smaller values led to smaller estimates of k. This observation supports the idea that extra-Poisson variation is greater for large values relative to small ones. This led to the revised model:

$$s_i = k\left(m_i\right)^p + e_i .$$

The value $p = 1$ yields the original model; a value of $p > 1$ reflects extra-Poisson variation that is relatively greater for larger values. This model was fit for a variety of values of p.

Table 3.1 Percentage Variation Explained for Various Values of *p*

p	Percent
1.0	20.5
1.1	21.7
1.2	22.8
1.3	23.6
1.4	24.1
1.5	24.2
1.6	24.1
1.7	23.3

The percentage of variability in s_i that is explained by the model, as a function of p, is given in Table 3.1. The value $p = 1.5$ was selected and the formulas for variance were recalculated to include this adjustment. The new model then assumes that the un-normalized film read, F_i / A_i, has a distribution with mean f_i / A_i and variance $k\left(f_i / A_i\right)^{1.5}$. Therefore,

$$E(F_i) = f_i \text{, and}$$
$$Var(F_i) = Var[A_i(F_i / A_i)] = A_i^2 Var(F_i / A_i)$$
$$= A_i^2 k(f_i / A_i)^{1.5} = A^{0.5} k f_i^{1.5} .$$

To estimate the variance of $D = \sum_{i=1}^{N}\left(M_i W_i F_i\right)$, we use the standard statistical formula

$$Var(D) = Var[E(D \mid F)] + E(Var(D \mid F) .$$

First, compute the left-hand term in the expression for $Var(D)$.

$$E(D|F) = E\left[\sum_{i=1}^{N}\left(M_i W_i F_i\right) | F\right] = \sum_{i=1}^{N} F_i W_i E\left(M_i\right) = \sum_{i=1}^{N} F_i W_i m_i = \sum_{i=1}^{N} W_i m_i F_i$$

$$Var[E(D\,|\,F)] = Var\left(\sum_{i=1}^{N} W_i m_i F_i\right) = \sum_{i=1}^{N} W_i^2 m_i^2 \operatorname{var}(F_i) = \sum_{i=1}^{N} W_i^2 m_i^2 A_i^{0.5} k f_i^{1.5}$$

Next, compute the right-hand term in the expression for $Var(D)$.

$$Var(D\,|\,F) = Var\left[\sum_{i=1}^{N}\left(M_i W_i F_i\right) | F\right] = \sum_{i=1}^{N}\sum_{j=1}^{N} F_i F_j W_i W_j Cov\left(M_i, M_j\right) = \sum_{i=1}^{N}\sum_{j=1}^{N} F_i F_j W_i W_j v_{ij}$$

$$\begin{aligned} E[Var(D\,|\,F)] &= E\left(\sum_{i=1}^{N}\sum_{j=1}^{N} F_i F_j W_i W_j v_{ij}\right) = \sum_{i=1}^{N}\sum_{j=1}^{N} E\left(F_i F_j\right) W_i W_j v_{ij} \\ &= \sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} E(F_i) E(F_j) W_i W_j v_{ij} + \sum_{i=1}^{N} E(F_i^2) W_i^2 v_{ij} \\ &= \sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} f_i f_j W_i W_j v_{ij} + \sum_{i=1}^{N}\left[Var(F_i) + E(F_i)^2\right] W_i^2 v_{ii} \\ &= \sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} f_i f_j W_i W_j v_{ij} + \sum_{i=1}^{N}\left(A_i^{0.5} k f_i^{1.5} + f_i^2\right) W_i^2 v_{ii} \end{aligned}$$

Combining the left-hand side and right-hand side expressions, we obtain:

$$Var(D) = \sum_{i=1}^{N} W_i^2 m_i^2 A_i^{0.5} k f_i^{1.5} + \sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} f_i f_j W_i W_j v_{ij} + \sum_{i=1}^{N}\left(A_i^{0.5} k f_i^{1.5} + f_i^2\right) W_i^2 v_{ii}$$

To estimate the above variance, we need estimators of the unknown components:

- Assume that we have $\hat{v}_{ij}$, estimates of v_{ij}, based on the REML analysis from which we computed the M_{ij}'s. The computation of these estimates is described in Appendix II.

- F_i is an unbiased estimate of f_i, except in the expression in which f_i is squared or $f_i^{1.5}$.

- In the expression containing f_i^2 (the third term in the variance formula), we note that $E(F_i^2) = Var(F_i) + E(F_i)^2 = A_i^{0.5} k f_i^{1.5} + f_i^2$. This implies that F_i^2 is an unbiased estimator of $A_i^{0.5} k F_i + f_i^2$.

- In the first term of the variance formula, we substitute the estimator $F_i^{1.5}$ for the value $f_i^{1.5}$. This estimator is positively biased. The size of this bias is investigated below.

- To obtain an estimator for m_i^2 we note that $E(M_i^2) = v_{ii} + m_i^2$. This implies $E(M_i^2 - v_{ii}) = m_i^2$. Therefore, $(M_i^2 - v_{ii})$ is unbiased for m_i. Substituting $\hat{v}_{ii}$ for v_{ii}, we use $(M_i^2 - \hat{v}_{ii})$ as an estimator for m_i^2.

Substituting these estimates into the variance formula, we obtain

$$\hat{V}(D) = \sum_{i=1}^{N} W_i^2 (M_i^2 - \hat{v}_{ii}) \left(A_i \right)^{0.5} k \left(F_i \right)^{1.5} + \sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} F_i F_j W_i W_j \hat{v}_{ij} + \sum_{i=1}^{N} \left(F_i^2 \right) W_i^2 \hat{v}_{ii} .$$

The second and third term can be combined.

$$\hat{V}(D) = \sum_{i=1}^{N} W_i^2 (M_i^2 - \hat{v}_{ii}) \left(A_i \right) k \left(F_i \right)^{1.5} + \sum_{i=1}^{N} \sum_{j=1}^{N} F_i F_j W_i W_j \hat{v}_{ij}$$

We recognize the above formula as only a slight modification to the old formula from Appendix I:

$$\hat{V}(D) = \sum_{i=1}^{N} W_i^2 (M_i^2 - \hat{v}_{ii}) A_i k F_i + \sum_{i=1}^{N} \sum_{j=1}^{N} F_i F_j W_i W_j \hat{v}_{ij} .$$

The new formula is

$$\hat{V}(D) = \sum_{i=1}^{N} W_i^2 (M_i^2 - \hat{v}_{ii}) A_i^{0.5} k F_i^{1.5} + \sum_{i=1}^{N} \sum_{j=1}^{N} F_i F_j W_i W_j \hat{v}_{ij} .$$

When comparing the new formula to the old formula we note the following differences:

- All changes are to the first term (single sum); the second term remains unchanged.

- The exponent on the A factor is now 0.5.

- The exponent on the F factor is now 1.5.

- The value of k is now 0.62 rather than the previous value of 4.1.

The net effect of this formula will be to increase the variance estimate for individuals that have many high values, reflecting the fact that the variation in the normalized reads increases with the mean to the 1.5 power. It is interesting to note that this is half way between the Poisson distribution, for which the variance increases proportionally to the mean to power 1.0, and the lognormal distribution, for which the variance increases proportionally to the mean to the power 2.0.

4.0 Graphical Comparison of the Two Variance Models

The first model assumed that the variance of F_i was a constant multiple of F_i,

$$Var(F_i) = A_i k f_i \,,$$

where k is estimated as 4.1. The second model assumed that the variance of F_i was a slight different multiple of $F_i^{1.5}$,

$$Var(F_i) = \left(A_i\right)^{0.5} k \left(f_i \right)^{1.5},$$

where k is estimated as 0.6.

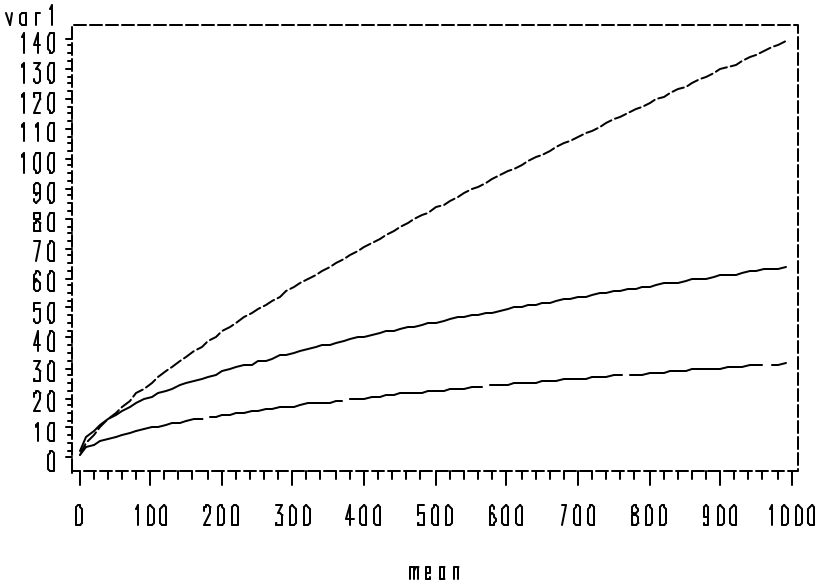

Figure 4.1 The standard deviation versus the mean for three variance models

The two assumptions are compared graphically in Figure 4.1, where the standard deviations of the models (square root of variance) are graphed versus the mean value. The basic Poisson model without extra-Poisson variation (k = 1) is included for reference. The bottom line refers to the model without extra-Poisson variation. The variability implied by this model is clearly too low. The middle line refers to the model with constant extra-Poisson variation (k = 4.1). The top line refers to the modified assumption that assumes variance increases proportionally to $f_i^{1.5}$. The top and middle lines describe very similar variance estimates when the mean is 100 or less. For larger values of the mean, the model with $f_i^{1.5}$ gives much higher variance estimates. These higher variances will result in much larger variance estimates for individuals, particularly individuals with high film reads. This choice is supported by the data. This choice could also be described as "worker favorable," in that a larger estimated variance will increase the upper limit of the confidence bound for individuals with high values.

5.0 Estimation of the Size of the Bias Resulting from Estimating $f_i^{1.5}$ Using the Estimator $F_i^{1.5}$

A crude approximation to the expectation of the estimator $F_i^{1.5}$ can be obtained using a two-term Taylor series expansion for the function $f(x) = x^{1.5}$.

$$\begin{aligned}
F^{1.5} &\cong f^{1.5} + 1.5 f^{0.5}(F - f) + 1.5(0.5) f^{-0.5}(F - f)^2 / 2 \\
E\left(F^{1.5}\right) &\cong f^{1.5} + 1.5 f^{0.5} E(F - f) + 1.5(0.5) f^{-0.5} E(F - f)^2 / 2 \\
&\cong f^{1.5} + 0 + 1.5(0.5) f^{-0.5} Var(F) / 2 \\
&\cong f^{1.5} + 1.5(0.5) f^{-0.5} A^{0.5} (0.62) f^{1.5} / 2
\end{aligned}$$

Taking $A^{0.5} \cong 1.0$, and simplifying we obtain

$$E(F^{1.5}) \cong f^{1.5} + 0.23 f\ .$$

The bias is then $0.23 f$, which is very small relative to the $f^{1.5}$ term. We therefore conclude that estimating $f_i^{1.5}$ using the estimator $F_i^{1.5}$ is acceptable.

6.0 Implementation of the Variance Formulas

The estimation and variance formulas were communicated to Jerry Follmer, who programmed them into the ORISE database. SAS Proc IML programs were written to compute the same estimation and variance formulas. The results of Jerry's program and the SAS Proc IML program were compared by using the data of two different individuals in the database, over several different time periods. The two sets of computations agreed to within round-off error.

Appendix IV

Notional Dose Methodology

September 19, 2004

Phillip Chapman, Ph.D.

Outline

1.0 Prediction of Neutron Doses Based on the Same Building in the Previous Year

2.0 Prediction of Neutron Doses for Individual Badges in Building 71 Based on Data from the Same Year

3.0 Prediction of Neutron Doses in Building 71 Based on Data After Subdividing Yearly Data into Groups Representing Different Monitoring Cycles

4.0 Selection of the Notional Dose Estimation Methodology

5.0 Uncertainty Estimation for the Final Notional Dose Estimate

6.0 Conclusions

Summary

The neutron dose methodology described in Appendices I, II, and III applies to the estimation of the neutron dose during periods for which neutron films exist. This document describes the estimation of neutron dose during gap periods for which neutron doses do *not* exist. These estimates are based on two methodologies: (1) estimation using neutron film reads from non-missing periods within the same year and (2) estimation using the gamma doses recorded during periods of missing neutron dose, together with the estimated neutron-to-gamma ratio. Because estimation of neutron doses for missing periods is somewhat speculative, we use the term "notional dose" to distinguish these estimates from those based directly on reread neutron films, which we believe have a very solid justification.

The regression model for estimating the neutron doses, based on gamma values, and the methodology for assigning a variance to those estimates is discussed in Section 4 of Appendix I. That discussion is not repeated here. In this document we describe data analysis that supports the choice of the specific methodology used for notional dose estimates and their associated variance estimates. The methodology is developed using a "matched pairs" data set in which neutron film values were paired with gamma values for the same periods. The data set contained approximately 76,000 records. For some analyses neutron and gamma doses are summed by year, yielding one gamma/neutron pair for each individual in each building in each year (approximately 8700 records).

The data analyses demonstrated that notional dose estimates based on interpolated or extrapolated neutron reads are generally much more accurate than the corresponding estimates based on neutron/gamma ratios. The data analyses also demonstrated that notional dose estimates computed from neutron/gamma ratios are better when based on building, rather than individual, neutron/gamma ratios. The notional dose estimator that was finally chosen was a weighted average of an estimate based on the individual's neutron reads from the non-gap period in a year and the individual's gamma reads from the gap period for the same year multiplied by the building neutron/gamma ratio for that building in that year. The estimator weighted the neutron film portion of the estimator according to the ratio of the non-gap days to the sum of gap and non-gap days for an individual in a given year. Thus, an individual who had neutron reads available for 80% of the year and a gap for 20% of the year, during which only gamma values are available, would receive a notional dose estimate for the gap period that was 80% derived from the neutron read average and 20% derived from the gamma value. An individual who had no neutron reads for a year would receive a notional dose estimate for the year based entirely on his/her gamma value for the year multiplied by the building neutron/gamma ratio.

The variance estimate for all notional doses was computed as if the entire notional dose had been obtained from the neutron-to-gamma ratios. This choice was made partially due to the difficulty of finding a variance estimator that would be applicable for all of the possible configurations of gap periods and partially due to the desire to be conservative (i.e., estimate high) with the variance estimate. The notional dose estimates should be considered somewhat speculative, and their variance estimates should be considered quite approximate. However, the actual precision of the estimates is thought to be generally better than claimed, particularly for individuals for whom the notional dose estimate is derived primarily from the neutron portion of the estimator.

1.0 Prediction of Neutron Doses Based on the Same Building in the Previous Year

The following calculations are based on the yearly totals. The database had been summed over the multiple badges of the same year to give a neutron total for the year, along with its corresponding gamma total for the same individual in the same year. The distribution of records by building and year were as given in Table 1.1. Based on Table 1.1 and guidance from Roger Falk, the analysis is focused on building years 1965 to 1969 for Buildings 76 and 77 and years 1963 to 1969 for Building 71.

Table 1.1 Frequency of Annual Records by Building and Year

Bldg./Yr.	1953	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	Total
21/22/23	0	0	0	4	4	0	0	0	0	0	0	0	0	0	8
23	0	0	0	0	6	6	23	20	15	34	0	9	29	0	142
44	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
705	0	0	0	0	0	0	0	0	0	0	0	24	0	0	24
71	0	50	117	118	113	457	681	707	640	674	679	710	616	0	5562
76	0	0	72	120	0	0	0	1	216	257	225	268	255	4	1418
76/77	0	0	0	0	0	0	0	0	254	0	0	0	0	0	254
77	0	0	12	0	0	0	6	5	151	167	152	121	102	55	771
78	0	0	0	0	0	0	0	0	0	0	25	26	26	0	77
79	0	0	0	0	0	0	0	0	0	0	29	21	0	0	50
79-05	0	0	0	0	0	0	0	0	0	0	0	16	20	0	36
86	0	0	0	0	0	0	0	0	15	16	18	23	22	17	111
91	7	0	84	58	12	9	9	10	22	22	0	10	9	0	252
Total	**7**	**50**	**285**	**300**	**135**	**472**	**719**	**743**	**1313**	**1170**	**1128**	**1229**	**1079**	**76**	**8706**

The objective of the analysis was to compare various methods of estimating the yearly total for individuals based on data from the same individuals in the previous year. This analysis mimics the situation where no neutron values are recorded in a building in the entire year.

The strength of the relationship between gamma and neutron data within a year appears relatively weak, as indicated by Figure 1.1. However, in the log scale, Figure 1.2, the positive relationship can be clearly seen.

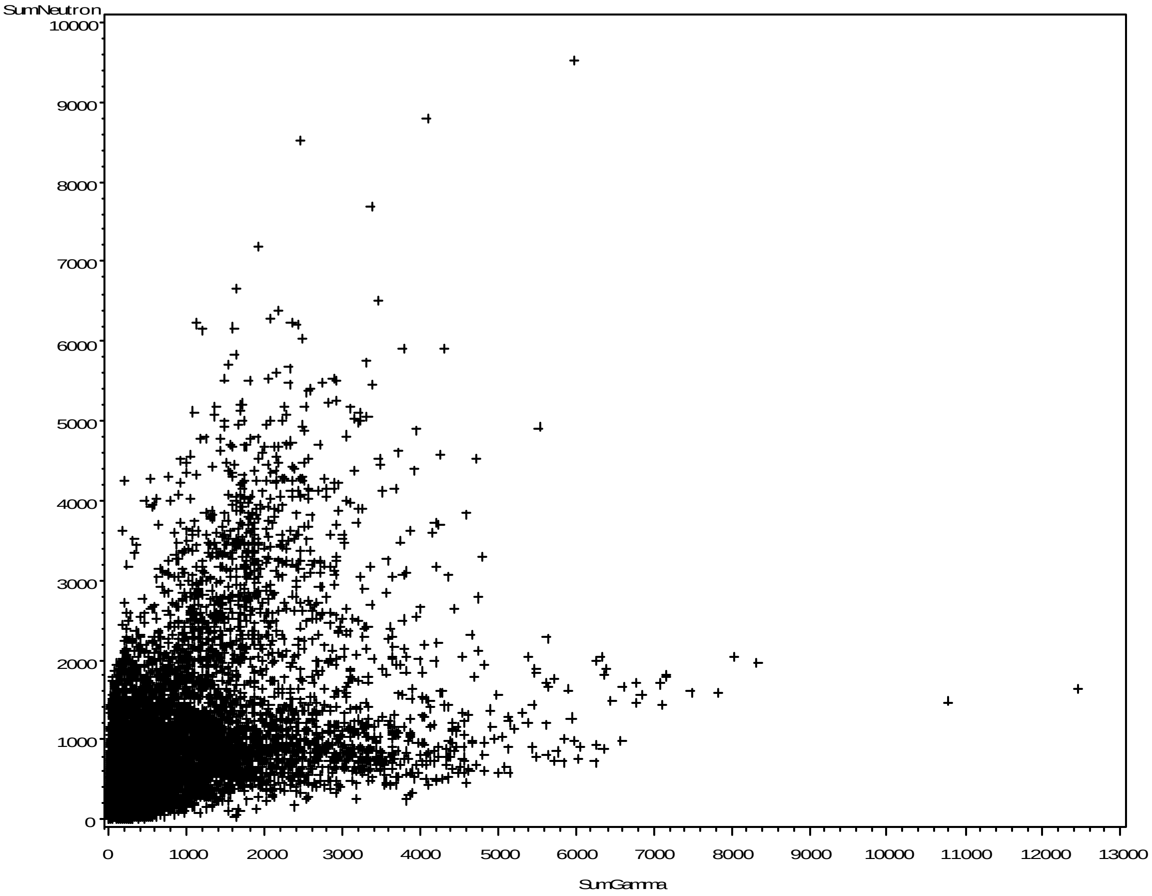

Figure 1.1 Annual Neutron Dose Versus Annual Gamma Dose for Individuals

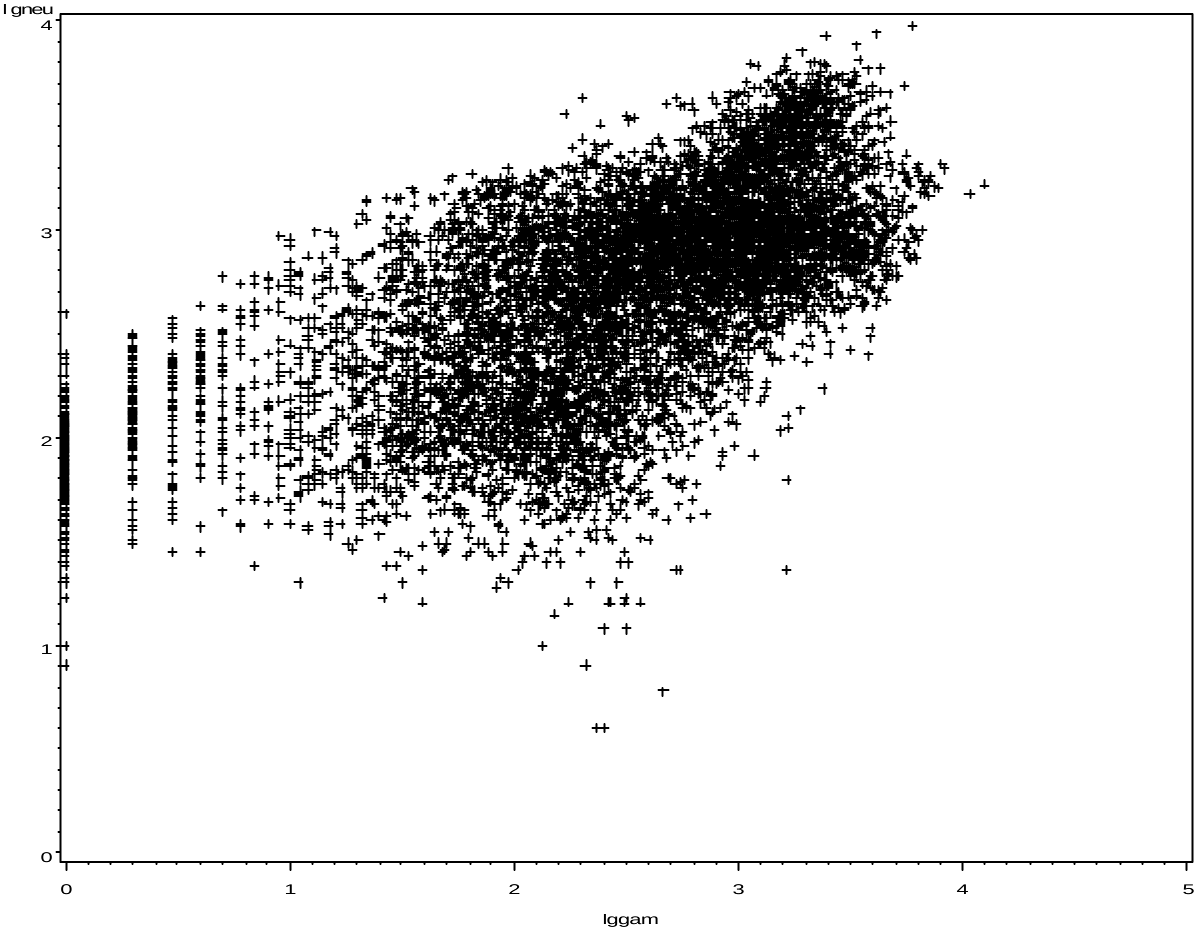

Figure 1.2 Log Annual Neutron Dose Versus Log Annual Gamma Dose for Individuals

Table 1.2 Comparisons of Estimation Methods When Data from One Year Are Used to Estimate the Dose for the Following Year

						Basic		**Common**		**Individual**		**Bounded**		**Weighted**	
Bldg	**Year2**	**Freq**	**Neutron2**	**Ratio1**	**Ratio2**	**Error**	**Bias**	**Error**	**Bias**	**Error**	**Bias**	**Error**	**Bias**	**Error**	**Bias**
71	1963	372	1813	2.2	2.3	1016	165	788	124	2496	1570	1110	163	850	180
71	1964	565	1574	2.3	3.0	391	216	867	-370	1282	375	705	-384	725	-446
71	1965	538	954	3.0	1.1	633	607	1720	1554	3064	3018	1418	1311	1413	1293
71	1966	470	864	1.1	0.6	260	104	993	846	1542	1469	1012	941	926	877
71	1967	478	861	0.6	0.7	374	93	491	-85	1559	1067	532	47	416	-77
71	1968	501	908	0.7	1.3	396	-73	536	-400	748	-66	543	-270	513	-332
71	1969	451	1027	1.3	1.4	345	-78	427	-119	857	393	513	44	449	-36
76	1966	146	466	0.3	0.3	158	-107	394	266	1929	1750	543	425	399	317
76	1967	167	661	0.3	0.3	190	-95	265	-157	296	-121	211	-121	212	-142
76	1968	132	884	0.3	0.9	219	-53	477	-460	505	-416	483	-431	486	-469
76	1969	116	761	0.9	2.1	152	-51	254	-246	295	-109	235	-174	234	-218
77	1966	120	659	0.8	0.5	177	31	732	552	714	625	684	589	651	548
77	1967	132	766	0.5	0.6	132	-36	369	-84	300	1	277	-24	264	-26
77	1968	90	973	0.6	1.0	141	43	319	-288	310	-252	311	-252	311	-264
77	1969	87	767	1.0	0.9	96	87	179	12	375	255	222	97	166	39
Total/Average		**4365**	**929**	**1.1**	**1.1**	**312**	**57**	**588**	**76**	**1085**	**637**	**587**	**131**	**534**	**83**

Five methods of estimating annual neutron dose are compared.

1. “Basic” estimate: Uses the individual’s neutron dose from the previous year, multiplied by the ratio of the days monitored in the year (Days2) to the number of days monitored in the previous year (Days1) to adjust for the differing lengths of monitoring.

2. “Common” estimate: Uses the building neutron-to-gamma (N/G) ratio from the previous year multiplied by the gamma dose from the current year.

3. “Individual” estimate: Uses an individual’s N/G ratio from each year to estimate his/her own N/G ratio for the following year.

4. “Bounded” estimate. Same as the individual estimate above, except all N/G ratios above 5.0 are replaced by 5.0 and all ratios below 0.20 are replaced by 0.2.

5. “Weighted” estimate: Uses a weighted average of the common estimate and the bounded estimate, where the bounded estimate is weighted according to the number of days on which the individual’s N/G ratio was based (days/365). The common estimate is weighted as (1 – days/365).

The results of the analyses are reported in Table 1.2. The quantities reported in that table are the following:

1. The year of the data being estimated: Year2.

2. The number of individuals being estimated for that year. The same individual must have been present during Year2 and the previous year.

3. The average neutron total for Year2.

4. The N/G ratio for both years.

5. The average of the absolute values of the prediction errors for each method.

6. The average bias (the average of the true values minus the predicted values).

From the simulation results of Table 1.2 several conclusions are apparent. The method with the smallest average absolute error is the basic method, in which the neutron dose for an individual is estimated by the neutron dose from the same individual from the previous year, adjusted to the number of days of monitoring. The method with the largest average absolute error is the individual method, in which the neutron-to-gamma ratio N/G from the previous year is used together with the neutron dose for the current year to estimate the neutron dose for the current year. It is clear that individual N/G ratios are far too erratic to use. The performance of the individual ratios improves when the individual ratios are bounded or combined with the common building ratio.

This analysis supports the idea of using an individual's own observed neutron information to estimate neutron dose for missing periods, whenever that is possible. There are, however, several factors that constrain the ability to use neutron values in this way. This analysis was performed on Buildings 71, 76, and 77 and only for years in which those buildings were consistently monitored. The analysis also was only performed on individuals who worked in the same building for both years under consideration. A substantial portion of the missing observations, for which estimates are needed, would not have such neutron data available.

2.0 Prediction of Neutron Doses for Individual Badges in Building 71 Based on Data from the Same Year

The following analysis used the badge level data to estimate neutron dose for randomly selected badges for each individual. The procedure is described below. Initial runs used all data from a given year. Subsequent analysis, reported in the next section, divided data from some years to "year groups," based on the length of monitoring.

Data preparation was as follows:

1. The average N and (sum N)/(sum G) ratio were calculated for each year.
2. The number of badges for each Unique ID in each year was calculated. Individuals with more than 27, or fewer than 3, badges in a year were eliminated.
3. One badge for each individual in each year was randomly selected.
4. For each individual in each year the (sum N)/(sum G) ratio was calculated based on the badges *not* selected.

Estimation methods were as follows:

1. Base estimate of badge N. The N for each badge was estimated using the average N for badges from that individual in that building in that year. (No adjustment was made for the length of time each badge was worn.)
2. Common estimate of badge N. The N for each badge was estimated using the N/G ratio for that year, multiplied by the badge G value.
3. Individual estimate of badge N. The N for each badge was estimated using the N/G ratio for that individual in that year, multiplied by the badge G value.
4. Bounded estimate of badge N. The same as the individual estimate, except ratios above 10 were reset to 10 and ratios below 0.1 were reset to 0.1.
5. Mixed estimate for badge N. The average of the common and the individual estimates.

The two types of results reported were:

1. Abs, absolute deviation between the estimate and the badge N value being estimated
2. Bias, the average of the estimates, minus the average of the badge N values being estimated

Table 2.1 Absolute Error and Average Bias When Predicting Individual Badge Neutron Based on Data from the Same Year

		Bldg Neutron	Bldg Ratio	Basic		Common		Individual		Bounded		Mixed	
Year	**Freq**			**Error**	**Bias**	**Error**	**Bias**	**Error**	**Bias**	**Error**	**Bias**	**Error**	**Bias**
1959	105	150.9	1.3	83.8	-2.0	121.9	20.1	133.2	37.9	127.8	31.5	95.9	18.0
1960	49	94.1	2.9	33.8	-4.0	65.4	-22.4	71.4	-2.4	61.5	-33.5	42.4	-3.2
1961	104	182.2	1.7	79.6	-12.0	105.7	-4.6	97.9	10.0	95.2	3.0	71.7	-1.0
1962	181	194.1	2.2	92.7	7.5	96.1	-5.5	109.7	23.0	99.7	5.2	85.1	15.3
1963	604	96.3	2.3	46.4	4.5	63.1	-10.7	80.5	15.6	56.5	-19.6	51.6	10.0
1964	579	81.1	3.0	30.9	4.7	71.8	-3.0	79.6	22.2	57.1	-24.6	46.2	13.5
1965	519	105.2	1.1	51.5	-3.2	105.1	-8.5	108.7	9.6	91.7	-14.0	72.1	3.2
1966	493	95.0	0.6	40.2	3.8	79.4	3.0	81.0	14.2	79.3	14.0	52.5	9.0
1967	528	83.7	0.7	41.2	6.5	75.3	6.5	71.6	18.7	67.5	14.2	47.8	12.6
1968	510	91.0	1.3	56.1	3.0	75.7	-1.5	76.7	9.0	72.4	2.9	58.7	6.0
1969	475	98.7	1.4	39.2	7.6	74.3	-0.8	107.7	43.2	74.9	2.4	62.5	25.4
Average	**4147**	**100.9**	**1.6**	**47.5**	**3.4**	**79.9**	**-2.2**	**88.4**	**18.9**	**73.9**	**-3.2**	**58.1**	**11.1**

Table 2.2 Absolute Error and Average Bias When Predicting Individual Badge Neutron Based on Data from the Same Year (Results Modified by Adding 15 to Each Gamma Value)

		Bldg Neutron	**Bldg Ratio**	**Basic**		**Common**		**Individual**		**Bounded**		**Mixed**	
Year	**Freq**			**Error**	**Bias**	**Error**	**Bias**	**Error**	**Bias**	**Error**	**Bias**	**Error**	**Bias**
1959	105	150.9	1.2	68.1	14.0	75.0	7.4	97.3	24.4	95.0	22.0	71.7	19.2
1960	49	94.1	2.0	36.5	-6.5	55.2	-14.9	46.8	-5.1	47.0	-11.2	37.1	-5.8
1961	104	182.2	1.5	71.4	-12.7	85.7	-11.9	81.0	2.9	81.4	1.8	60.7	-4.9
1962	181	194.1	1.9	91.9	2.4	80.2	-18.5	86.3	2.1	82.8	-4.3	80.0	2.2
1963	604	96.3	1.7	43.8	4.6	51.1	-5.0	46.5	0.2	45.8	-1.6	38.4	2.4
1964	579	81.1	1.9	33.4	-0.4	46.6	-9.7	40.6	-3.0	39.7	-7.8	33.1	-1.7
1965	519	105.2	1.0	48.1	0.5	96.9	2.6	89.2	13.6	87.8	10.5	61.7	7.0
1966	493	95.0	0.5	41.6	3.1	75.9	3.3	71.5	11.6	73.5	15.0	49.7	7.3
1967	528	83.7	0.6	46.4	0.8	64.7	-5.4	53.6	1.5	54.6	3.8	43.6	1.1
1968	510	91.0	1.1	59.4	-1.8	76.1	1.7	66.9	0.9	67.4	1.5	56.9	-0.4
1969	475	98.7	1.2	37.5	8.1	65.8	5.8	61.1	13.6	59.6	9.0	42.0	10.8
Average	**4147**	**100.9**	**1.2**	**47.5**	**1.9**	**68.4**	**-2.3**	**63.0**	**5.3**	**62.6**	**3.8**	**48.5**	**3.6**

The various methods of estimation were run with and without stabilizing the gamma values by adding 15 to the gamma values (this is almost like putting the background back in). The results are reported in Tables 2.1 and 2.2.

Of the methods considered, the method with the smallest average absolute errors is the method that estimates the badge neutron value using the average of the other neutron badge values from the same individual in the same year. The methods that use the N/G ratio did not perform as well. The building average N/G ratio works better than the individual N/G ratios, although the performance of the latter improves when the individual ratios are bounded. The method that mixes the building N/G and the individual N/G ratios also shows promise.

The gamma readings in the data set had been adjusted for estimates of the background gamma radiation. The neutron readings in the data set were not so adjusted. As a result of the gamma background adjustment, many individual badges estimate gamma levels of zero. The zeros in the database were replaced with the value 1 mrem. The large numbers of very small gamma values inflated the building ratio and led to erratic estimates. To investigate remedies to this problem, methods were considered that involved adding a small constant to the individual gamma readings. The small constant lowered the estimates of the building ratios. When the modified gamma readings were multiplied by the new ratio, the results were neutron estimates that were closer to the average neutron value for the building; that is, small neutron estimates were increased and high neutron estimates were lowered. The new estimates had, on average, smaller absolute errors. The merits of this approach will be discussed in Section 4.

3.0 Prediction of Neutron Doses in Building 71 Based on Data After Subdividing Yearly Data into Groups Representing Different Monitoring Cycles

This section reports some further data analysis exploring potential methods to improve the quality of the estimates. The methods of the previous section ignored the length of the badge cycle. The basic estimated neutron dose for a badge was computed as the average dose of the other badges for the same individual in the same year. The averages were simple averages, ignoring the number of days in the badge replacement cycle. We did not expect that this method would negatively affect the basic method, because an individual who stayed in the same job would probably stay in the same badge cycle throughout the year. There was a concern, however, that combining badges representing different cycle lengths would affect the estimates based on the N/G ratio, because N/G estimates were based on a common ratio for individuals, which was estimated using individuals on varying badge cycles. Different badge cycles might represent different jobs, which would have different ratios of N/G.

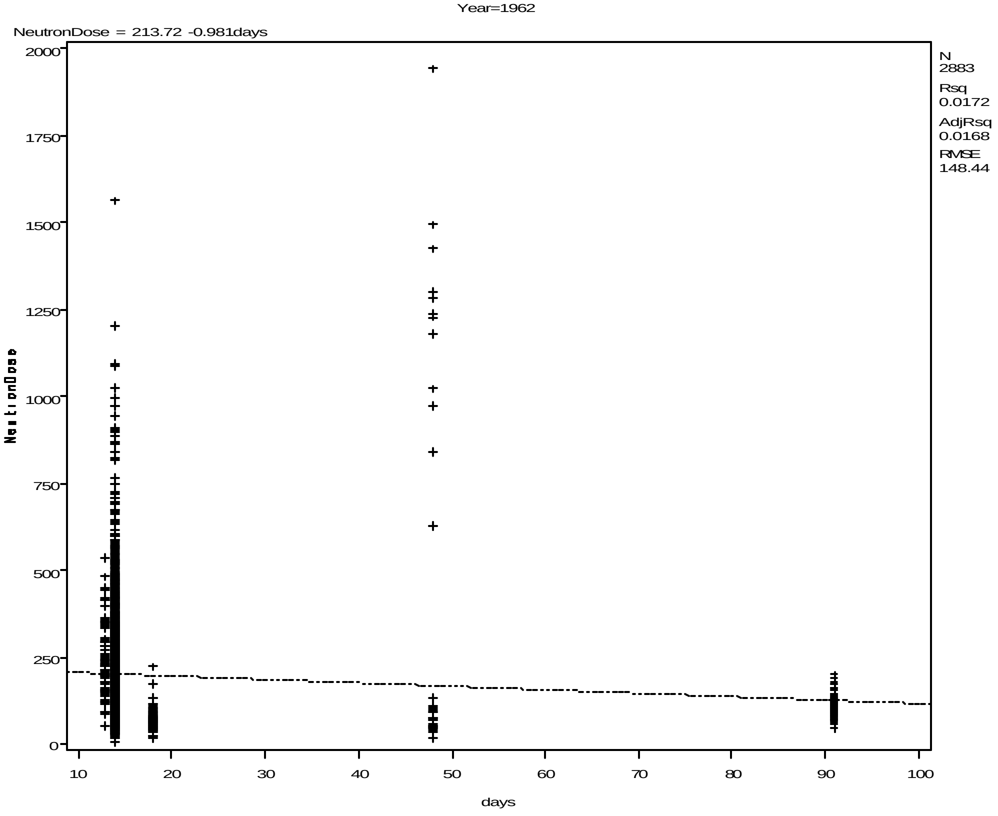

Figure 3.1 Plot of Neutron Dose by Days in the Badge cycle for Building 71, 1962.

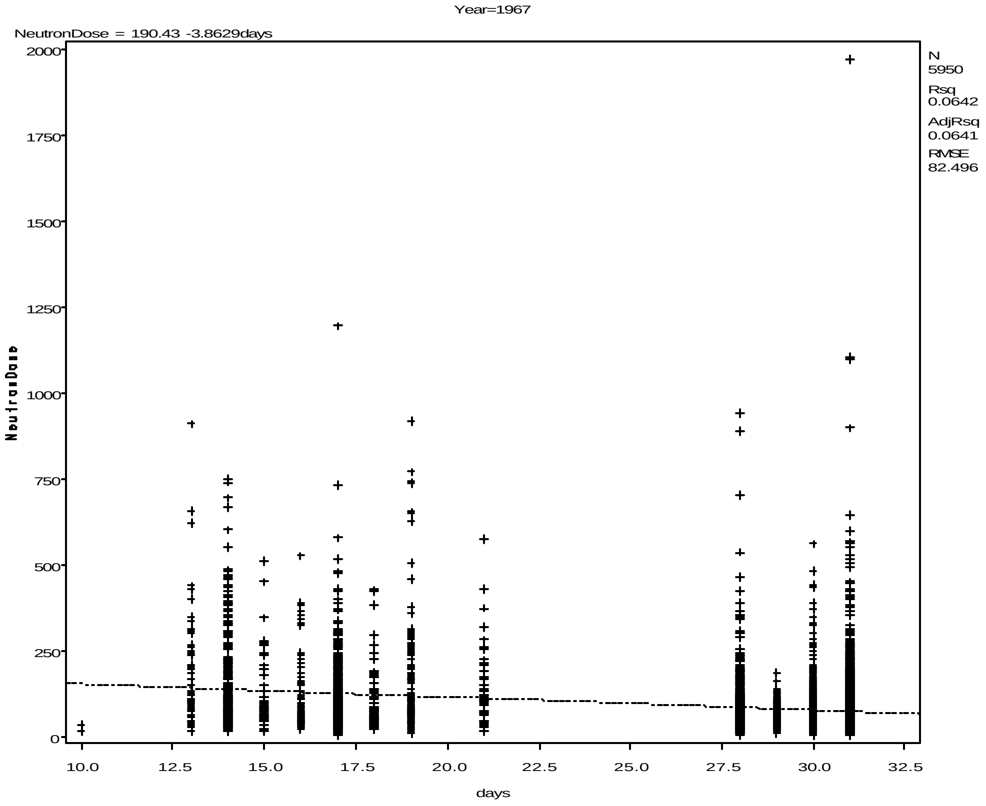

Figure 3.2 Plot of Neutron Dose by Days in the Badge Cycle for Building 71, 1967

Figures 3.1 and 3.2 are examples of building/year combinations in which one can easily identify groups of individuals with different badge cycles. Ordinarily, one would expect that badges worn for longer periods of time would represent higher doses. In general, this did not turn out to be the case; often badges worn on longer cycles recorded less total radiation. This is probably because individuals in jobs most likely to have high exposure were assigned shorter badge cycles.

Based on inspection of graphs and knowledge of building history from Roger Falk, year data were split into badge cycle groups. Various runs were made with different groupings of badge cycles into finer or coarser groupings. The results of one of the coarser groupings are reported in Table 3.1, and the results of the same analysis, with 15 added to stabilize the estimates, are reported in Table 3.2. In these tables only the averages of the absolute errors are reported, not the average bias.

Table 3.1 Simulation Results for Various Methods: Years Subdivided into Badge Cycle Groups

Year/Group	Freq	Bldg neutron	Bldg N/G ratio	Base Com	Base Ind	Base Mix	N/G Com	N/G Ind	N/G Ind Bnd	N/G Mix
1959	107	150.9	1.3	81.5	72.1	71.9	99.9	98.0	98.0	96.1
1960	116	94.1	2.9	35.2	30.5	32.9	92.7	103.4	96.7	88.7
1961	105	182.2	1.7	65.7	58.9	59.1	113.0	102.1	101.6	101.4
1962a	199	197.4	2.4	92.8	87.2	90.8	100.3	108.5	105.0	99.0
1963	622	96.3	2.3	42.8	34.1	35.8	65.6	83.0	70.3	64.8
1964	635	81.1	3.0	32.1	29.5	29.8	68.4	70.0	58.1	59.8
1965	559	105.2	1.2	47.3	47.7	46.9	102.7	132.5	114.7	114.5
1966	548	95.0	0.6	41.2	38.4	38.1	82.8	107.3	90.6	81.6
1967	574	83.7	0.7	49.2	42.6	43.2	76.1	72.2	67.9	66.7
1968a	188	116.5	1.6	99.2	97.7	95.8	108.3	99.1	99.1	100.9
1968b	411	67.7	1.0	28.9	30.6	28.6	54.1	70.7	66.3	59.5
1969a	185	106.6	1.3	43.9	40.3	39.7	74.3	81.3	81.4	77.6
1969b	318	87.6	1.7	32.6	37.5	33.5	77.6	120.3	90.6	87.3
Totals	**4567**	**99.2**	**1.6**	**46.3**	**43.2**	**43.1**	**79.9**	**93.3**	**82.4**	**79.2**

Table 3.2 Simulation Results for Various Methods: Years Subdivided into Badge Cycle Groups (15 Added to Gamma Value for Each Badge.)

Year/Group	Freq	Bldg neutron	Bldg N/G ratio	Base Com	Base Ind	Base Mix	N/G Com	N/G Ind	N/G Ind Bnd	N/G Mix
1959	107	150.9	1.2	75.6	65.4	66.7	90.8	106.0	106.0	101.9
1960	116	94.1	2.0	38.7	36.8	37.3	55.3	54.1	54.1	51.2
1961	105	182.2	1.5	70.6	59.0	65.3	92.3	84.5	84.5	82.8
1962a	199	197.4	2.0	81.6	83.1	82.9	78.5	81.5	81.5	79.0
1963	622	96.3	1.7	46.6	35.6	37.8	50.2	49.9	49.9	47.3
1964	635	81.1	1.9	32.5	30.7	30.4	49.2	41.1	41.1	40.5
1965	559	105.2	1.0	47.8	50.3	48.2	91.4	82.3	82.3	83.1
1966	548	95.0	0.6	42.6	40.6	40.0	72.7	72.4	72.4	66.0
1967	574	83.7	0.6	43.1	37.3	37.8	62.9	48.5	48.5	51.0
1968a	188	116.5	1.3	89.4	91.7	86.8	79.0	83.3	83.3	78.6
1968b	411	67.7	0.8	24.6	27.8	24.7	49.9	49.2	49.2	46.3
1969a	185	106.6	1.1	46.3	48.0	45.1	62.5	62.7	62.7	58.6
1969b	318	87.6	1.3	41.2	42.3	40.8	75.0	67.8	67.8	68.0
Totals	**4567**	**99.2**	**1.2**	**45.8**	**43.5**	**42.9**	**66.1**	**61.8**	**61.8**	**60.1**

Estimation methods are as follows:

1. “Base Com.” The N for each badge was estimated using the average N for that building in that year or year group.

2. “Base Ind.” The N for each badge was estimated using the individual’s average N for that building in that year or year group.

3. “Base Mix.” The N for each badge was estimated using a mix of the Com and the Ind, where the Ind was weighted according to proportion of 365 days that were accounted for by the individual’s badges.

4. “NG Com.” The N for each badge was estimated using the NG ratio for that year or year group, multiplied by the badge G value.

5. “NG Ind.” The N for each badge was estimated using the NG ratio for that individual in that year or year group, multiplied by the badge G value.

6. “NG Ind Bnd.” The same as NG Ind, except ratios above 10 were reset to 10 and ratios below 0.1 were reset to 0.1.

7. “NG Mix.” The average of the NG Com and the NG Ind Bnd estimates.

The results of the simulation experiment lead to several conclusions. Grouping the data into badge cycles within each year yielded little or no improvement in the estimates. The estimates of individual missing badges using the non-missing badges from the same individual working in the same year still appears to give the estimates with the smallest average absolute errors. The methods based on the N/G ratio are much more variable. Some stabilization of the N/G method by adding 15 to each gamma dose value reduces average absolute. The relative merits of this stabilization will be discussed in the next section.

4.0 Selection of the Notional Dose Estimation Methodology

In this section we describe the notional dose estimation procedure that was selected. The selection was influenced by the preceding analyses as well as other practical considerations.

The primary conclusion from the data analysis is that for a short gap in the neutron film record the best single estimate of a neutron dose is based on the average daily neutron dose recorded during the non-gap periods for the same individual in the same year. However, for large gaps, which comprise a large portion of the year, this method carries substantial risk because: (1) the non-gap periods are short and contain relatively few neutron badges, (2) short non-gap periods are likely to be concentrated in a single portion of the year, which may not be representative of the whole year. Due to these risks it was decided not to base the entire notional neutron dose estimate for gap periods on the reread neutrons films. It was decided that the notional neutron dose estimate should be based on a combination of neutron badge values and estimates from N/G ratios.

Estimates based on N/G ratios were generally more accurate when the common building N/G ratio was used rather than individual worker N/G ratios. Some combinations of common and individual ratios were considered; however, these were rejected as too complicated and not consistently better than the common ratio by itself. In the data analysis the individual N/G ratios were highly variable. This variability was aggravated by the adjustment for background, which left many gamma dose values at or near zero and the ratio very large. (For the purposes of N/G ratio estimation, zero estimates were converted to 1 mrem in the data set.) The estimation of individual N/G ratios was improved by bounding the ratio estimate to what were considered by NDRP personnel to be reasonable values. There was no formal analysis investigating which level of bounding would produce the best results. However, bounding was only an issue in three years in Building 91 for which bounds of ten were fixed.

Building N/G ratios were estimated using aggregation methods suggested by Roger Falk, based on knowledge of building process history. Individual estimates were made for Buildings 71, 76, 77, and 91. Years for which no matched N/G pairs were available were extrapolated from neighboring years, again based on the knowledge of Roger Falk. Data to estimate N/G ratios for all other buildings were believed insufficient for separate estimation. They were considered similar enough to pool together. The results of Roger's efforts are given in Table 11.1 of the Neutron Dose Reconstruction Protocol.

The estimation method chosen for the notional dose is a weighted average between the estimate based on the reread neutron films and the estimate based on the N/G ratio. The two estimates are weighted according to the number of days for which neutron films are present, relative to the total number of days for which neutron films are present plus the number of days in the gap. The formulas to implement this method are given below.

- N = total neutron dose estimate from reread films for the non-gap periods for an individual in a given year.

- D_N = number of days represented by those reread neutron films for the non-gap periods.
- D_G = number of days of gap, for which only gamma doses are available.

- G = the gamma dose for the gap period.

- R = the neutron to gamma ratio for that building in that year (from Table 11.1 of the Neutron Dose Reconstruction Protocol).

Then N/D_N is the neutron dose per day based on the reread films and $(D_G)(N/D_N)$ is the notional dose estimate for the gap based on the reread film. $(R)(G)$ is the notional dose estimate based on the N/G ratio method.

The two estimates are combined using $W_N = D_N/(D_N + D_G)$ and $W_G = D_G/(D_N + D_G)$ into a single estimate (E) as follows:

$$E = W_N(D_G)(N/D_N) + W_G(R)(G)\,.$$

When the gap is small, the notional dose is determined primarily by the reread film values from the same year. When the gap is large, the notional dose is determined primarily by the N/G ratio and the gamma values in the gap periods. Although the idea of the method is reasonable, the choice of proportional weights was somewhat arbitrary. No attempt was made to identify an optimal combination of weights.

There are two implications of the choice of estimator that warrant some further discussion. Note that the weighting formula defaults to an estimate based entirely on the N/G ratio for building/year combinations in which there were no neutron badge readings (i.e., $D_N = 0$ and $W_N = 0$). One can make an argument based on the first data analysis, in which the neutron dose from an individual in one year was used to estimate the neutron dose for the same individual in the following year, that neutron dose estimates from neighboring years might be a better estimate than the estimate based on the N/G ratios. Although this argument may have some validity, there was a strong preference for basing the notional dose estimates on some measurement (e.g., the gamma value) taken directly during the year in question. The notional dose estimation process sometimes involved estimating neutron doses several years removed from actual neutron readings. It was believed that the N/G ratio would be more stable over a longer period of time than the neutron value itself. Another reason for using the chosen method was that it did not require making separate adjustments for the many individual situations that are possible in the estimation effort. The method chosen was a fixed rule.

The other issue that merits discussion was the choice not to stabilize the N/G ratios by adding a constant to the gamma value of each film. Various constants were tried, and the value 15 appeared to significantly reduce the average absolute error in the simulations, although no formal attempt at optimizing this particular value was made. In general, addition of a small constant reduced the estimate N/G ratios substantially. The use of the reduced N/G ratio estimated after adding 15, along with the individual gamma doses after adding 15, left the *average* neutron estimate based on those values nearly unchanged. However, the method raised the low estimates and lowered the high estimates, generally "shrinking" all estimates closer to the center. Bringing the estimates closer to the center reduced the variability in the estimates and reduced the average absolute errors of estimation. The use of this method was strongly opposed by Neutron Dose Reconstruction Project (NDRP) personnel over three concerns: (1) That the mechanism of adding 15 to the gamma value might be perceived as an arbitrary change in the estimate of the gamma dose, rather than just a mechanism for stabilizing the neutron dose estimates, (2) since the stabilization method involved adding 15 to each gamma film, the amount added to an individual's gamma dose total for the year would depend on the number of gamma films included in the gap, leading to unreasonably large increases in the neutron estimates for some individuals, and (3) there was a concern that this attempt to make the *average* absolute error smaller would increase the absolute error for some individuals whose neutron doses were truly high. In view of the objections and uncertainties, it was decided not to use the stabilization constant.

5.0 Uncertainty Estimation for the Final Notional Dose Estimate

The notional dose estimate described in the previous section was

$$E = W_N\,(D_G)(N/D_N) + W_G(R)(G)\ .$$

In principle, a variance estimate for this weighted sum could be obtained by summing variance estimates for the two individual terms. Summing would be justified because the gamma doses obtained during the gap periods could reasonably be argued as independent of the reread neutron films obtained during the non-gap periods. A variance estimation method for the right-hand term has already been derived and presented in Section 4 of Appendix I. A variance estimator for the other term is more problematic. If the gap periods were missing at random, a variance estimator could be developed using individual badge simulations much like the ones used in Section 2 of this appendix. Such estimates would have to be adjusted for a variety of situations involving the number and configuration of gap periods within the year, and also the level of dose values for the non-gap periods. (Individuals at high dose levels would be expected to have larger variances than individuals at lower doses.) The result of such an effort would be complicated and speculative.

It was decided that the variance estimation method derived for the N/G portion of the estimate would be used and that this method would be applied to the entire estimate as if the weight of the last term in the variance equation (W_G) were 1.0. This decision could be viewed as conservative, because the variance of the portion of the notional dose that was based on reread neutron films has been demonstrated to have lower variance than the portion estimate using the N/G ratios. Therefore, it is likely that the true variance of the estimate would be lower than the estimate based solely on the N/G methodology. This decision also could be viewed as "worker favorable," because an overestimate of the variance widens confidence intervals and leads to higher upper confidence limits. An upper confidence limit may be interpreted informally as an upper limit on where the individual's true neutron dose during the gap period is likely to lie. Higher upper confidence limits support the possibility of higher levels of true exposure.

The estimated variance of a notional dose based on N/G ratios for a particular building/year combination was given in Appendix I as

$$\hat{s}^2 G + G^2 \frac{\hat{t}^2}{\sum_{i=1}^{n} g_i}\ ,$$

where

- G is the total gamma dose for the gap periods for that individual in that building in that year.

- g_i is the gamma dose for the i^{th} individual in the matched pairs data set used to estimate the N/G ratio for that building in that year.

- Y_i is the total neutron dose corresponding to g_i in the matched pairs data.

- $\sum_{i=1}^{n} g_i$ is the total of the gamma doses in the matched pairs data set for that building in that year.

- $\hat{b} = \frac{\sum_{i=1}^{n} Y_i}{\sum_{i=1}^{n} g_i}$ is the estimated N/G ratio for that building in that year (called R in the earlier discussion).

- $\hat{t}^2 = \frac{1}{n-1} \sum_{i=1}^{n} \frac{\left(Y_i - \hat{b} g_i\right)^2}{g_i}$.

- $\hat{s}^2 = \hat{t}^2 - k\hat{b}$, where k is the overdispersion parameter estimated as 4.1 in Appendix III (prior to the modification of the overdispersion model described in that appendix).

These formulas were derived prior to the modifications to the overdispersion model that are described in Appendix III. These formulas use the simpler model of Appendix I, in which the overdispersion was proportional to the mean, rather than the model of Appendix III, which assumed that overdispersion was proportional to the mean to the 1.5 power. For the purposes of notional dose variance estimation, we kept the simpler model. We did this for two reasons:

1. The proportionality assumption of Appendix I allows variance formulas to take a very simple form. Under the model of Appendix I, the term $\hat{t}^2 = \hat{s}^2 + k\hat{b}$ has a simple additive structure. When the more complicated model of Appendix III is used, the computations become much more complicated.

2. The $\hat{s}^2$ part of the formula is the weighted variance of the *true* neutron values around the N/G regression line. The $k\hat{b}$ part is the adjustment for the fact that the actual regression is based on read neutron values, which differ to some degree from the true value. For all of the building/year combinations considered the $k\hat{b}$ part of the formula is very much smaller than the $\hat{s}^2$ part, so the choice of model

for overdispersion has relatively little effect on the final variance estimate. Inspection of the estimates of $\hat{t}^2$ and $\hat{s}^2$ for all of the building/year combinations are given in Tables 5.1 and 5.2. Note that the tausq ($\hat{t}^2$) and sigsq ($\hat{s}^2$) columns are generally very close. Therefore, the adjustment for overdispersion had little effect.

Table 5.1 The ssgamma ($\sum_{i=1}^{n} g_i$), tausq ($\hat{t}^2$) and sigsq ($\hat{s}^2$) Estimates (Rounded) for Buildings 71, 76, and 77

Building	Year	Ratio	Freq	ssgamma	sigsq	sigsqp	tausq	tausqp
71	1959	1.4	117	197,644	1017	1017	1023	1023
71	1960	2.8	118	110,097	3978	3978	3989	3989
71	1961	1.7	113	179,888	1119	1119	1126	1126
71	1962	2.2	457	255,005	1069	1069	1078	1078
71	1963	2.3	681	407,313	2701	2701	2710	2710
71	1964	3.1	707	319,674	5922	5922	5935	5935
71	1965	1.2	640	487,639	1394	1394	1399	1399
71	1966	0.6	674	806,021	534	534	537	537
71	1967	0.7	679	736,127	723	723	726	726
71	1968	1.3	710	458,506	813	813	818	818
71	1969	1.5	616	373,646	1960	1960	1966	1966
Building	Year	Ratio	Freq	ssgamma	sigsq	sigsqp	tausq	tausqp
76	1959	0.6	72	89,207	165	994	168	996
76	1960	0.6	120	110,012	1489	994	1492	996
76	1965	0.4	216	251,876	268	268	269	269
76	1966	0.3	257	504,990	360	360	361	361
76	1967	0.4	225	438,757	172	172	173	173
76	1968	0.9	268	134,919	1126	1126	1129	1129
76	1969	2.1	255	32,646	1310	1310	1319	1319
Building	Year	Ratio	Freq	ssgamma	sigsq	sigsqp	tausq	tausqp
77	1959	1.3	12	6,088	2665	1637	2670	1643
77	1963	1.6	6	5,448	252	1637	258	1643
77	1964	1.6	5	996	544	1637	551	1643
77	1965	0.8	151	108,896	765	765	768	768
77	1966	0.5	167	225,762	868	868	870	870
77	1967	0.6	152	201,847	500	500	503	503
77	1968	0.9	121	79,696	1118	1118	1121	1121
77	1969	0.9	102	31,139	393	393	396	396

Shaded rows indicate variances from years with similar ratios that were pooled to increase sample size.

Table 5.2 The ssgamma ($\sum_{i=1}^{n} g_i$), tausq ($\hat{t}^2$) and sigsq ($\hat{s}^2$) Estimates (Rounded) for Buildings 91 and Other Combined Buildings

Building	Year	Ratio	Freq	ssgamma	sigsq	sigsqp	tausq	tausqp
91	1959	3.6	84	6,198	1944	1944	1959	1959
91	1960	6.8	58	1,798	4917	4917	4945	4945
91	1961	7.4	12	777	13653	14719	13683	14760
91	1962	10.0	9	341	35353	14719	35394	14760
91	1963	10.0	9	480	5959	14719	6000	14760
91	1964	10.0	10	606	10005	14719	10046	14760
91	1965	3.3	22	2,174	2622	3441	2636	3450
91	1966	1.2	22	3,183	4816	3441	4821	3450
91	1968	2.1	10	525	2140	3441	2148	3450
91	1969	7.3	9	432	9639	14719	9669	14760
Building	Year	Ratio	Freq	ssgamma	sigsq	sigsqp	tausq	tausqp
Other	1959	1.2	253	299,137	1387	1387	1392	1392
Other	1960	1.8	254	221,974	4682	4682	4690	4690
Other	1961	1.8	131	180,890	3117	3117	3124	3124
Other	1962	2.3	472	255,988	1999	1999	2009	2009
Other	1963	2.3	715	414,476	2821	2821	2831	2831
Other	1964	3.0	739	321,898	5924	5924	5937	5937
Other	1965	0.9	1031	895,391	1255	1255	1259	1259
Other	1966	0.5	1062	1,544,851	898	898	900	900
Other	1967	0.6	1000	1,381,714	1045	1045	1047	1047
Other	1968	1.2	1028	680,689	1512	1512	1517	1517
Other	1969	1.5	996	446,527	2411	2411	2418	2418

Shaded rows indicate variances from years with similar ratios that were pooled to increase sample size.

When sample sizes were sufficient, error variances (tausquare and sigsquare) were estimated for individual year/building combinations. When sample sizes were small, years having similar N/G ratios were pooled for the purpose of estimating variances.

- Building 71: Minimum sample size was 113. No years were pooled.
- Building 76: Years 1959 and 1960 were pooled together.
- Building 77: Years 1959, 1963, and 1964 were pooled together.

- Building 91: Years 1961, 1962, 1963, 1964, and 1969 were pooled. Also, years 1965, 1966, and1968 were pooled.

- Other buildings: Minimum sample size was 129. No years were pooled.

The pooled values are in a column just to the right of the original estimates. The rows that were pooled together are indicated with a common level of shading.

Inspection of the $\hat{t}^2$ and $\hat{s}^2$ values in the tables indicates that the estimates of variance are large and highly variable. It was discovered that the size and the variability of the estimates could be reduced by omitting from the estimation procedure observations that were below a small cutoff value. Cutoff values of 5, 10, and 15 were considered. Increasing the cutoff was found to decrease the estimates $\hat{t}^2$ and $\hat{s}^2$. (Details of this analysis are not presented here.) It was concluded that this was a symptom of lack of fit to the model. According to the model, the variance of the estimates should be a constant multiple of the gamma dose. However, it was discovered that for low gamma dose levels, the relative variance of the estimate about the true neutron value was higher than the corresponding variance for high dose levels. The presence of the lower gamma values in the average greatly increased the average variance estimate, because the very high relative errors associated with the lower gamma values. Thus, use of the cutoff produced lower and more stable variance estimates because the relatively larger variances of the small values were omitted. The use of the cutoff would be expected to generate lower variance estimates, particularly for individuals with high values.

It was decided that the cutoffs would not be used. The estimates computed without the cutoff were larger, so this choice of methodology was conservative in that it resulted in larger variance estimates. The choice was also “worker favorable” in that it would result in a wider confidence interval.

6.0 Conclusions

The quality of the notional dose estimates is probably somewhat uneven. For building/year combinations in which neutron films are widely available, and the notional dose represents an occasional missing film, the notional dose estimate should be very good, much better than claimed by the variance estimate. For building/year combinations in which neutron films are not available, the notional doses are highly speculative. We operate on the assumption that the N/G for those years can be estimated by N/G ratios from adjacent, or sometimes even distant, years. There is no way to check that assumption. In those cases notional dose estimates should be taken as “better than nothing.” To reflect this uncertainty, methodological choices have been made at every stage of the analysis that will tend to overstate, rather than understate, the claimed variability of the estimates.