Neutron Dose Assignment for K-25 and Portsmouth Gaseous Diffusion Plants

White Paper

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INTRODUCTION

Neutron dose to workers at gaseous diffusion plants (GDP) has been an issue of concern because some workers were unmonitored or monitored for exposure to photon and beta radiation only. Information is provided on this topic in the U.S. Department of Energy (DOE) *Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities* (DOE 2009), but the basis for the information in that document is limited. Therefore, this white paper focuses on measurements and calculations of the neutron dose and neutron-to-photon (N:P) ratio from various uranium compounds with an emphasis on exposures to highly enriched uranium (HEU) compounds at the K-25 and Portsmouth Gaseous Diffusion Plants.

PURPOSE

The purpose of this white paper is to determine a reasonable N:P ratio that can be used to assign dose for GDP energy employees during periods when neutron dose data were not reliable, not available, or not recorded. For K-25, this time period consists of the era prior to 1992. In the case of Portsmouth, although limited neutron monitoring began in 1987, monitoring of all employees with the potential for neutron exposure did not occur until 1995.

BACKGROUND

The interaction of alpha particles from uranium with nuclei of fluorine, oxygen, and other low-atomic weight atoms generates neutrons with energies of approximately 2 MeV (DOE 2009). The magnitude of the neutron flux varies based on total activity of the uranium (a function of enrichment) and the chemical compound (combining of uranium with fluorine or oxygen). In the case of UF_6, the typically measured neutron dose equivalent rates for storage containers are as follows (DOE 2009):

Natural uranium (NU) to 5% enriched uranium (EU):	0.01 to 0.2 mrem/hr
Very highly enriched uranium (97%+):	2 to 4 mrem/hr (contact) 1 to 2 mrem/hr (3 ft or 1 m)

The potential for significant worker exposures to neutrons generated by (α,n) reactions in uranium compounds is not very high unless a worker spends a large amount of time near storage containers of uranium fluoride or uranium oxide compounds or in processing areas for large quantities of those materials (DOE 2009). At very high ^{235}U enrichments, the N:P dose ratio can be as much as 2:1, and neutrons can be the limiting radiation source for whole-body exposure (DOE 2009). As stated previously, there is a significantly limited basis for this information from the DOE *Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities* (DOE 2009). The N:P ratio of 2:1 should be considered an upper bound of the potential range of ratios seen in facilities handling HEU. The neutron doses from low-enriched ^{235}U compounds or from uranium metals are not limiting doses (DOE 2009).

The current technical basis documents for K-25 and Portsmouth Gaseous Diffusion Plants both recommend assignment of neutron dose (before 1997 at Portsmouth and for any era at K-25) using an N:P ratio of 0.20, based on survey data from the Paducah Gaseous Diffusion Plant (PGDP) discussed below.

NEUTRON DATA DEVELOPMENT AND ANALYSIS

Studies have been published of measured neutron doses and N:P ratios near storage cylinders containing depleted uranium (DU), NU, low-enriched uranium (LEU), or HEU in the form of UF_6 at the Paducah, Portsmouth, and K-25 Gaseous Diffusion Plants. In some cases, these studies focused on large (14-t) cylinders in outside storage yards, while others were measurements of smaller HEU storage cylinders inside the facilities. These studies include:

- UF_6 cylinder yard survey (Paducah)
- HEU storage cylinder dose rates (Portsmouth)
- HEU storage vault/storage cylinder measurements (Portsmouth)
- Area monitoring: neutron and photon dose measurements (Portsmouth)
- Personnel monitoring: neutron and photon dose measurements (Portsmouth)
- Neutron dose rate survey results (K-25)
- Neutron and photon dose rate modeling for cylinder yards (K-25)
- Neutron and photon survey data area and area monitoring results (K-25)
- Personnel monitoring: neutron and photon dose measurements (K-25)
- Static dosimetry measurements (Y-12 Plant)
- Neutron and photon survey data (Y-12 Plant)
- Personnel monitoring: neutron and photon measurements (Y-12 Plant)

Paducah

At the Paducah plant, measurements during a UF_6 cylinder painting project in the cylinder storage yard gave values for N:P dose ratios ranging from 0.14 to 0.42 with an approximate average of 0.2 (BJC 1999). These cylinders, however, contained either DU or NU.

Portsmouth

Neutron Dose Rate Data

Cardarelli (1997) quotes values for measurements of the neutron dose near small (5-inch diameter) HEU storage containers that ranged from 3.0 mrem/hr (contact) to <0.5 mrem/hr (at 1 meter). These values are in reasonably good agreement with the values in the DOE *Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities* (DOE 2009). This report also cites the neutron dose component of total external dose as 12.5% based on a monitoring study of uranium material handlers in 1995. It is important to note that this study included workers exposed to a variety of uranium enrichments.

In 1992, measurements taken in the product withdrawal (PW) vault (Building X-326) at Portsmouth indicated a neutron dose rate of 0.8 mrem/hr at a distance of 0.6 to 1.3 m facing a group of HEU cylinders (Soldat and Tanner 1992). Another survey was conducted in 1995 of a single 5A cylinder (97% HEU) in the X-345 Building. The recorded neutron dose rates at that time were 2.1 mrem/hr and 0.77 mrem/hr at distances of 15.2 cm and 30.5 cm, respectively (Scherpelz and Murphy 1995). Unfortunately, photon measurements were not made in either of these two studies.

Neutron and photon rate measurements were documented in a 1986 memo for four empty and six full 5-inch product cylinders stored in the X-326 PW vaults. Surface neutron and photon dose rates for the empty cylinders were ≤ 0.5 mrem/hr and ≤ 1.0 mR/hr, respectively (N:P ratio = 0.5). Neutron and photon dose rates for the full cylinders were ≤ 3.0 mrem/h and ≤ 2.4 mR/hr, respectively (N:P ratio = 1.25). At a distance of 1.0 meter, the combined neutron and photon dose rate was 0.2 mrem/h for empty cylinders and 0.5 mrem/hr for full cylinders (Bassett 1986).

N:P Ratio Data from Area Monitoring Measurements

A summary memorandum from 2008 provides annual Portsmouth area dosimetry data that were collected to meet the requirements of *Dosimetry Program Standards* (PGDP 2002). Outdoor annual neutron and photon dose measurements for the period 2004 to 2008 were available for the following radiological facilities: X-326, X-330, X-333, X-342, X-343 X-344, X-530, X-705, X-710, and X-745. Data were also provided for nonradiological facility areas as well as Perimeter Road near the cylinder yards. Paired positive photon and neutron measurements were recorded at the following facilities/areas: X-330, X-344, X-343, X-530, X-745, and Perimeter Road near the cylinder yards. The average N:P ratio derived from this data was 0.147 ± 0.09 with a minimum value of 0.01 and a maximum value of 0.398 (McGuire 2008).

N:P Ratio Data from Employee Dosimetry Measurements (1992 to 2013)

Four databases containing historical dosimetry records for Portsmouth Gaseous Diffusion Plant employees were reviewed in order to calculate a claimant-favorable N:P ratio. The databases reviewed are as follows:

- 3_Individual_Dose_Ports (overlaps with REMS_Portsmouth 1992–2013 Exp Recs database)
- Extra_REIRS_Ports (overlaps with 3_Individual_Dose_Ports database)
- REIRS_Portsmouth 1992–2013 Exp Recs
- REMS_Portsmouth 1992–2013 Exp Recs

The Portsmouth Radiation Exposure Information and Reporting System (REIRS) database was not useful in calculating an N:P ratio because no neutron dose records were included. In addition, as indicated above, two of the databases were actually subsets of other databases. Thus, only the 1992 to 2013 Radiation Exposure Monitoring System (REMS) database was used. Positive paired neutron and photon doses from this database were used to calculate a claimant-favorable N:P ratio that can be applied to certain workers in facilities where enriched uranium was handled. It should be noted that positive neutron results appeared in the REMS database beginning in 1999 (Bechtel Jacobs era).

Evaluation of REMS_Portsmouth 1992–2013 Exp Recs Database

A total of 38,964 records are contained in the Portsmouth REMS database. These encompass the period 1992 to 2013. A review of these records reveals the following information:

- A total of 10,721 unique individuals were monitored by external dosimetry during this period.
- Of the 10,721 individuals monitored, 722 were also monitored for neutrons (7%) at one time or another.
- This database indicates that neutron monitoring began at Portsmouth in 1996, although the hard copy records in the NIOSH Division of Compensation Analysis and Support Claimant Tracking System (NOCTS) indicate an earlier date:
    - 1987 – sporadic monitoring for a few individuals
    - Fall 2005 – widespread monitoring
- It should be noted that United States Enrichment Corporation (USEC) dosimetry records began to be included in a separate database beginning in 1997 (REIRS).
- Of the 722 individuals monitored for neutrons, 56 had at least one neutron monitoring result that exceeded the neutron limits of detection (LOD) of 10 mrem.
- Positive neutron results do not appear in the REMS database until 1999. Health Physics Records System printouts in NOCTS, however, indicate positive neutron dose as early as 1987 for one individual (PGDP date unknown).
- USEC personnel wore a combined thermoluminescent dosimeter (TLD).
- DOE personnel wore an albedo neutron dosimeter separate from their regular issued TLD.

Table 1 shows a breakdown of monitored individuals by year, based on a review of the REMS database.

Table 1. Portsmouth employee dosimetry data (1992–2013).

Year	# Individuals Monitored for Total External Dose	# Individuals Monitored for Neutron Dose (ND)
1992	3,628	0
1993	3,589	0
1994	4,404	0
1995	4,485	0
1996	3,957	444 (all ND)
1997[a]	144	0
1998	176	4 (all ND)
1999	204	36
2000	421	30
2001	639	32
2002	640	39
2003	541	26
2004	650	25
2005	643	64
2006	762	40
2007	731	31
2008	803	33
2009	1,219	95
2010	1,544	144
2011	2,718	142
2012	2,737	184
2013	2,662	147

Source: Portsmouth REMS Database 1992–2013.

a. Databases split in 1997; beginning in 1997, the REIRS database contains all USEC employees but no neutron monitoring results.

Development of N:P Ratio Based on Portsmouth Dosimetry Data

A total of 161 records in the REMS database indicate neutron dose values greater than the LOD of 10 mrem. These values were divided by their paired photon dose values to calculate an N:P ratio for each line of data. These ratios were then averaged to obtain an overall N:P ratio. If a positive neutron dose had a corresponding photon dose of less than its LOD of 10 mrem, the photon dose was set equal to 10 mrem. This occurred with 10 records. In addition, a doubling of the radiation weighting factor from 10 to 20 was accounted for beginning in 2010. Based on this approach, the average N:P ratio was calculated to be 0.369.

K-25

Neutron Dose Rate Data

Discussions of N:P ratio values were found in a variety of documents written to address radiological safety issues associated with the K-25 cylinder storage yards. In a May 2000 report, an N:P ratio of 0.25 was cited, with the notation that many of the neutron dose rate measurements were zero (BJC 2000). A final safety analysis report (FSAR) for the K-25 cylinder yards, written in 1997, indicated contact dose rate values between 1 and 6 mrem/hr and general area dose rates between 1.5 and 2 mrem/hr. The FSAR further indicated that neutron dose was one-sixth of the dose received from photon radiation (N:P = 0.166) (LMES 1997). Data from an area characterization study done along the outside boundary of the K1066E cylinder yard in 2000 indicated an N:P ratio of 0.274. This value was based on 9 locations that had positive neutron values out of a total of 86 sampling points (DOE ETTP 2000).

N:P Ratio Data from Modeling Study

A modeling study for the neutron dose and N:P ratio from a typical array of large storage containers (14-t cylinders) of DU, NU, and LEU (5% enrichment) at the Oak Ridge K-25 Gaseous Diffusion Plant can be found in *Determination of Neutron to Gamma Dose Ratios for the* UF_6 *Cylinder Yards* (NISYS 2000). The array of tanks consisted of two rows of cylinders stacked 2 cylinders high and 25 cylinders long on a 6-inch thick concrete pad. Calculations of the neutron dose and N:P ratio were made at distances ranging from 1 meter to 300 meters at the mid-length of the array of tanks. These calculations considered the effects of radiation scattering by the 6-inch thick concrete pad and by air with a relative atmospheric humidity of 30%, 60%, and 90% (NISYS 2000). For tanks containing DU, NU, and LEU (5% enrichment), at 1 meter the N:P dose ratios were approximately 0.10, 0.22, and 0.88, respectively (NISYS 2000). The calculations at farther distances from the tanks containing DU, NU, and LEU (5% enrichment) were used to estimate bounding N:P ratios for radiation exposures at the tank yard of approximately 0.2, 0.4, and 1.5, respectively (NISYS 2000).

N:P Ratio from Equipment and Area Monitoring Surveys

A summary of K-25 survey data was provided in 2015 by East Tennessee Technology Park (ETTP) (previously known as the K-25 Site) personnel. The data cover the period January 1999 through November 2006 (at which time the last of the UF_6 cylinders were removed). Over 6,000 paired neutron and photon survey data points were available that corresponded with equipment and general area measurements. Analysis of the equipment survey data yielded N:P ratio values of 0.099, 0.085, and 0.122 for distances on contact, 1 foot, and 1 meter, respectively. An N:P ratio of 0.605 ± 0.408 was calculated from 445 neutron/photon data points associated with general area measurements (Pope 2015).

N:P Ratio Data from Employee Dosimetry Measurements (1989 to 2012)

In the past, dosimetry services for K-25 were provided by either the Oak Ridge National Laboratory (ORNL) or the Y-12 Plant. Therefore, to establish an N:P ratio, dosimetry record data for the Oak Ridge Gaseous Diffusion Plant (K-25), also known as ETTP, employees were extracted based on employee information and collated into a merged copy of the Y-12 Plant Dosimetry and ORNL Safety and Health Databases (dated February 6, 2013). Although the integration of the two databases resulted in a version containing a variety of different tables, only records extracted from Table 3, *Individual_Dose_ETTP* (hereafter referred to as Table 3 ETTP) were used, as the others did not have neutron dosimetry information, contained duplicate data, were limited to extremity dose, or contained only Portsmouth Gaseous Diffusion Plant records.

Evaluation of Table 3 ETTP

Table 3 ETTP initially contained a total of 187,295 records; dates ranged from January 1, 1989, through December 31, 2012. Duplicate data were removed, leaving only unique dosimetry records for K-25 employees during the period of interest. Also of note:

- Personnel wore the Harshaw four-element beta/photon dosimeter and a separate four-element neutron dosimeter.
- 129,132 unique photon/beta dosimeters remained after duplicates were removed.
- 16,701 unique neutron dosimeters remained after duplicates were removed.
- 11,599 individuals were monitored for photon/beta radiation from 1989 through 2012.
- 404 individuals were monitored for neutrons from 1989 through 2012.
- Approximately 3.5% of the individuals were monitored for beta/photon **AND** neutron radiation.
- The first positive neutron result occurred in 1993.
- Results from 369 neutron dosimeters were greater than or equal to the LOD.
- Neutron monitoring seldom occurred from 1990 through 1996 but seems to have been more frequent from 1999 through 2012.

Table 2 tabulates the number of photon/beta and neutron dosimeters exchanged for K-25 employees by year.

Table 2. K-25 annual photon and neutron badge exchanges 1989–2012.

Year	Photon/Beta Dosimeter Exchanges	Neutron Dosimeter Exchanges	Neutron Dosimeters (results > or = to the limit of detection)
1989	232	0	0
1990	401	7	0
1991	359	5	0
1992	550	2	0
1993	461	4	1
1994	327	3	0
1995	169	6	0
1996	253	12	0
1997	6,005	79	1
1998	6,304	59	0
1999	5,920	183	9
2000	5,980	773	20
2001	7,107	1,138	35
2002	7,002	1,415	11
2003	8,096	1,769	21
2004	10,239	1,923	26
2005	12,515	2,283	20
2006	10,637	2,030	25
2007	9,040	877	60
2008	8,137	959	44
2009	8,419	904	19
2010	8,618	857	54
2011	7,518	852	20
2012	4,843	561	3

Source: K-25_PORTS_Exposure Database

N:P Ratio Based on K-25 Dosimetry Data

A total of 369 records in Table 3 ETTP had individual neutron doses greater than or equal to the LOD of 10 mrem. An analysis of dosimeters with paired photon and neutron doses greater than the LOD was performed. The N:P ratio was calculated by dividing the neutron dose by the deep dose for each badge exchange. A ratio of 0.490 was calculated based on the average of the paired N:P ratios. Starting January 1, 2010, ORNL adopted the 1990 International Commission on Radiological Protection (ICRP) recommendations on neutron weighting factors (O'Connell 2011). Based on this information, an N:P ratio of 0.420 was calculated.

ADDITIONAL DATA ANALYSIS OF EMPLOYEE DATA MEASUREMENTS FOR K-25, PORTSMOUTH, AND THE Y-12 PLANT

An additional method of analysis was applied to the employee dosimetry datasets for K-25 and Portsmouth. This method – quantile regression – is discussed in ORAUT-RPRT-0087, *Applications of Regression in External Dose Reconstruction* (ORAUT 2018). In summary, this method uses quantile regression to fit a linear model to the neutron and photon doses (not an N:P ratio), giving the 50th- and 95th-percentile regression fits directly, with the added benefit of requiring no special treatment of data that might yield a traditional N:P ratio of 1. This approach also allows for exploratory data analysis, i.e., deriving fits for the 50th- and 95th-percentile exposed populations.

The Y-12 Plant site profile discusses historical dosimetry information that can be used to determine neutron and photon exposure near HEU operations (ORAUT 2009). For this report, individual worker quarterly data for pairs of neutron and photon doses from workers in Y-12 Plant Departments 2301 (Development Operations) and 2160 (Material Engineering) during the period from 1955 to 1959 were combined and used as a basis for obtaining an average N:P ratio. These data were selected because unique work activities involving EU were carried out in these departments during this period as indicated in *Recycled Uranium Mass Balance Project Y-12 National Security Complex* (BWXT 2000). Excerpts from this report stated:

> *In the late 1950s, continuous solvent extraction equipment was installed in the B-1 wing (of Building 9212). This period covered the transition from small-scale batch operations to the existing continuous recovery operation equipment in use today.*
>
> *The 9206 building has been used extensively over its lifetime for the chemical processing of uranium. Enriched uranium processes, activities, and/or missions of the 9206 Facility have included: conversion of UF_6 to UF_4 to uranium metal for weapons (1954 to 1964) and casting and machining of HEU metal for weapons (1955 to 1965).*

Film-badge data for Departments 2160 (Material Engineering) and 2301 (Project Design Development and Analytical Development) appear to be somewhat typical of the N:P ratio for workers who were exposed to neutrons from HEU sources in Buildings 9202, 9206, and 9212. The data analysis shown in Figure 3 is based on 89 paired neutron:photon results for 47 different workers in Departments 2160 and 2301.

Table 3 provides the results of the quantile regression fits for K-25, Portsmouth, and Y-12 Plant and data for all three sites combined. In the case of K-25, the entire dataset from 1989 to 2012 was used since the site was in a single (postproduction) mode during that era. The 50th- and 95th-percentile regression fits for K-25 can be seen in Figure 1. At Portsmouth, enrichment activities ended in 2001, so the fits seen in Figure 2 are based on data from 1992 to 2001. Figure 3 illustrates the fits for Y-12 Plant from 1955 to 1959. Finally, Figure 4 illustrates the fits for combining the datasets for all three sites.

Table 3. Summary of quantile regression fit parameters for K-25, Portsmouth, and Y-12 Plant employee data measurements.

Site	N	50th Percentile Slope	50th Percentile Intercept (rem)	95th Percentile Slope	95th Percentile Intercept (rem)
K-25 (1989–2012)	375	0.139	0.01	0.112	0.03
Portsmouth, Production Era (1992–2001)	3,727	0.133	0.002	0.231	0.004
Y-12 Plant (1955–1959)	89	0.14	0.03	0.7	0.1
K-25/Portsmouth/Y-12 Plant Combined	4,191	0.195	0.002	0.846	0.002

The slope data for K-25, Portsmouth during the production era, and Y-12 Plant – especially at the 50th percentile – show good agreement. Please note that production of HEU product at Portsmouth ended in 1991; therefore, this production dataset represents work with mostly LEU product.

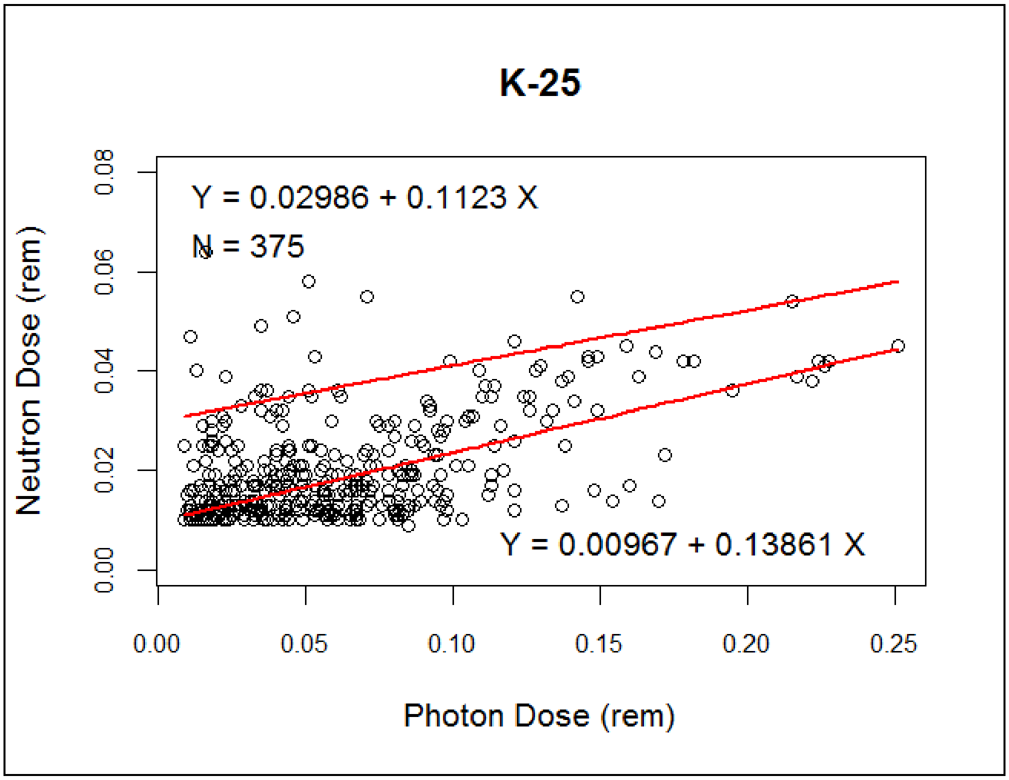

Figure 1. Quantile regression results for K-25 employee dosimetry data (1989–2012).

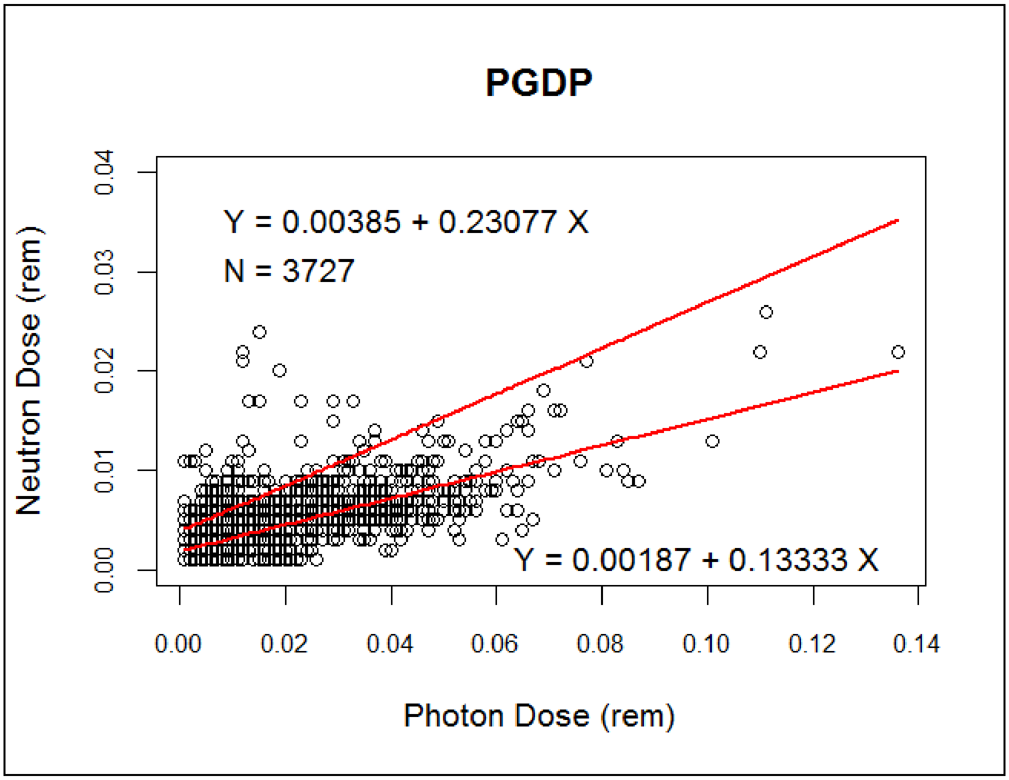

Figure 2. Quantile regression results for Portsmouth employee dosimetry data, production era (1992–2001).

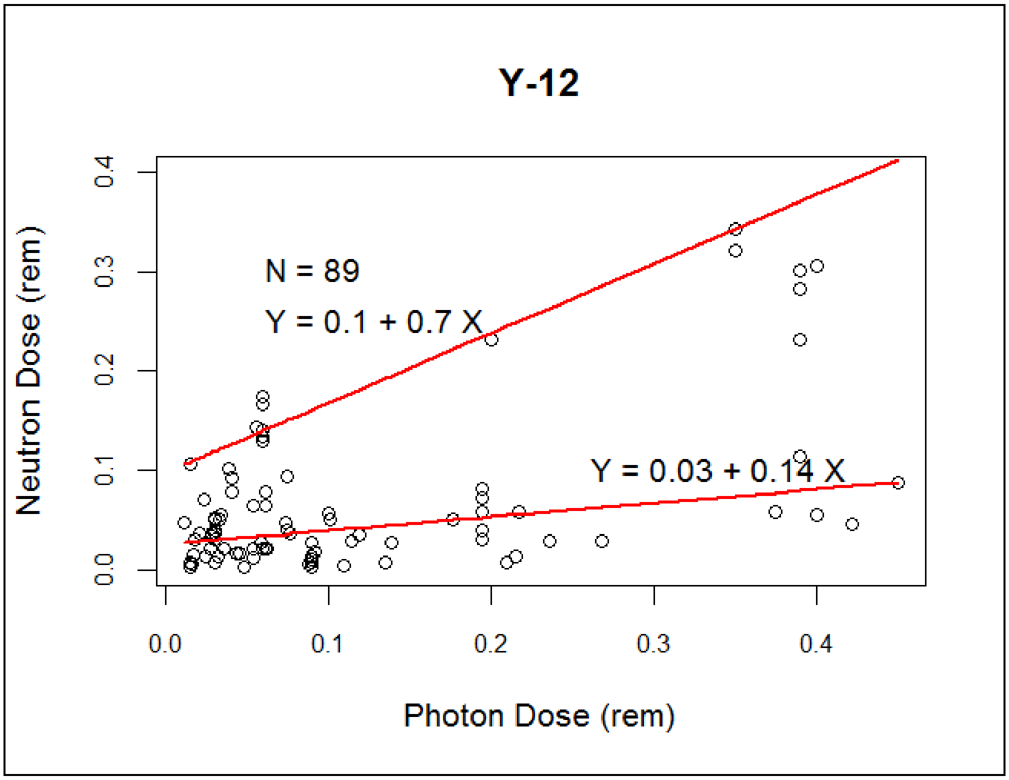

Figure 3. Quantile regression results for Y-12 Plant employee dosimetry data (1955–1959).

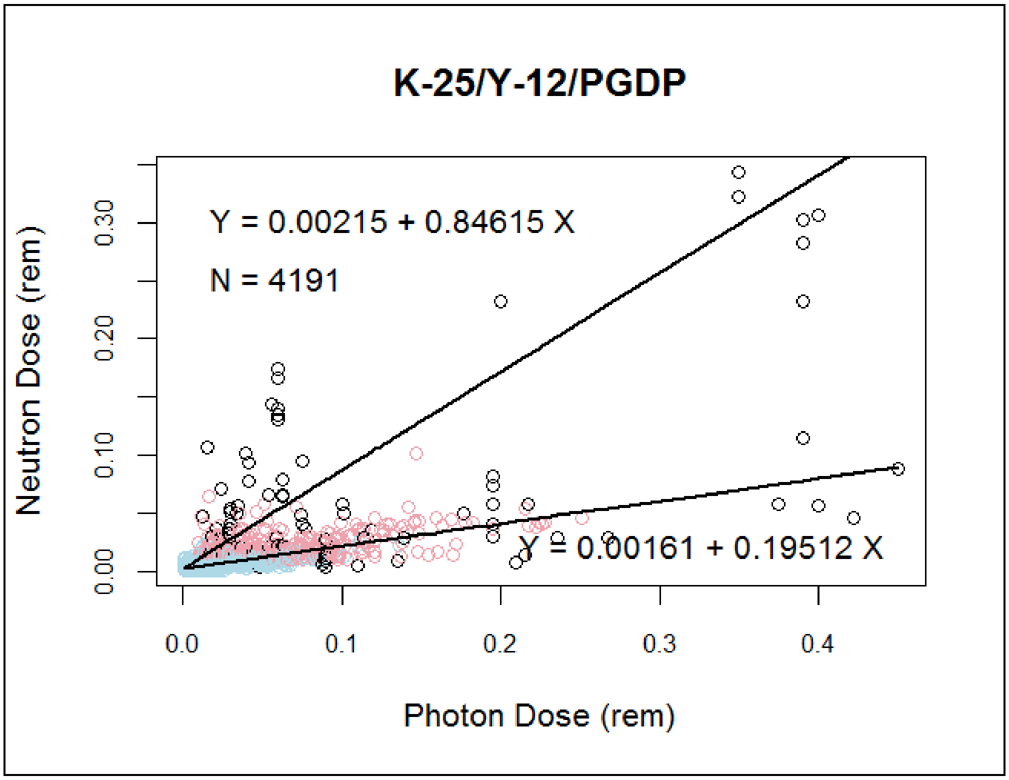

Figure 4. Quantile regression results for the combined K-25, Y-12, and Portsmouth employee dosimetry data sets. (Data for K-25 are in red, data for Portsmouth are in blue, and data for Y-12 are in black).

Additional Data for HEU Exposure

Since the K-25 and Portsmouth data for exposure to HEU are limited, the following data from Y-12 Plant are included here. A study was conducted in 1989 of neutron and photon emissions from small storage containers of HEU in Building 9212 at the Y-12 Plant in Oak Ridge, Tennessee (Soldat et al. 1990). At the time of the measurements, the storage area in Building 9212 held small HEU containers of both UF_4 and UO_3. These small HEU containers were placed on a rack of shelves and arranged in a matrix that was criticality safe (Soldat et al. 1990). The exact enrichment value was not given, but the nature of the work in 9212 (as well as buildings 9202 and 9206 discussed below) would indicate an enrichment value of 90% or greater. The measurements were made at a height of 39 in. (1 m) above the floor and 27 in. (0.7 m) from the nearest container. The location of the measurements was also selected so that it was near only containers of UF_4 (Soldat et al. 1990). The characterization of the neutron field consisted of measurements of the neutron energy spectrum and personal dose equivalent from both neutrons and photons. The measured values for the neutron dose rate ranged from 0.7 to 2.08 mrem/hr. An N:P ratio was derived from this data by comparing the integrated neutron dose of 76.2 mrem for a period of 40.1 hours, as determined from measurements made with a tissue equivalent proportional counter, and the integrated photon dose of 68.0 mrem, as measured by phantom-mounted thermoluminescent dosimeters over the same time period. The resulting N:P ratio for these measurements was 1.12.

Table 4 summarizes N:P ratio data based on survey information from Y-12 Plant for the period 1992 to 2004. The readings were taken either in general work areas or at a distance of 30 cm.

Table 4. Summary of Y-12 N:P Plant ratio data, 1992–2004.

Date	Building	Room	N:P Range	N:P Average	Reference
06/02/1992	9981/9998	G-2/G-5	0.13–1.0	0.37	Y-12 2013; SRDB Ref ID: 129045
02/28/2001	9212	D-107	0.06–0.50	0.2	Y-12 2013; SRDB Ref ID: 126485
07/11/2002	9212	1004	0.1–0.5	0.3	Y-12 2013; SRDB Ref ID: 128511
12/05/2003	9212	1004	0.25–1.0	0.6	Y-12 2013; SRDB Ref ID: 128511
12/08/2003	9212	1004	0.25–1.0	0.6	Y-12 2013; SRDB Ref ID: 128511
05/25/2004	9212	1014	0.22–0.43	0.31	Y-12 2013; SRDB Ref ID: 126498

GENERAL CONCLUSION

Tables 5 and 6 provide summaries of the neutron dose rate, photon dose rate, and N:P ratios data associated with K-25, Portsmouth, and Y-12 Plant operations that can be used to develop a neutron to photon ratio for assigning neutron doses for time periods at each facility (pre-1992 for K-25, pre-1996 for Portsmouth) when neutron dose data were either not reliable, not available, or not recorded. Although a wide range of survey, modeling, and static dosimetry data are available for all three sites, the quantile regression results from the personnel dosimetry measurements at each site would yield the most accurate N:P ratio result. In addition, good agreement was seen – especially at the 50th-percentile level – between the personnel measurement results from all three sites.

The personnel data take into account the actual distances and residence time personnel would have had near potential source terms, whereas the survey data – by their nature – are static measurements taken during a snapshot of time. Survey data are typically taken at maximum dose rate locations to set bounds for radiological control purposes; thus, the survey data can be considered an upper bound. Most of the surveys indicate N:P ratios less than 0.4:1 with only three slightly greater than 1.2:1. This further confirms that the 2:1 upper bound N:P ratio discussed in the DOE *Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities* (DOE 2009) is indeed a conservative upper bound. Given multiple work locations and personnel movement between areas of neutron exposure with N:P ratios less than 0.4 – and areas of no neutron exposure – the data resulting from the quantile regression analysis of personnel dosimetry provide the best estimate for an overall N:P ratio for unmonitored workers.

An N:P relationship based on the quantile regression analysis of dosimetry data for all three sites combined – as summarized in Tables 3 and 6 – is recommended for assigning neutron dose for unmonitored workers in eras as described above. Application of the guidance in Appendix A yields a lognormal distribution that reflects the 50th- and 95th-percentile fits for the quantile regression analysis of the personnel dosimetry data from K-25, Portsmouth, and the Y-12 Plant combined. This distribution is to be combined with photon dose (defined as a constant or distribution) – using Monte Carlo methods as needed – to yield a distribution of neutron dose.

Table 5. Summary of neutron dose rates, photon dose rates, and N:P ratios associated with natural, depleted, and enriched uranium materials at Paducah, Portsmouth, and K-25 Gaseous Diffusion Plants and the Y-12 Plant.

Location/Reference	Material	Neutron Dose Rate (mrem/hr)	Photon Dose Rate (mrem/hr)	N:P Ratio
DOE Good Practices Guide (DOE 2009)	NU to 5% EU	0.01-0.2	NA[a]	2:1
DOE Good Practices Guide (DOE 2009)	97% HEU	2-4 (contact) 1-2 (1 m)	NA	2:1
Paducah GDP, Cylinder Storage Yard (BJC 1999)	DU, NU	NA	NA	0.2
Portsmouth GDP (Cardarelli 1997)	HEU	3 (contact)	NA	0.125
Portsmouth GDP (Cardarelli 1997)	NU, EU, HEU	<0.5 (1 m)	NA	0.125
Portsmouth GDP, X-326, Full 5" Cylinders (Bassett 1986)	97% HEU	≤3.0 (surface)	≤2.4 (surface)	1.25
Portsmouth Area Monitoring Results (McGuire 2008)	DU, NU, LEU, HEU	NA	NA	0.147 (avg) 0.01 (min) 0.398 (max)
K-25 GDP, Cylinder Storage Yard (NISYS 2000)	DU	0.07 (1 m)	0.70 (1 m)	0.10 (1 m)
K-25 GDP, Cylinder Storage Yard (NISYS 2000)	NU	0.15 (1 m)	0.68 (1 m)	0.22 (1 m)
K-25 GDP, Cylinder Storage Yard (NISYS 2000)	5% LEU	0.60 (1 m)	0.68 (1 m)	0.88 (1 m)
K-25, FSAR (LMES 1997)	DU, NU, LEU, HEU	1.5-6 (contact) 1.5-2 (general area)	1.5-6 (contact) 1.5-2 (general area)	0.166
K-25 Equipment and Area Monitoring Surveys (Pope 2015)	DU, NU, LEU, HEU	NA	NA	0.099 (contact) 0.085 (1 ft) 0.122 (1 m) 0.605 (general area)
Y-12 Plant, Bldg. 9212 (Soldat, et al., 1990)	HEU	1.9	1.7	1.12
Y-12 Plant, Bldg. 9981, 9998, and 9212 (Y-12 1992, pp. 4-7) (Y-12 2001, p. 4) (Y-12 2003, p. 18) (Y-12 2003, p. 6) (Y-12 2003, p. 4) (Y-12 2004, p. 4)	HEU	 2–32 1–1.8 0.4–8 0.1–0.4 0.1–0.5 1.4–1.8	 1–4 0.1–0.5 0.2–0.4 0.1 0.1 0.4–0.6	 0.37 (1 ft) 0.2 (1 ft) 0.3 (1 ft) 0.6 (1 ft) 0.6 (1 ft) 0.31 (1 ft)

a. NA = not applicable.

Table 6. Summary of N:P ratios and quantile regression relationships associated with natural, depleted, and enriched uranium materials at Portsmouth, K-25, and Y-12 Plants, based on personnel dosimetry.

Location	Material	N:P Ratio	Quantile Regression Relationship
K-25 Personnel Dosimetry, 1989–2012	DU, NU, LEU, HEU	0.420	50th neutron = 0.139 [photon (rem)] + 0.01 (rem) 95th neutron = 0.112 [photon (rem)] + 0.03 (rem)
Portsmouth Personnel Dosimetry, 1992–2013	DU, NU, LEU, HEU	0.369	50th neutron = 0.133 [photon (rem)] + 0.002 (rem) 95th neutron = 0.231 [photon (rem)] + 0.004 (rem)
Y-12 Plant Personnel Dosimetry, 1955–1959	HEU	NA[a]	50th neutron = 0.14 [photon (rem)] + 0.025 (rem) 95th neutron = 0.7 [photon (rem)] + 0.098 (rem)
K-25/Portsmouth/Y-12 Plant Combined	DU, NU, LEU, HEU	NA[a]	50th neutron = 0.195 [photon (rem)] + 0.002 (rem) 95th neutron = 0.846 [photon (rem)] + 0.002 (rem)

a. NA = not applicable.

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APPENDIX A: QUANTILE REGRESSION ANALYSIS IMPLEMENTATION WITHIN INTERACTIVE RADIOEPIDEMIOLOGICAL PROGRAM (IREP)

Using a quantile regression analysis of paired photon/neutron data, an N:P ratio can be derived for calculating neutron dose based on photon dose using the following inputs (note that this N:P ratio derivation is needed to implement the quantile regression results in the calculation tools used by ORAUT):

1. 50th-percentile equation
2. 95th-percentile equation
3. Known photon dose (normal or lognormal distribution)

The neutron dose at any photon dose is assumed to have a lognormal distribution, the parameters of which are described by the 50th- and 95th-percentile equations.

In this discussion, $N_{50}(p)$ denotes the 50th-percentile neutron dose for a given photon dose p and $N_{95}(p)$ denotes the 95th-percentile neutron dose for a given photon dose (p).

The lognormal parameters for the N:P ratio of a given photon dose are:

$$GM(p) = \frac{N_{50}(p)}{(p)} \qquad \text{(A-1)}$$

where

z_{95} = 1.64485 (normal standard deviation for the 95th-percentile)

and

$$GSD(p) = e^{\left(\frac{\ln \frac{N_{95}(p)}{N_{50}(p)}}{z_{95}}\right)} \qquad \text{(A-2)}$$

To obtain the neutron dose, the derived N:P ratio is multiplied by the photon dose distribution (see example calculation).

Example Calculation

N:P ratio from quantile regression relationship from K-25/Portsmouth/Y-12 Plant combined:
$N_{95}(p) = 0.846\,p + 0.002$
$N_{50}(p) = 0.195\,p + 0.002$
Photon dose p = 0.05 rem

Calculation of N:P Ratio from Photon Dose and Quantile Regression Neutron Dose

$$GM(p) = \frac{0.011366}{0.05} = 0.22732 \quad \text{(A-3)}$$

and

$$GSD(p) = e^{\left(\frac{\ln \frac{0.0444575}{0.011366}}{1.64485}\right)} = 2.291481 \quad \text{(A-4)}$$

Monte Carlo Simulation to Assign Neutron Dose

Photon dose (*p*) = 0.05 rem ± 0.015 rem (normal distribution)

N:P ratio: Geometric Mean (*GM*) = 0.22732, Geometric Standard Deviation (*GSD*) = 2.291481 (lognormal distribution)

A sample from the normal photon dose distribution is multiplied by a sample from the derived N:P ratio. This process is repeated for 10,000 iterations and a distribution is fit to the resulting data set (see results in Figure A-1).

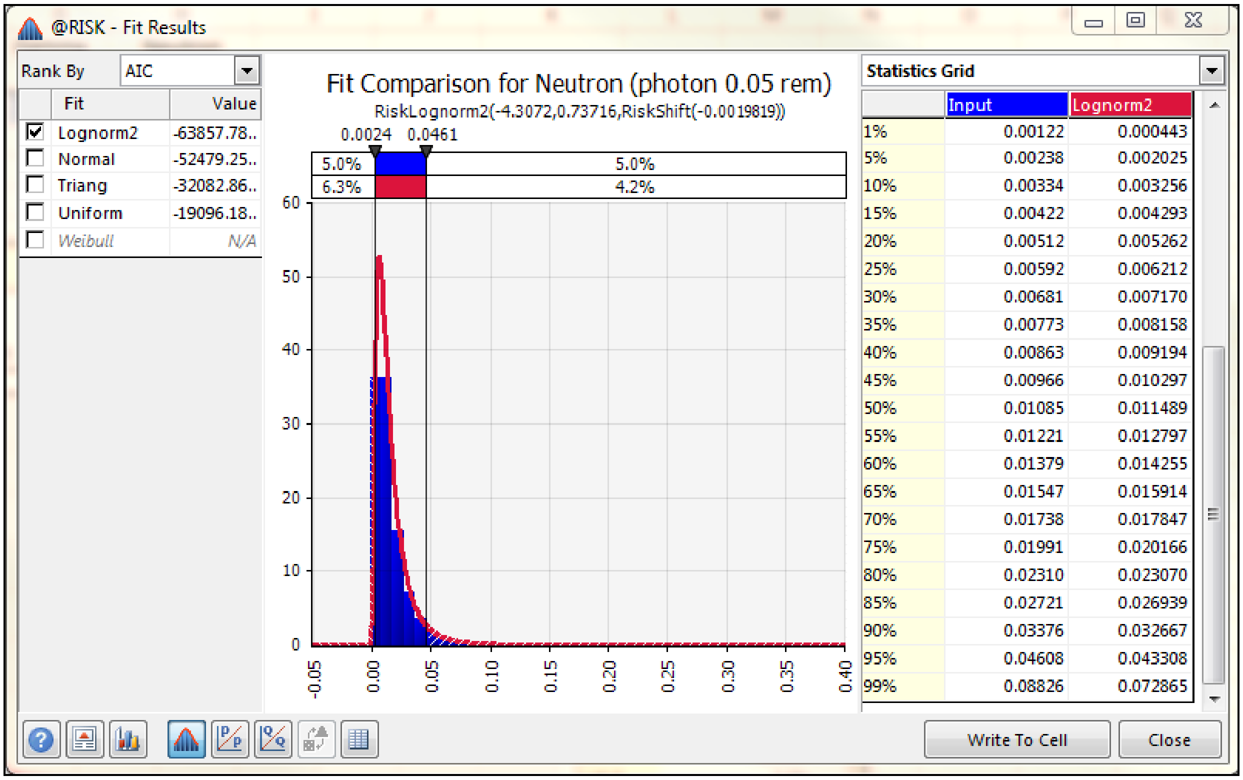

Figure A-1. Lognormal distribution fit of calculated neutron data based on photon sample and N:P ratio sample. Neutron dose lognormal fit from photon sample: 0.05 ± 0.015 rem. (The parameters for this fitted lognormal are mean = -4.3072 rem and standard deviation = 0.73716, and for use with IREP, GM = 0.0135 rem, GSD = 2.090, and shift = -0.0019819).