Paper

A BOUNDING ESTIMATE OF NEUTRON DOSE BASED ON MEASURED PHOTON DOSE AROUND SINGLE PASS REACTORS AT THE HANFORD SITE

Timothy D. Taulbee,* Samuel E. Glover,* Gregory V. Macievic,* Mickey Hunacek,[†] Cheryl Smith,[†] Gary W. DeBord,[‡] Donald Morris,[†] and Jack Fix[†]

Abstract—Neutron and photon radiation survey records have been used to evaluate and develop a neutron to photon (NP) ratio to reconstruct neutron doses to workers around Hanford's single pass reactors that operated from 1945 to 1972. A total of 5,773 paired neutron and photon measurements extracted from 57 boxes of survey records were used in the development of the NP ratio. The development of the NP ratio enables the use of the recorded dose from an individual's photon dosimeter badge to be used to estimate the unmonitored neutron dose. The Pearson rank correlation between the neutron and photon measurements was 0.71. The NP ratio best fit a lognormal distribution with a geometric mean (GM) of 0.8, a geometric standard deviation (GSD) of 2.95, and the upper 95th % of this distribution was 4.75. An estimate of the neutron dose based on this NP ratio is considered bounding due to evidence that up to 70% of the total photon exposure received by workers around the single pass reactors occurs during shutdown maintenance and refueling activities when there is no significant neutron exposure. Thus when this NP ratio is applied to the total measured photon dose from an individual film badge dosimeter, the resulting neutron dose is considered bounded.
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INTRODUCTION

ALL WORKERS entering one of the Hanford restricted areas, such as the B, D/DR, C, F, H, KE, or KW single pass cooling reactor areas, were assigned a beta/photon personnel dosimeter that monitored their expo-

sure (Parker 1948). Neutron exposures at the Hanford single pass reactors were primarily monitored using portable instruments and activation analysis of various metal foils to determine the neutron fluence rate and thus dose. Some workers who would enter neutron exposure areas were monitored using Nuclear Track emulsion film type A (NTA film) and slow neutron pencil dosimeters. There has been some question as to the accuracy of the NTA film due to a combination of a neutron energy threshold coupled with the relative sensitivity of the film. The site discontinued the use of NTA film around reactors in April 1966 (HAPO 1966) due to the neutron energy limitation. For dose reconstructions under the Energy Employees Occupational Illness Compensation Program Act (EEOICPA), neutron exposures have been estimated based on the use of a neutron to photon ratio (NP ratio). The general hypothesis is that increased neutron doses around reactor facilities are accompanied by an increase in photon doses. To evaluate this hypothesis, paired neutron and photon survey data have been identified, captured, and analyzed to establish a method that allows for the determination of neutron doses to workers around the single pass reactors.

It is important to note that this paper was developed in support of EEOICPA dose reconstructions. The methods used to evaluate and determine the NP ratio are inherently conservative in nature and tend to overestimate the true (unbiased) neutron exposure. In the following text there are examples illustrating the conservative assumptions used in this analysis as well as a discussion explaining why the assumptions were used for EEOICPA purposes. In addition, where appropriate, we have included in the discussion how the presented data should be modified in order to obtain a best estimate of the neutron dose as opposed to the bounding estimate used for EEOICPA.

METHODS

Survey data identification

Through some trial and error, samples of survey records were identified that contained neutron survey measurements that were recorded in the mid 1950's on "Radiation Survey Logsheets." A keyword search on the word "survey" was conducted on the multiple Hanford computerized records systems to identify these records. A total of 748 boxes of records were identified that appeared to contain radiation survey data from 1945 through 1972. Of these, 238 were from the reactor areas, 231 from the separations areas, 59 were from the fuel and target manufacturing area, and the remaining 220 were not indicated or could not be determined due to inadequate area identification in the database. A sampling matrix for selecting boxes was developed with the goal to obtain: 1) at least one box of records per year; 2) a complete temporal history of F reactor; and 3) 1 y for all reactors.

Data capture

During the data capture, 64 boxes containing survey sheets were reviewed by a team of health physicists and the pages containing neutron survey measurements were tagged for scanning. In general, there were about 2,500 pages of surveys in each box. On average there were only about 15 pages per box that contained paired neutron and photon measurements useful to develop the NP ratio. For this effort, five health physicists spent approximately 8 d ($\approx$320 person hours) to identify the survey sheets to be captured. In total 57 of the 64 reactor area boxes contained paired neutron and photon measurements. The tagged sheets were scanned and converted into PDF files for data coding.

Data coding

From the 57 boxes, 5,583 paired neutron and photon measurements were coded, along with an additional 190 paired measurements extracted from weekly and monthly reports from 1945 to 1955 that were found on the Hanford Declassified Document Retrieval System (DDRS). These periodic reports helped fill some gaps in the early monitoring records. These gaps resulted from limited photon measurements that could be paired to the neutron measurements. Howell et al. (1989) was found to be an excellent source of information concerning the historical timeline of the different neutron survey instruments used at Hanford.

Neutron energy determination

Starting in April 1958, a new neutron survey instrument using a bare, single moderated and double moderated BF$_3$ detector was introduced by DePangher (1958).

By determining the ratio (r) between the double moderator (dosimeter) and the single moderator (fluence rate meter), the average neutron energy of the field being measured could be determined (DePangher 1958). The total neutron dose was then recorded as a combination of either:

- r <0.22 [total neutron = slow neutron (bare) + the intermediate neutron (fluence rate meter)]; or
- r >0.22 [total neutron = slow neutron (bare) + the fast neutron (dosimeter)].

As discussed in the results section of this analysis, the dominant neutron dose rate was from fast neutrons with energy greater than 0.025 MeV. Table 1 provides the generic breakdown of neutron energies at Hanford (HAPO 1956) and the conversion factors from fluence rate to dose rate.

DePangher (1958) determined the response of ratio (r) as a function of neutron energy, by exposing the fluence rate meter and the dosimeter to mono-energetic neutron beams. Fig. 1 depicts this relationship. For computational ease, the following equations were used to convert the ratio data to energy information.

Ratio (r) less than 0.6 (DePangher 1958):

$$E(\text{MeV}) = \frac{r-0.215}{0.366}. \qquad (1)$$

Ratio (r) greater than 0.6 but less than 1.3:

$$E(\text{MeV}) = e^{-3.87 + 5.0657r^{0.5}}. \qquad (2)$$

Eqn (2) is a simple fit of the data provided in DePangher (1958).

The moderated BF$_3$ detector represents high quality data that have been and continue to be used today in modern REM balls with the technology essentially unchanged. In fact, from a measurement perspective, the additional practice of recording three different measures (bare BF$_3$—thermal neutrons; single moderated BF$_3$—intermediate energy neutrons; and double moderated BF$_3$—fast neutrons) is in many ways of higher quality than that observed in most industrial neutron surveys in which a single neutron value is reported. The comparison

Table 1. Neutron energy groups and conversions.[a]

Neutron group (category)	Energy range	Hanford conversion factors
Slow neutrons (SN)	0.025 eV–100 eV	120 n/cm^2–s/mrem
Intermediate neutrons (IN)	100 eV–25 keV	48 n/cm^2–s/mrem
Fast neutrons (FN)	25 keV–10 MeV	8 n/cm^2–s/mrem

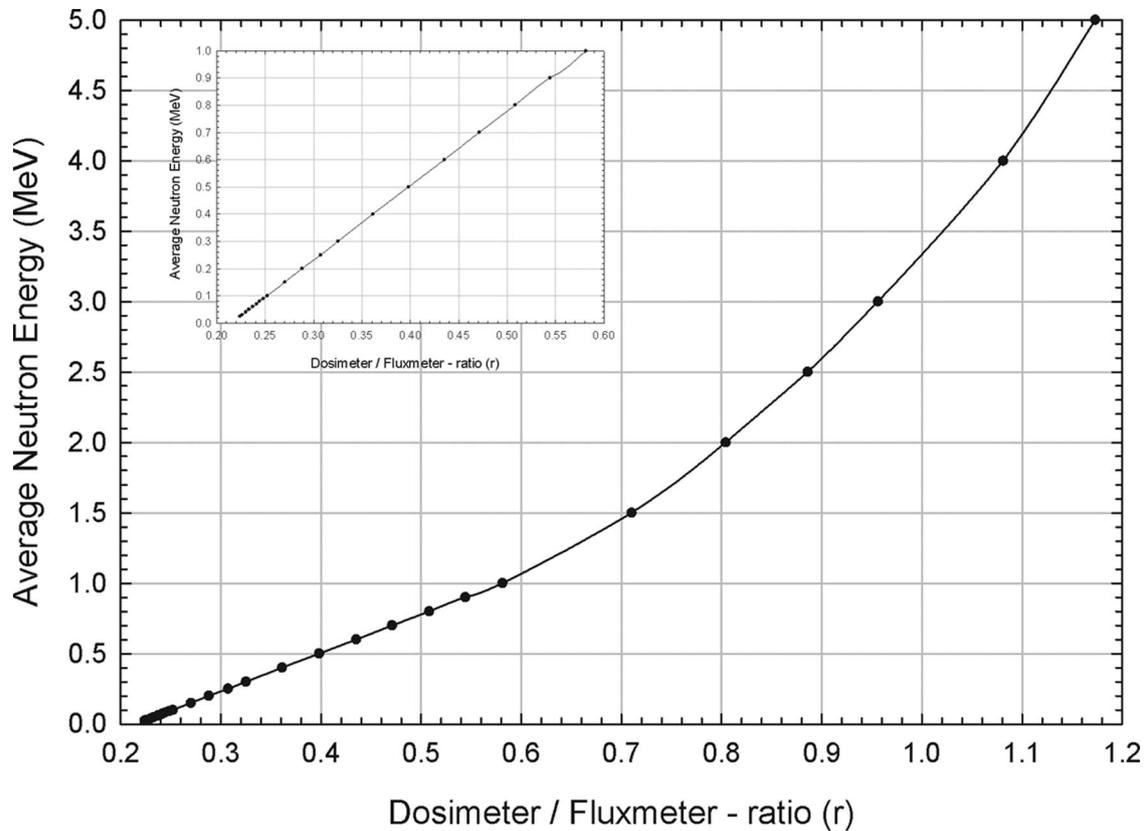[a] Traditional units are used in this table to preserve the historic conversion factors.

Fig. 1. Energy calibration curve for the Hanford neutron survey instrument (DePangher 1958).

of the single and double moderated BF_3 (ratio determination) for average energy reflects the care and sensitivity the operators were taking to ensure the energy response of the instrument was not interfering with the dose rate measurement. Since the measurement data post-1958 represents very high quality data using the double moderated dosimeter and 78% of all of the measured data is in this time frame, there is significant confidence that the overall NP ratio is based on sound measurement data.

RESULTS

The results of the sampling matrix and subsequent coding effort are provided in Fig. 2. The numbers in each cell indicate the number of data points for a particular reactor for a given year. The gray bold bars surrounding the data in the figure indicate the years that the particular reactor was operating (Marceau et al. 2003). The horizontal totals to the right provide the number of data points for each year of all reactors and the vertical totals are the number of data points for a particular reactor across all years. The sparse number of data points for

some years resulted from limited data in monthly operating reports. The years where there is a larger number (i.e., >20) of measurements generally correspond to measurement data found in the 64 boxes. Fig. 2 also indicates that paired measurements were generally more difficult to obtain from the records prior to 1958. In this sampling, only 21% of the total number of data points coded were recorded prior to 1958. This information does not necessarily infer that neutron dose rates were measured at a lower frequency, but was more of a result of our inability to pair neutron and photon dose rate measurements in the early years.

In general, we were successful in capturing at least some paired neutron photon survey data for all years except 1958. However, capturing data from startup through shutdown of the F reactor was only marginally successful. This was the result of the biology research area being located in the F area. Several of the boxes thought to contain F area reactor surveys actually contained survey data for the biological research area, none of which pertained to the reactor. The third goal of the sampling effort was successful in that we were able to obtain some paired measurements for all reactors between 1956–1957 so that NP ratios could be compared across reactors.

	B	C	D	DR	F	H	KE	KW	Total
1944									
1945	11		17		45				73
1946			4						4
1947			6		3				9
1948	26		7		82				115
1949	8		2		1	1			12
1950	46		1		8	1			56
1951	5		1		82	26			114
1952			160	1	16	89			266
1953	4	1	5		4				14
1954		2	1	1	51	79			134
1955	9	1	2	24	7	33	21	4	101
1956		16		36	9	53	18	11	143
1957	13	18	48	50	18	49	24		220
1958									0
1959						39		123	162
1960	1	282	42	29	1	1	1	114	471
1961		318	57					250	625
1962		90					44	293	427
1963		24			6		49	197	276
1964				23			57		80
1965		1					68	1	70
1966	92	133	67				141	179	612
1967	27	382	114				213	166	902
1968		166					113	153	432
1969							118	214	332
1970							94	11	105
1971							18		18
Total	242	1434	534	141	356	371	979	1716	5773

[a] The bold boxed areas indicate reactors operating years.

Fig. 2. Distribution of paired neutron and photon measurements.

Based on a review of the survey data, annual neutron surveys were routinely conducted and were typically documented in January of each year. Subsequently, monthly neutron surveys were conducted at select locations to ensure neutron dose levels were not changing significantly. According to an interview with a radiation monitor, additional neutron surveys were conducted if there was a change in power level of the reactor (DeHaven 2007[§]). Again, only spot checks at routine locations were generally conducted in accordance with these power changes to verify the neutron dose rate was still within the range measured during the annual or monthly survey. Thus, during our sampling effort, if a box was not retrieved in the January time frame, typically only measurements from the routine checks were obtained.

During the coding effort it became evident that most neutron surveys were conducted predominantly in seven general locations around the single pass reactors. Fig. 3 depicts a cutaway of a typical reactor building obtained from the Hanford DDRS, with the seven general locations identified. Table 2 lists these locations and some of the specific areas that have been categorized in a general location. These general locations are typically associated by

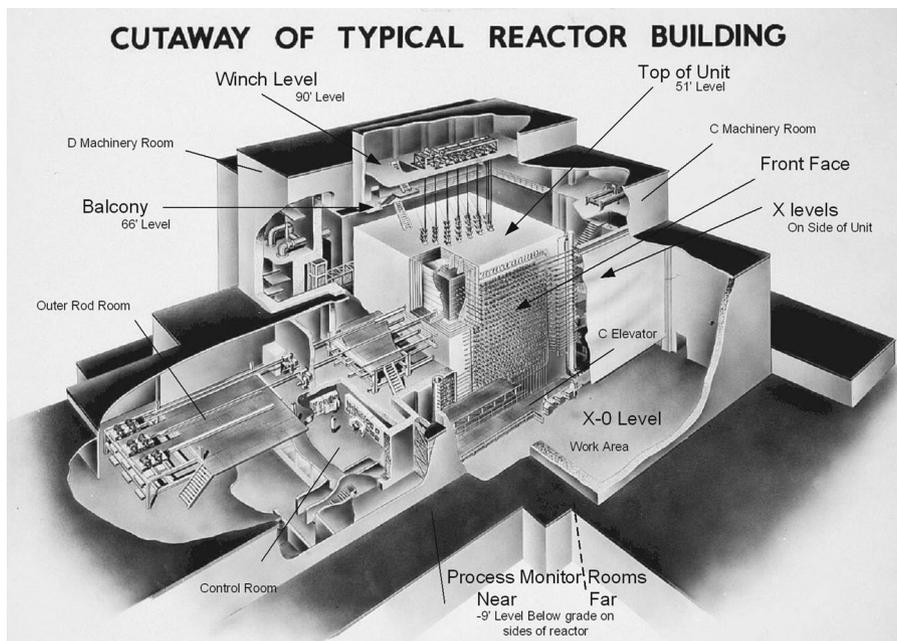[§] Dehaven H. Retired Hanford site radiological worker. Personal communication; 2007.

Fig. 3. Cutaway view of typical reactor building illustrating locations where neutron exposures can occur [Illustration obtained from the Hanford Declassified Document Retrieval System (DDRS; U.S. DOE 2008); annotations to the drawing have been added for clarity].

Table 2. General locations of paired neutron and photon measurements.

Location	Specific areas	Elevation[a]	Total #	%
Process monitor room	Near and far instrument cubicles	−9′ Level	354	6.1
X-0 level	Outer rod room, work area, viewer	0′ Level	503	8.7
Front face	C elevator	0′−45′ Level	1610	27.9
X levels	Experimental test hole areas	20′&38′ Level	1510	26.1
Top of unit	Area around VSR enclosure	51′ Level	869	15.0
Balcony	C and D machinery rooms	66′ Level	800	13.9
Winch		90′ Level	118	2.0
Other	Rear face[b]		9	0.2
		Total	5,773	

[a] Elevations based on KE and KW reactors, other reactors were slightly smaller (shorter in height).
[b] The rear face is not occupied during operation. Access to the rear face area where irradiated fuel slugs are discharged is controlled and limited even when the reactor is shutdown (DeHaven 2007).

elevation of the particular area. The main areas of neutron exposure were on the charging elevator (C elevator) and the experimental levels (X levels). Although access was limited during reactor operation, work on the front face using the charging elevator was occasionally conducted. Some of this work included pushing ruptured fuel elements, addition of shielding for poorly shielded tubes, and emergency repairs. On the experimental levels, routine neutron exposure occurred as test samples were introduced or retrieved from the reactor test ports on the side of the reactor. These operations were usually conducted with the radiological control assistance. Most of the reactors had only one experimental level, however the larger KE and KW reactors appear to have two experimental levels. The top of the reactor housed the vertical safety rods (VSRs) enclosure and the associated drive mechanisms. The balcony was above the VSR enclosure. Adjacent to the balcony, although apparently a few steps higher, were the charging (C) and discharging (D) elevator machinery rooms. Part of the routine radiation surveys was to conduct a neutron measurement around the VSR enclosure, the balcony, and the C and D machinery rooms. In general, the neutron dose rate on the upper levels of the reactors was much higher compared to the front and the sides of the reactor. This is attributed to the open holes in the reactor for the VSRs to drop during power level adjustments or a reactor scram. These open holes provided for more neutron leakage, based on the number of surveys around the VSR enclosure; the radiological control group was clearly cognizant of this potential exposure. According to a retired Hanford radiation monitor/health physicist, general work was not conducted on the top of the reactor during operation, and typically only the radiation control monitors went into the areas as part of their routine surveys (DeHaven 2007).

Access to several other areas of the reactor were restricted from occupancy without approval such as with a special work procedure as described in the respective *Radiation Hazards Bulletins*, particularly #1, #7, #8, #9,

#10, etc. (DeHaven 2007; HAPO 1947). In particular, the access to the rear face and the inner rod rooms were restricted, and measurement data for these areas were not included in this analysis.

Combined data analysis

The first analysis was to simply plot the neutron dose rate vs. the photon dose rate to determine whether the two measurement sets are correlated (Fig. 4). Note that the abscissa in Fig. 4 is a different scale than the ordinate with both labeled using the current SI units. Since all of the measurement data used in this analysis were collected prior to 1972, the historical units of millirem and milliRoentgen (mR) were preserved and used throughout this work. The NP ratio is calculated as mrem/mR or 0.01 mSv/mR or 0.01 mSv/(2.58×10^{-7} C kg^{-1}).

Using the data plotted in Fig. 4, the Pearson Product Moment Correlation and the Spearman Rank Order Correlation coefficients were computed to be 0.71 and 0.55, respectively. The p-values of less than 0.001 indicate a reasonable degree of correlation between the two sets of measurements. Thus, from a hypothesis
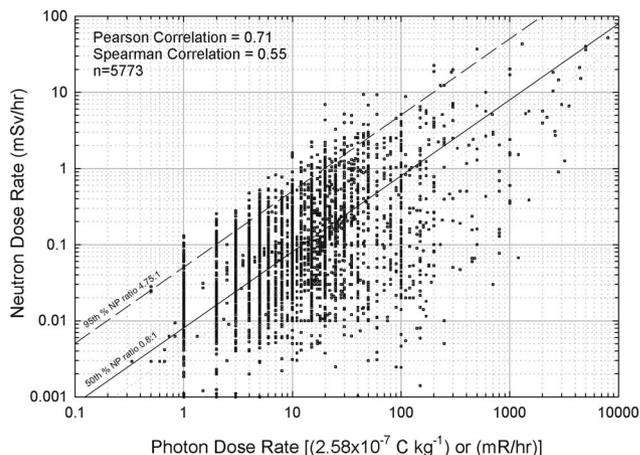
**Fig. 4.** Scatter plot of paired neutron and photon dose and exposure rate measurements.

standpoint, there is a relationship between neutron and photon dose that could be used to estimate unmonitored or poorly monitored neutron dose, using a worker's measured photon dose.

The dashed line on the plot in Fig. 4 indicates the 95th percentile NP ratio of 4.75:1 of the combined data set, and the solid line indicates the median NP ratio of 0.8:1. The original Hanford External Dose Reconstruction Technical Basis Document (ORAUT 2007) indicated a median value of 0.4:1 based on 35 non-independent data points and an estimate of the NTA measured neutron dose fraction due to the energy limitation. This value is approximately half of the estimated NP ratio calculated in this analysis. Fig. 5 depicts the ordered NP ratios from the paired measurements with the NP ratio plotted on a log scale as a fraction of cumulative probability. While the distribution of the NP ratio does not exactly follow a lognormal distribution, especially over the lower 1/3 of the data set, it is reasonably approximated by a lognormal distribution. The plotted solid line depicts a lognormal distribution with the same median (0.8) and the same upper 95th percentile of 4.75. The Geometric Standard Deviation (GSD) of a lognormal distribution based on these two measures is estimated to be 2.95 (eqn 3) (Groer 2003):

$$GSD = \left(\frac{X_{95\text{th}\%}}{X_{50\text{th}\%}}\right)^{\frac{1}{1.64485}}. \quad (3)$$

Probability distributions

During the coding effort, the neutron and photon measurements from the top of the reactor appeared to routinely result in a higher NP ratio than the front face. As a result, a second analysis was conducted to compare the probability distributions from the seven general locations to determine if any should be combined. Fig. 6
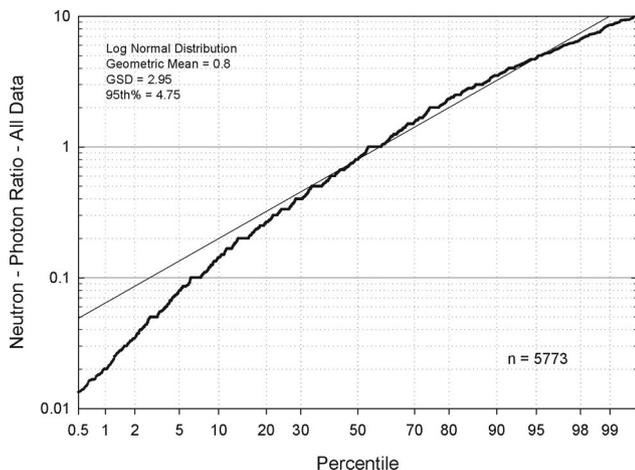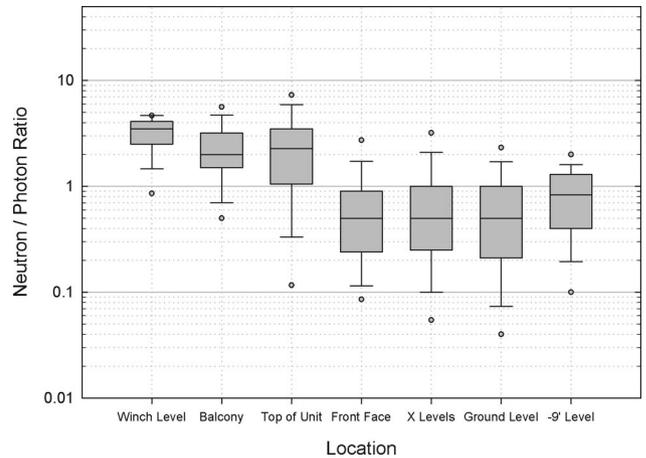

Fig. 6. Comparison of NP ratio data for different reactor locations. Note the box and whisker plots throughout this paper are slightly different than the normal convention. The circle points outside the whisker represent the 5th and 95th percentile of the data, the lower whisker represents the 10th percentile, the lower boundary of the box is the 25th percentile, the line is the 50th percentile, the upper boundary of the box represents the 75th percentile, the upper whisker is the 90th percentile and the second circle represents the 95th percentile.

is a box and whisker plot of the NP ratios for the seven general locations and illustrates that the upper levels of the reactor (top of unit, balcony and winch levels) had a higher NP ratio compared to the front face, ground level, and the experimental (X) levels. These areas were generally limited during operation, thus workers were not routinely exposed. The −9′ process monitor room (instrument cubicles) tended to be in between the front face and the upper levels. Since work on the front face and X levels tended to be different (spline adjustments vs. sample retrievals), these areas were kept separate. However, from an NP ratio standpoint, there was no significant difference between the datasets. Based on this information, the seven locations were combined into 4 groups as indicated in Table 3, which reports the median NP ratio and the correlation coefficients for each group.

Both the front face and X level probability distributions closely follow a lognormal distribution. The distribution of the upper levels only followed a lognormal distribution for the upper 75% proportion of the data. However, if the distribution parameters were based on the upper 95th percentile and the median values, the estimated geometric mean (GM) and GSD would result in a slightly conservative overestimate of the total probability distribution. Using Crystal Ball®, a commercially available program (2004 Version; Decisioneering, Inc., 1515 Arapahoe St., Suite 1311, Denver, CO, USA 80202), the lognormal distribution was generally the best-fit distribution for the combined general locations. Table 3 presents

Fig. 5. Probability distribution of the NP ratio. The thin solid line represents the eqn (3) fit.

Table 3. Summary of combined locations and the associated NP ratio.

Combined location	Sub-groups	# of data points (% of total)	NP ratio		Correlation	
			GM	GSD	Spearman rank	Pearson
Upper levels	Winch, balcony, top of unit	1,787 (31%)	2.333	1.84	0.691	0.430
Front face	Front face	1,610 (28%)	0.500	2.79	0.518	0.494
X levels	X-0, X-1, X-2 levels	2,013 (35%)	0.500	2.97	0.671	0.849
−9′ level	−9′ level	354 (6%)	0.833	1.70	0.578	0.418
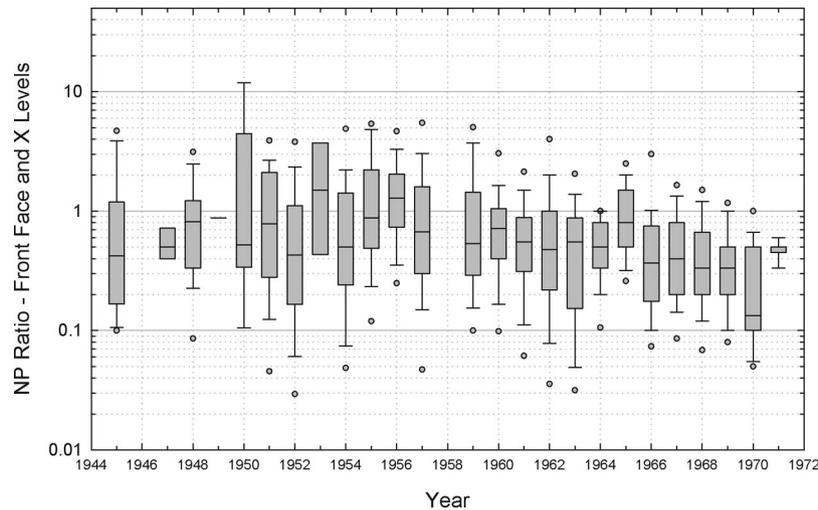
Fig. 7. Annual box and whisker plot of the NP ratio at the front face and X levels for all reactors combined.

the lognormal distributions parameters using the method depicted by eqn (3).

NP ratio changes over time

Although only a sampling of paired neutron and photon measurements was retrieved and coded, some analysis of the changes in the NP ratio over time could be conducted for each of the 4 combined areas. Fig. 7 provides a box and whisker plot of the NP ratio for the front face and X levels over time interval from 1945 to 1971. Box and whiskers data without the 5th and 95th percentiles (which indicates a small number of data points) should not be considered when looking for trends. Overall, there does not appear to be any significant trend in the NP ratio over time since the inner 2 quartiles of the data in 1945 are not significantly different than those in 1967.

The most interesting information revealed from this plot is that although the neutron dose increased significantly with an increase in reactor power, the photon dose also increased proportionally, thus the NP ratio remained relatively unchanged. Additionally, although the instrumentation in the earlier years (prior to 1958) used a combination of the BF_3, moderated BF_3, the Chang and Eng or the Hanford Neut (fast neutron instrument similar to Chang and Eng) to measure slow, intermediate and fast neutrons, respectively, the relative NP ratio was not significantly different compared to the superior portable

BF_3 or double moderator neutron dosimeter method introduced by DePangher (1958). For this reason, even though only 22% of the data is from the early time frame, the overall NP ratio should be reasonably representative of the entire reactor operating period.

NP ratios between reactors

A second goal of the sampling effort was to evaluate potential differences in the NP ratio among reactors. Fig. 8 depicts the NP ratio for all eight single pass reactors between 1956 and 1959. When more than 20 data points were available for analysis, a Kruskal-Wallis one-way analysis of variance on ranks indicated that there was no statistically significant difference in the median NP ratios among the groups since the p value was 0.384. Only B and D reactors, which only had 13 and 16 data points, respectively, had a reduced NP ratio. The NP ratio for these reactors would likely have been higher had more data been available for analysis.
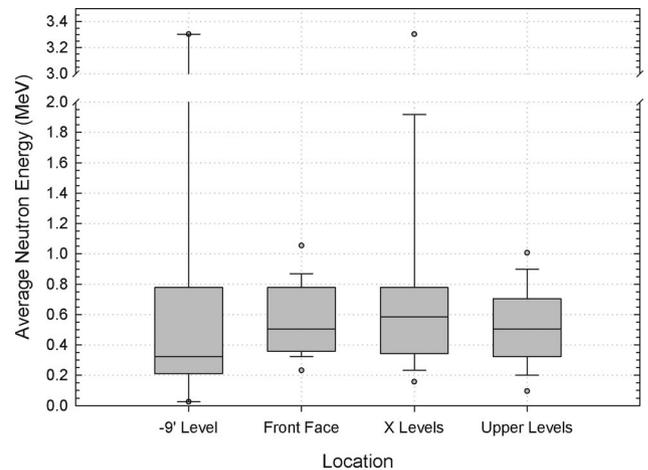
Average neutron energy

One goal of this analysis was to evaluate the neutron energy spectra among the different areas. Due to instrument limitations, the neutron energy spectra could not routinely be measured until the introduction of the double moderator neutron dosimeter in 1958. As noted above, DePangher (1958) calibrated this instrument such that the average
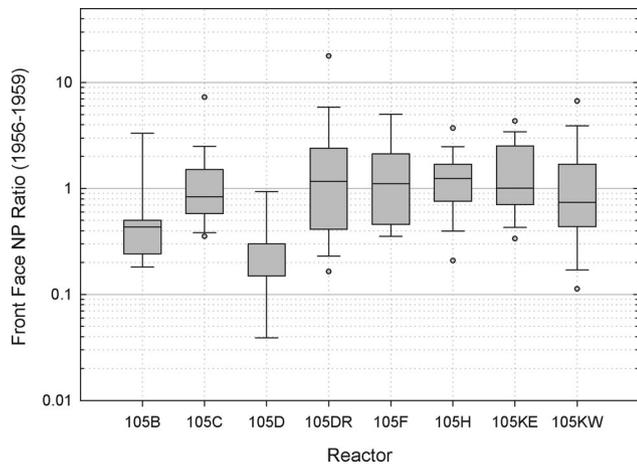
Fig. 8. Comparison of the NP ratio across single pass reactors from 1956–1959.

Fig. 9. Average neutron energy distribution by general location.

neutron energy could be determined, based on the ratio of readings with the instrument operated as a fluence rate meter and alternatively as a dosimeter. If this ratio was greater than 0.22, then the total neutron dose was the combination of the dosimeter dose (double moderator) and the bare BF_3 detector dose (slow neutrons). Based on the 1,319 paired fluence rate meter and dosimeter readings obtained after 1958, only 31 measurements (<2.4%) resulted in a ratio less than 0.22, which was the indication of only intermediate energy neutrons. Thus, the bulk of the neutron dose around the reactors was from fast neutrons with an average energy greater than 25 keV. Based on the data, the average neutron energy was significantly greater than 25 keV, and less than 5% of the ratio measurement data indicated an average neutron energy less than 100 keV.

Using these paired fluence rate meter and dosimeter measurements, a distribution of the average neutron energy could be determined for the various general locations (Fig. 9). In general, the median neutron energy was around 500 keV. This is quite close to the NTA film energy threshold of 428 keV (based on a 3 grain proton-recoil track with a grain size of 0.6 μm (Yagoda 1949; Lehman 1961). According to Watson (1951), Hanford defined a proton-recoil track as being 4 or more grains. This definition corresponds to an average neutron energy of 570 keV. More than 75% of the neutron energy was below 800 keV, which is a 6 grain track that is quite easy to identify. For this reason, the NTA film calibrated using even a low energy PuF_4 source with an average energy of 1.4 MeV (Brackenbush and Faust 1970) would still significantly under respond to the neutron field. For the NTA film to have responded appropriately, the film should have been calibrated to a 500 keV neutron source. Since the early calibrations (prior to 1957) were conducted with RaBe, PoBe, PoBo, and PuBe neutron

sources (high energy) and post-1957 with PuF_4 (Fix et al. 1997), the dosimetry data from the NTA film worn by workers around the single pass reactors are biased low.

Neutron energy distribution

The final component of this analysis was to partition the total neutron dose into the appropriate neutron energy intervals for input into the Interactive Radio-Epidemiological Program (IREP) (Kocher et al. 2008). Based on Fig. 9, the average neutron energy was rarely ($\approx$10%) measured to be in excess of 1.0 MeV in the reactor areas. Thus, assuming a normal distribution or a worst case uniform distribution, the upper neutron energy would be approximately 2 MeV. Thus, the three lowest energy intervals defined by IREP (<10 keV, 10–100 keV, 100–2,000 keV) appear to be the most practical for the neutron energy spectra around the single pass reactors. This also makes fundamental sense in that the average neutron energy from fission is approximately 2 MeV and, given the massive quantity of graphite for moderation, one would expect the average neutron energy to be significantly lower. In this case the average is approximately a factor of 4 lower. Thus, for a given fission spectrum, one might expect the general shift of fission spectra to be about a factor of 4.

In addition to the fluence rate meter and dosimeter measurements, the bare BF_3 detector was also used to measure the slow neutron dose. Fig. 10 provides a histogram of the slow neutron dose fraction of the total dose. Although the neutron fluence rate of the thermal neutrons was higher than the fast neutron fluence, when converted to dose rate, approximately 75% of the paired measurements indicated that the slow neutron dose comprised less than 10% of the total neutron dose.

It is important to note that all of the paired neutron measurements made with the double moderator neutron dosimeter (slow, fluence rate meter, and dosimeter) always
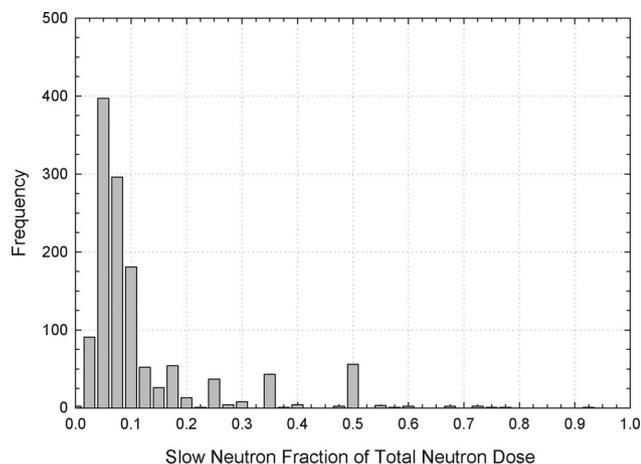
Fig. 10. Histogram of the slow neutron fraction of the total measured neutron dose using the Double Moderated Dosimeter (DePangher 1958).

Table 4. Neutron energy dose distribution.

IREP neutron energy interval	Percentage of total neutron dose
<10 keV	10%
10–100 keV	10%
0.1–2 MeV	80%

included some slow neutrons. Although the slow neutron dose component was generally less than 10% of the total neutron dose, starting in 1958, the Hanford neutron dosimeter badge used a combination of Sn and Cd filters to measure the slow neutron dose based on the (n,γ) reaction on Cd (Wilson 1987). The reporting limit appears to be around 0.06 mSv for this dosimeter. Thus, applying a simple 10:1 fast neutron to slow neutron ratio, a measured slow neutron dose should be approximately 1/10 of the total neutron dose. Thus, it is highly unlikely that an individual could ever have been exposed to a very high neutron fluence rate without some indication on his or her dosimeter badge.

At Hanford, the definition of intermediate energy neutrons was significantly different than the definition used in the IREP program. At Hanford, neutrons between 100 eV to 25 keV were considered intermediate energy (HAPO 1956). In IREP, intermediate energy neutrons are defined as those with energy greater than 10 keV but less than 100 keV; therefore, there is some overlap in the definitions. The measured average neutron energy of approximately 500 keV must be partitioned between the 10–100 keV interval and the 0.1–2 MeV interval. Assuming a uniform distribution of neutron energy, for the average to be 500 keV, the minimum would be 0 and the maximum would be approximately 2 times the average or 1,000 keV. Using this approach, the fraction of the neutron dose that is less than 100 keV would be approximately 10%. In the absence of other data, this assumption is considered either claimant favorable or at least claimant neutral, considering the radiation effectiveness factor is significantly greater for neutrons in the 0.1–2 MeV energy interval. Table 4 summarizes the breakdown of the neutron energy intervals based on this analysis that should be used in proportioning the neutron dose.

DISCUSSION

Reactor power increase

As noted in the methods section, one of the goals of the sampling matrix was to cover the entire time period of one reactor to evaluate whether reactor power increases changed the NP ratio. Throughout the weekly and monthly reports from the reactor areas there were indications that the neutron fluence rate densities (dose rate) around the pile increased proportionally with the increase in power (Patterson 1947; McAdams 1951; Jerman 1953). However, based on the results provided in Fig. 7, the conclusion can be drawn that, although the neutron dose rate increased during the reactor power increases, the photon dose also increased proportionally such that the NP ratio remained relatively unchanged. Thus, the application of the NP ratio over time as the reactors changed power does not need to be adjusted. Early records indicated that measuring the neutron dose around the reactors was a significant challenge due to the relatively low neutron dose rate measured when the B, D, and F reactors were operating at 270 MW. As the power increased, the doses were easier to measure because of the increase in the radiation induced signal over the background noise.
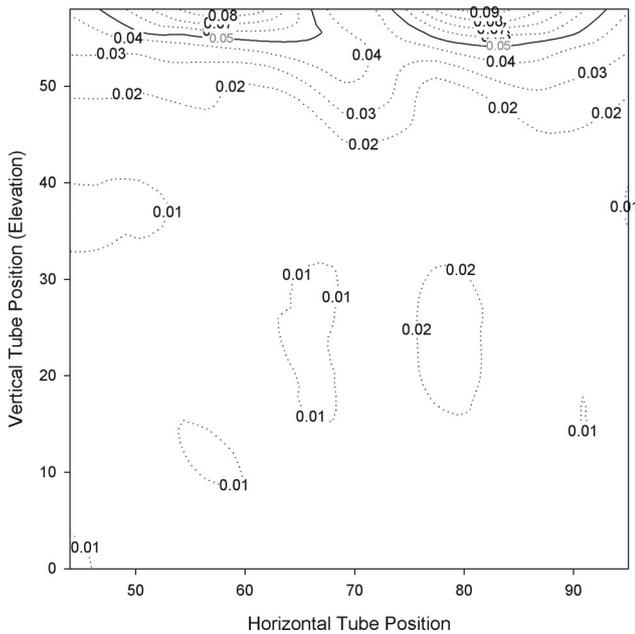
Neutron dose rates

During this analysis, we occasionally noted there were some differences in the neutron dose rate between reactors. It was also noted as early as 1945 that some reactors had higher total dose rates on the front face than others (Parker and Gamertsfelder 1945). To illustrate this point, Figs. 11 and 12 depict the neutron dose rate on the front face of the C and KW reactors in 1960 and 1967, respectively. Figs. 13 and 14 depict the corresponding NP ratio. The comparison between the four figures is important in that, although the neutron dose rate was an order of magnitude higher for the C reactor (0.10–0.20 mSv h^{-1}) compared to the KW reactor (0.01–0.02 mSv h^{-1}), the NP ratio for the C reactor was only about a factor of 2–3 higher. This indicates that the photon dose generally increases with the neutron dose. Thus the use of an NP ratio would result in a reasonable estimate or upper bound of the neutron dose, regardless of the actual neutron dose rate.
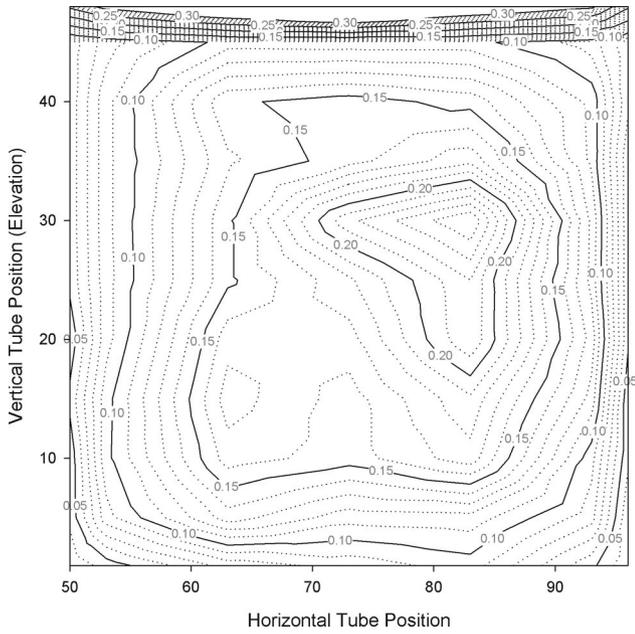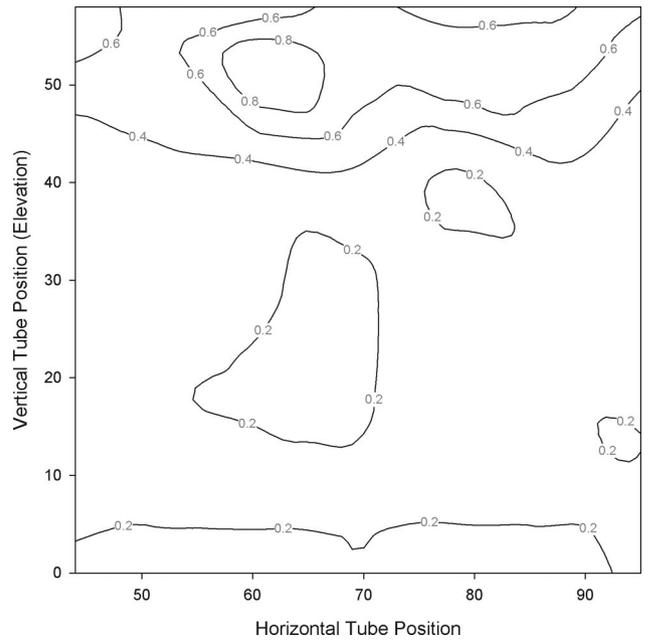
Fig. 11. Neutron dose rate (mSv h^{-1}) on the front face of the C reactor in 1960.
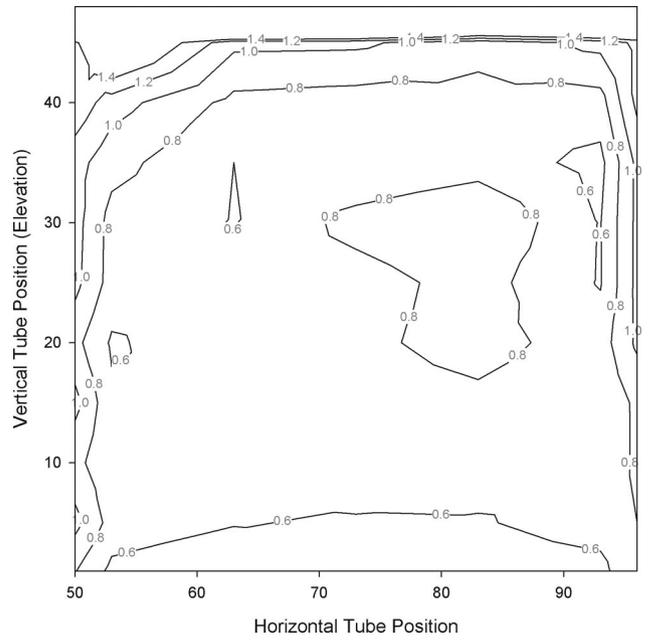
Fig. 13. NP ratio (mSv/mSv) on the front face of the C reactor in 1960.

Fig. 12. Neutron dose rate (mSv h^{-1}) on the front face of the KW reactor in 1967.

Fig. 14. NP ratio (mSv/mSv) on the front face of the KW reactor in 1967.

The relatively low neutron dose rate for the KW reactor is also important. The neutron dose was generally less than 0.02 mSv h^{-1}, which would correspond to an implausible maximum neutron dose of 40.00 mSv y^{-1} considering an individual would have to be positioned on the front face platform for an entire work year. Thus, the magnitude of the neutron dose for some reactors is expected to be relatively low. This is consistent with

information provided by a site health physicist that the neutron dose would comprise only about 25% of the total photon dose (Dehaven 2007). The likely reason the KE and KW reactors had a much lower dose rate on the front face was that they were probably shielded better, being the last two single pass production reactors built.

Another interesting observation that can be made from Figs. 11–14 is that the neutron dose rate is highest

on the front face near the top of the reactor and the NP ratio is also highest in this area for both reactors. In general, the neutron and photon dose rates on the top of the unit and the upper levels were significantly greater than on the front face of the reactor.

Application bias

The bias inherent in the development and application of an NP ratio is an important concept to consider when reconstructing an individual's neutron dose. When using an NP ratio that is derived solely from paired neutron and photon survey data, the assumption is made that all photon dose recorded on a film badge dosimeter has an accompanying neutron dose. This results in a bias because the photon dose does not always have an associated neutron dose. There are areas around the reactor, particularly the wash pad area (where fuel and target elements were separated following a discharge), where there is significant photon dose with no neutron dose. In addition, when the reactor was shut down for discharging and charging operations, the neutron dose was effectively zero. The photon dose, however, was still significant due to the presence of fission products. Therefore, when working in the wash pad area or when the reactor was shut down, the NP ratio was zero.

Jerman (1957) reported that 30 questionnaires were sent out to supervisors of maintenance, processing and radiation monitoring personnel asking them to estimate exposures for various jobs. Jerman (1957) reported that this survey indicated that about 70% of the total exposure received was during shutdown activities. In addition, 50% of the total during shutdown was received in the discharge areas. Thus, in effect, only about 30% of the total photon exposure was estimated to be received when the reactor was operating. The combination of these two major factors (shutdown and non-neutron locations) is not considered in the development or application of the NP ratio to the measured photon dose under EEOICPA, thus the estimated neutron dose based on the NP ratio contains a very conservative (claimant favorable) bias and can be considered a bounding estimate. Under EEOICPA, reactor shutdowns and non-neutron exposure areas would not be considered because 42 CFR Part 82 (U.S. DHHS 2002) requires that dose reconstructions "give the benefit of the doubt to claimants in cases of scientific or factual uncertainty or unknowns."

In this particular application, while highly unlikely, it is feasible that a worker (e.g., intermittent crafts worker in the reactor areas) conducted his/her work on the charging elevator during a particular month when the reactor was operating and only wore a beta/gamma film badge. The worker then went to work at another non-radiological area and was not required to wear a dosimeter badge for the remainder of the month. As a result the worker's only photon exposure measured by the badge had an accompanying unrecorded neutron exposure. The use of the NP ratio in this instance would not result in a gross overestimate of his neutron dose but an estimate that relatively closely matches reality. In general, we recognize that when the NP ratio is applied to a routine worker's measured photon dose which covers a large time period when the reactor was both operational and shutdown, the neutron dose is going to be significantly overestimated.

Location bias

For the application of the NP ratio to EEOICPA dose reconstructions, consideration was given to the level of information typically in the dosimetry records to enable a dose reconstructor to identify the work location of an individual. Typically, only incidental information on work location is available, if radiation exposure cards happen to be in an individual's dosimetry file or there is a contamination incident noted in the file. Generally, no information on whether a worker was on top of the reactor, on the front face, or on the X levels is provided.

A retired Hanford radiation monitor/health physicist, who started working at the reactors in 1949, assisted us in understanding how long an individual might spend in the various work locations. Table 5 provides a summary and the corresponding relative fraction of time an individual worker might spend in the three main areas (DeHaven 2007). By summing the fractions of the shift and dividing by the sum, relative percentages of time in the three areas were calculated. Using these fractions, a weighted NP ratio was developed by multiplying the relative percentage by the GM (median) of the NP ratio for each area. This weighted NP ratio is estimated to be 0.59 and is considered to be closer to the best estimate.

However, the distribution of paired neutron and photon survey measurements might also be a good indication of the relative percentage as radiation monitors were typically conducting surveys prior to and after work was completed. Thus an argument could be made that the more frequent surveys indicate more work was conducted in the area. The alternate argument is that the higher the neutron dose rate (upper levels) the more frequent the surveys, as these areas would pose a

Table 5. Estimation of time spent in general locations.

General location	Fraction of shift	Relative percentage
Front face	1/2 shift	30%
X levels	Up to a whole shift	65%
Upper levels	1–2 h/wk (0.05)	5%

greater hazard and were therefore monitored more frequently regardless of worker activity in the area. Table 3 provides the distribution of paired measurements across the four combined locations. Using this methodology, the upper levels are weighted heavier than was likely the true case, thus the use of all of the data in the development of an NP ratio distribution is considered an additional conservative (claimant favorable) approach for EEOICPA dose reconstructions.

Assuming the survey proportion is a reasonable representation of the work in each general area, the simple evaluation of all of the NP ratio data combined results in a conservative (claimant favorable) NP ratio distribution. As indicated in the results section, the NP ratio is described as a lognormal distribution with a GM of 0.8 and a GSD of 2.95. The upper 95th percentile would be 4.75 (Fig. 4).

If the methods developed in this paper were applied to an epidemiologic study, both the application and the location biases should be removed to produce a best (unbiased) estimate of the neutron dose. Again, considering that approximately 70% of the total dose is received when the reactor is shut down (Jerman 1957), a reasonable argument can be made that the NP ratio from the front face and X levels, where most of the work was conducted, should be multiplied by 0.3 to obtain a best estimate or "true" neutron dose. This would indicate that the neutron dose is on the order of only 15% of the photon dose. An NP ratio of 15% is consistent with other studies that have reported an NP ratio on the order of 10% (Vasilenko et al. 2007). Thus, using an NP ratio of 0.8 for a compensation program purposes results in a neutron dose that on average is 5.3 times (533%) higher than would be applied in a traditional occupational epidemiologic study, in which the goal is to arrive at an unbiased estimate of the neutron dose. For purposes of a compensation program decision, however, one cannot definitively rule out that an individual worker's measured photon dose was only received in the presence of a neutron radiation field. Thus, on an individual worker basis, the application of the NP ratio results in a reasonably bounded estimate of the neutron dose.

CONCLUSION

Based on the results of this analysis, an NP ratio can be used to reconstruct an individual worker's neutron dose in a reasonable and claimant favorable manner. This can be accomplished by using this ratio in conjunction with the photon dose measured by a worker's photon dosimeter. For most workers around the single pass reactors, the measured photon dose in addition to the missed dose should be multiplied by the lognormal distribution with a GM of 0.8 with a GSD of 2.95 to estimate the neutron dose. This methodology results in a conservative (claimant favorable) estimate of an upper bound to the neutron dose. This neutron dose should be partitioned for input into IREP assuming that 10% is <10 keV, 10% is due to neutrons between 10–100 keV, and 80% is from neutrons from 0.1–2 MeV.

It is again important to recognize that the application of this NP ratio using an individual worker's photon dosimeter badge (total photon dose) will generally result in an overestimate of the "true" neutron dose since photon doses are received in many areas around the reactors where there is no neutron dose, and most of the photon dose occurred during shutdown. However, at this time, for compensation purposes the methodology presented above is considered the best and most appropriate estimate of neutron dose to workers around the Hanford single pass reactors.

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