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Basis for the Development of an Exposure Matrix for Aliquippa Forge, Pennsylvania, Period of Operation: January 1, 1947, through February 28, 1950

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
12/21/2004	00	New Technical Basis Document: Basis for the Development of an Exposure Matrix for Aliquippa Forge, Aliquippa, Pennsylvania, Period of Operation: August 16, 1948 through February 28, 1950. First approved issue. Initiated by Cindy W. Bloom.
11/18/2005	00 PC-1	Approved page change revision. Modified to note the covered period and the period of operation on page 1, 19 and in Section 2.0 on page 5. Modified pages 20, 21, and 22 in response to comments and guidance from OCAS. Updated Section 1.0 (page 5) standard wording. No sections were deleted. Retraining is not required. Initiated by Cindy W. Bloom. Approval: Signature on File 11/09/2005 Cindy W. Bloom, TBD Team Leader Signature on File 11/15/2005 Judson L. Kenoyer, Task 3 Manager Signature on File 11/15/2005 Patricia C. Kimpan, Project Director Signature on File 11/18/2005 James W. Neton, Associate Director for Science
04/26/2012	01	Revision initiated due to comments from the Advisory Board Subcommittee on Dose Reconstruction. Residual period approach in Section 5.0 updated per ORAUT-OTIB-0070 and additional data capture information. Added an internal approach to account for decommissioning and decontamination operations in 1988 and 1993/1994. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Mutty M. Sharfi.
11/16/2015	02	Revision initiated due to comments from the Advisory Board Subcommittee on Procedures Review. Residual period approach in Section 5.0 updated based on change in the treatment of an air sample from being treated as an operational air sample to a postoperational air sample. This resulted in a new source term depletion factor, internal intake rates, and external dose rates. Incorporates formal internal and NIOSH review comments. Training required: As determined by the Objective Manager. Initiated by Mutty M. Sharfi.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AWE	atomic weapons employer
BNI	Bechtel National, Inc.
CFR	Code of Federal Regulations
cm	centimeter
d	day
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
dpm	disintegrations per minute
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ft	foot
FUSRAP	Formerly Utilized Sites Remedial Action Program
GM	geometric mean
GSD	geometric standard deviation
HEPA	high-efficiency particular air
hr	hour
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
keV	kilovolt-electron, 1,000 electron-volts
L	liter
lb	pound
m	meter
MCNP	Monte Carlo N-Particle
MDA	minimum detectable activity
mL	milliliter
mR	milliroentgen
mrem	millirem
mrep	millirep
NIOSH	National Institute for Occupational Safety and Health
NYOO	New York Operations Office
OCAS	Office of Compensation Analysis and Support
ORAU	Oak Ridge Associated Universities
pCi	picocurie
R	roentgen

s	second
SEC	Special Exposure Cohort
SRDB Ref ID	Site Research Database Reference Identification (number)
t	ton
TBD	Technical Basis Document
U.S.C.	United States Code
yr	year
µCi	microcurie
µg	microgram
µm	micrometer
§	section or sections

1.0 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular Department of Energy (DOE) or Atomic Weapons Employer (AWE) facilities or categories of DOE or AWE facilities. They will be revised in the event additional relevant information is obtained about the affected DOE or AWE facility(ies). These documents may be used to assist NIOSH staff in the evaluation of Special Exposure Cohort (SEC) petitions and the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used to refer to an area, building, or group of buildings that served a specific purpose at a DOE or AWE facility. It does not mean, nor should it be equated to, an "AWE facility" or a "DOE facility." The terms AWE and DOE facility are defined in sections 7348l(5) and (12) of the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA), respectively. A DOE facility is defined as "any building, structure, or premise, including the grounds upon which such building, structure, or premise is located … in which operations are, or have been, conducted by, or on behalf of, the [DOE] (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program)," and with regard to which the DOE has or had a proprietary interest; or "entered into a contract with an entity to provide management and operation, management and integration, environmental remediation services, construction, or maintenance services." 42 U.S.C. § 7384l(12). On the other hand, an AWE facility means "a facility, owned by an atomic weapons employer, that is or was used to process or produce, for use by the United States, material that emitted radiation and was used in the production of an atomic weapon, excluding uranium mining or milling." 42 U.S.C. § 7384l(5). The Department of Energy (DOE) determines whether a site meets the statutory definition of an AWE facility and the Department of Labor (DOL) determines if a site is a DOE facility and, if it is, designates it as such.

Accordingly, a Part B claim for benefits must be based on an energy employee's eligible employment and occupational radiation exposure at a DOE or AWE facility during the facility's designated time period and location (i.e., covered employee). After DOL determines that a claim meets the eligibility requirements under EEOICPA, DOL transmits the claim to NIOSH for a dose reconstruction. EEOICPA provides, among other things, guidance on eligible employment and types of radiation exposure to be included in an individual dose reconstruction. Under EEOICPA, eligible employment at a DOE facility includes individuals who are or were employed by DOE and its predecessor agencies, as well as their contractors and subcontractors at the facility. Unlike the abovementioned statutory provisions on DOE facility definitions that contain specific descriptions or exclusions on facility designation, the statutory provision governing types of exposure to be included in dose reconstructions for DOE covered employees only requires that such exposures incurred in the performance of duty. As such, NIOSH broadly construes radiation exposures incurred in the performance of duty to include all radiation exposures received as a condition of employment at covered DOE facilities in its dose reconstructions for covered employees. For covered employees at DOE facilities, individual dose reconstructions may also include radiation exposures related to the Naval Nuclear Propulsion Program at DOE facilities, if applicable. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction.

On the other hand, under EEOICPA, eligible employment at a AWE facility is categorized as employment either (1) during "a period when the employer was processing producing, for the use by the United States, material that emitted radiation and was used in the production of an atomic weapon, excluding uranium mining and milling," (i.e., the operational period); or (2) during a period that NIOSH has determined that "there is a potential for significant residual contamination outside of the period in which weapons-related production occurred," (i.e., the residual contamination period). 42 U.S.C. § 7384l(3).

Based on the abovementioned definition for eligible employment during an AWE facility's operational period, NIOSH includes radiation exposures incurred in the performance of duty, such as medical X-rays received as a condition of employment for participating in DOE projects, at an AWE facility in dose reconstructions. This may include radiation exposure related to the Naval Nuclear Propulsion Program and any radiation exposure received from the production of commercial radioactive products that were concurrently manufactured by the AWE facility during the operational period. In contrast, only two categories of radiation exposure as defined in 42 U.S.C. § 7384n(c)(4) should be included in dose reconstructions for claims involving employment during the residual contamination period. First, NIOSH must include exposures to radiological contaminants resulting from activities that had a nuclear-weapon nexus or conducted by or on behalf of the DOE (with an exclusion of activities related to, among other things, the Naval Nuclear Propulsion Program) that took place during the operational period. 42 U.S.C. § 7384n(c)(4)(A). Second, radiation doses from sources not included in the first category but which cannot be distinguished through reliable documentation should also be included in dose reconstructions. 42 U.S.C. § 7384n(c)(4)(B). Furthermore, because all DOE-related activities have ceased during the residual contamination period, NIOSH does not include doses from medical X-rays performed during the residual contamination period (NIOSH 2007) in dose reconstructions.

Likewise, NIOSH does not consider the following types of exposure as those incurred in the performance of duty as a condition of employment for DOE-related activities at a DOE or AWE facility. Therefore these exposures are not included in dose reconstructions for covered employees (NIOSH 2010):

- Background radiation, including radiation from naturally occurring radon present in conventional structures

- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons

1.1 PURPOSE

This technical basis document (TBD) provides an exposure matrix for the Aliquippa Forge. The DOE Office of Worker Advocacy lists the Aliquippa Forge covered period from 1947 to 1950. The information that follows supports an assumed period of U.S. Atomic Energy Commission (AEC) operations at Aliquippa Forge from July 23, 1948, through February 28, 1950, that involved AEC-contracted uranium work. This analysis assumed that the residual contamination period extended from March 1, 1950, through December 31, 1987, and from January 1, 1989, to December 31, 1992.

1.2 SCOPE

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 6.0.

2.0 SITE DESCRIPTION AND OPERATIONAL HISTORY

The Aliquippa Forge radiological source term consisted primarily of natural uranium metal, uranium oxides, and natural uranium's short-lived progeny. Long-lived progeny prevent significant ingrowth past ^{234}U in the ^{238}U decay series and beyond ^{231}Th in the ^{235}U decay series.

Vulcan Crucible Steel Company operated Aliquippa Forge to produce uranium rods for the AEC from billets primarily by rolling. Operations with uranium at the forge began when a trial rolling occurred on July 23, 1948 (Jones 1948a). The AEC contract for production work (AEC 1948) was initiated on August 16, 1948, and was extended through February 28, 1950 (Belmore 1950; Wallo 1981). The rolling operation ended on March 30, 1949 (Kelley 1949) with decontamination consuming the rest of

the contract's term. Decontamination was completed by Vulcan Crucible in 1950 in accordance with then-current AEC guidelines.

The site consisted of about 19 buildings. The majority of the AEC work occurred in Building 3, the rolling mill. Survey results for Building 8 indicate its involvement with uranium activities (Adams and Payne 1992a, 1992b). In addition, there were indications of uranium in the locker room, tool room, and some areas outside Building 3. Figure 2-1 shows the layout of the site in about 1992, and Figure 2-2 shows the layout of the area that encompassed uranium operations. A sketch from 1948 (Piccot 1948) indicates that at least part of the Building 3/8 area was referred to as C Mill. That sketch showed billets in an area known later as Building 8 and a boxcar containing billets and rods to the northwest of Building 8; it also showed the lockers, showers, and toilets to the east of Building 3.

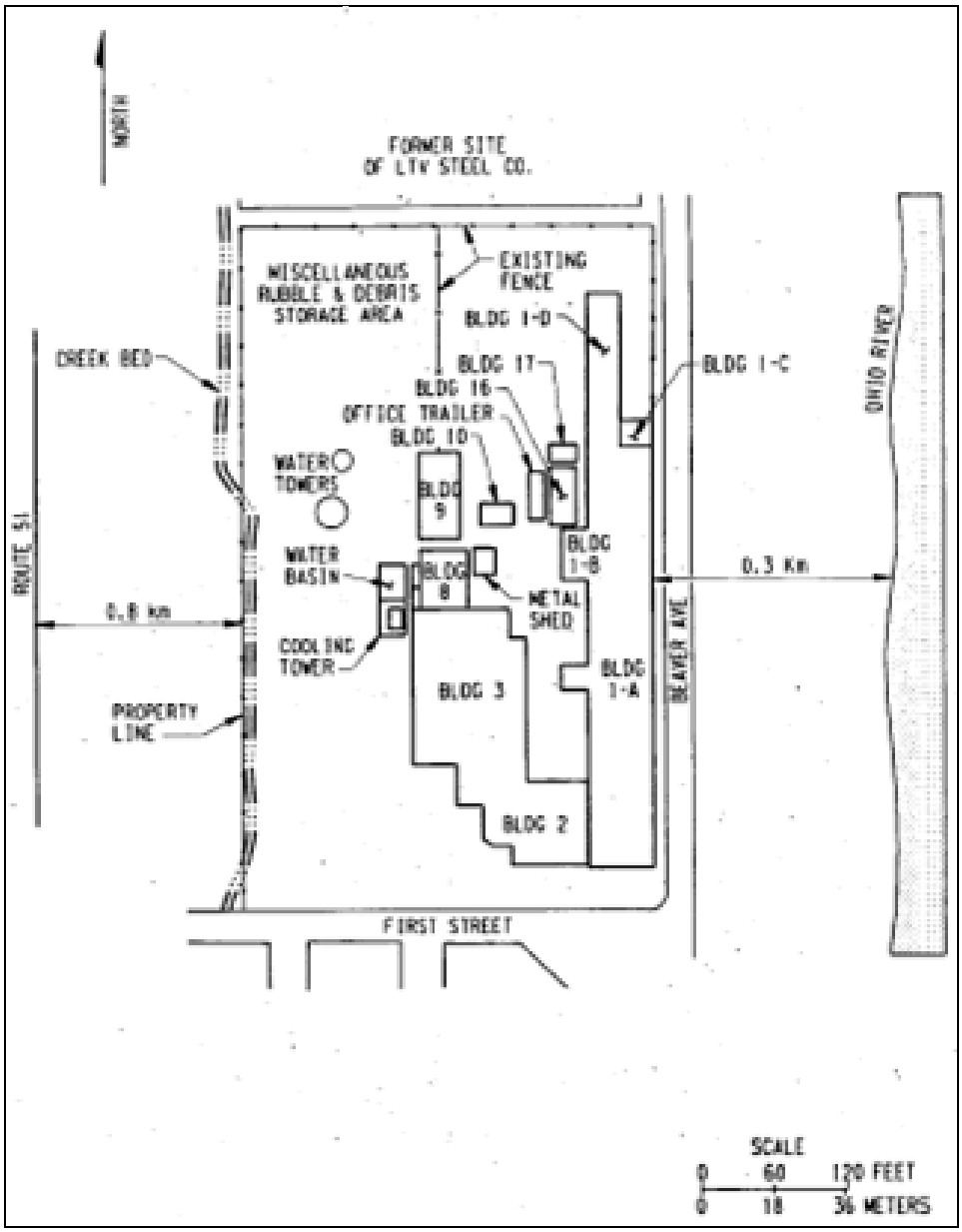

Figure 2-1. Aliquippa Forge site, circa 1992 (DOE1996a).

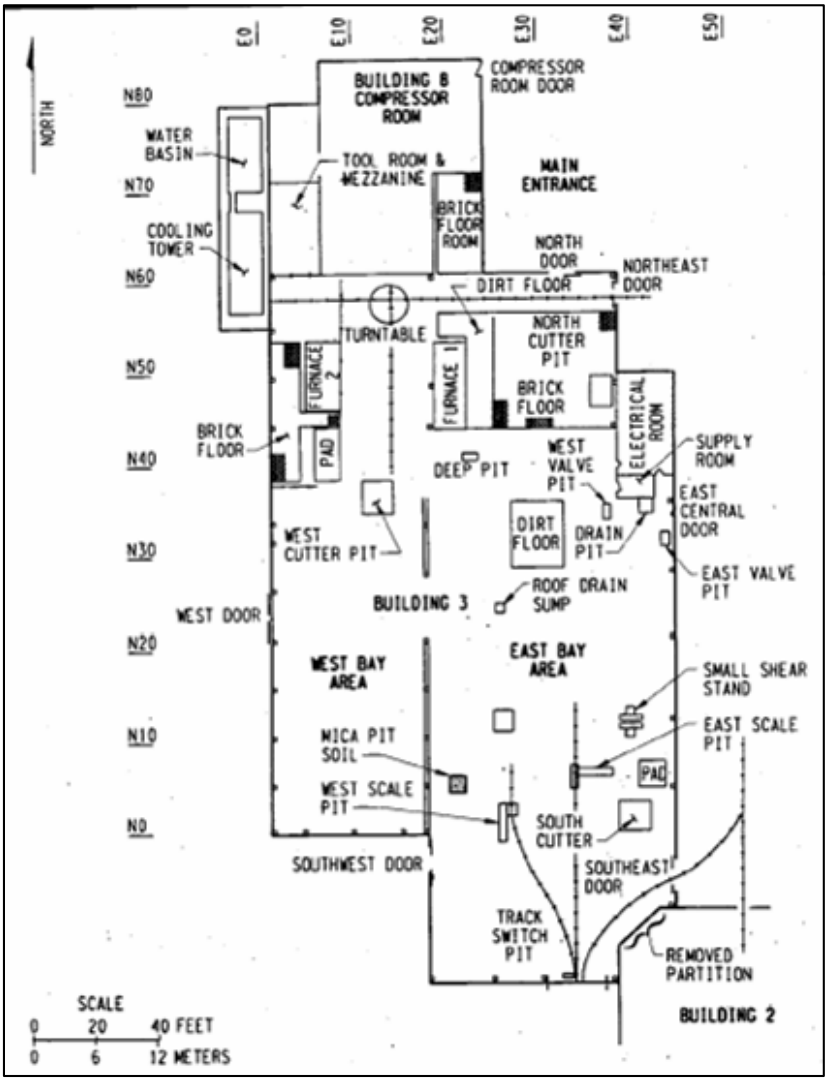

Figure 2-2. Aliquippa Forge Buildings 3 and 8 where AEC uranium operations occurred (DOE 1996a).

The uranium billets that were furnished by the AEC came primarily via boxcar from the Electromet facility in New York and the 300 Area on the Hanford Site in Washington (Stroke 1949a). The billets were 15 to 28 in. long, 4 to 5 in. in diameter, and weighed from 120 to 270 lb. Vulcan Crucible conducted a rolling operation in Building 3 to reduce the billets to rods about 1.5 in. in diameter with an increase in length of a factor of 9. The billets were heated and rough-rolled twice to increase the length, then finish-rolled and halved before quenching and weighing (Wallo 1981).

The process at Aliquippa Forge consisted of heating the billets to a temperature between 1,050°F and 1,100°F. A drag-down operator used a buggy to move the heated billets from the furnace to the north side of the roughing roll. The billets were passed through the roughing roll two to four times to produce rods of rough dimensions. The rods were then passed through the finishing rolls to achieve the desired dimensions. They were then dragged to the shears, cut in two, and dragged back to the quenching area for descaling. After the rods were stamped, they were conveyed to the shipping and receiving area to be weighed, recorded, and loaded into boxcars (Author unknown ca. 1949; AEC 1949a; Jones 1948b).

Little information is available on the actual uranium rollings that took place at Aliquippa Forge during the AEC contract period. Documents indicate that each rolling operation involved approximately

96 billets in an 8-hour shift (Stroke 1949b; Reichard 1948). Other documents indicate the Forge had a 9-hr workday with a rolling rate of 11 to 12 billets per hour (Breslin 1949), which seems consistent with the February 1949 workplace monitoring records, if 1 additional hour is assigned to lunch and breaks. Table 2-1 summarizes the available uranium rolling information. Although some documentation indicates that 20% of the time at Vulcan Crucible was spent rolling uranium billets for the AEC (Wallo 1981), the AEC contract required that Vulcan Crucible be prepared to perform rolling work at least 2 consecutive weeks out of every 5 consecutive weeks (AEC 1948), which would be 40% of the time.

Table 2-1. Documented uranium rollings at Vulcan Crucible.

Date of rolling	Type	Number of billets rolled
July 23, 1948[a]	Trial	8
August 23–September 2, 1948[b]	Production	822 Type B (80 t)
September 27, 1948[c]	Experimental forging	50
October 21–November 3, 1948[d]	Production	Unknown
October 21–November 3, 1948[d]	Experimental forging	52 forged
January 3–15, 1949[e]	Production	982 Type B billets 103 Type C billets (~120 t)
February 14–23, 1949[f]	Production	112 “small billets per shift”
March 30, 1949[g]	Unknown	70 “large billets per shift”

a. Jones (1948a).
b. Jones (1948b).
c. Schier (1948).
d. Hauff (1948), DOE (2002).
e. Padden (1949).
f. Breslin (1949), DOE (2002).
g. Breslin (1949).

Vulcan Crucible employed about 20 to 25 workers at the rolling plant with approximately 20% of the total rolling time occupied by AEC work (Wallo 1981). AEC personnel made occasional visits to assess working conditions in the mill and attended some, but not all, rolling operations.

As of September 2, 1948, the exhaust ventilation system consisted of two large roof ventilators for the building (Piccot 1948). The ventilator placement was not considered ideal for the uranium rolling operations.

During the September 1948 AEC visit, a large door and windows at the end of the mill were open, which reportedly carried dust to the southeast of the plant (Piccot 1948). The AEC Medical Division recommended that Vulcan Crucible upgrade the exhaust ventilation system and install a central vacuum to maintain cleanliness. The recommendations were transmitted to Vulcan Crucible on October 14, 1948, as requirements for “the contemplated metal rolling contract” (Belmore 1948). A November 2, 1948, memorandum indicates that the vacuum system had been installed (Reichard 1948). However, as of the rolling on February 15 and 16, 1949, the upgrade to the ventilation system had not been made (AEC 1949a), although temporary ventilation over the rollers was provided for that rolling campaign.

AEC visits were made before and after modifications to the ventilation system (Belmore 1948; Piccot 1948; AEC 1949a; Breslin 1949; Belmore 1949a). The *Monthly Status and Progress Report for April 1949* (Kelley 1949) states:

> *Since the Vulcan Crucible Steel Company cannot handle the larger-size billets which give better casting yields, it was decided to consolidate operation at Simonds. Because of this decision, rolling operations ceased at Vulcan after the March [1949] run. Portable Government property is to be removed immediately. Attached property is to be left at*

Vulcan, provision will be made for emergency standby facilities until the contract expires in August.

During World War II, permissible levels for uranium dust in air were set at 500 µg/m^3 for insoluble uranium compounds and 150 µg/m^3 for soluble uranium compounds. After the war, the University of Rochester lowered its recommendation for soluble uranium compounds to 50 µg/m^3 based on chemical toxicity, which for natural uranium is equivalent to 70 dpm/m^3. This level was based primarily on animal studies. The Medical Division of the AEC New York Operations Office (NYOO) felt that a "maximum permissible level" was unknown and should be based on human data. Therefore, the 50-µg/m^3 level was referred to as the "preferred level" (AEC 1949b).

The AEC visited Aliquippa Forge on September 1, 1948, to conduct a health physics survey and to determine (Piccot 1948):

1. The type of physical examination given to the workers.
2. The use of protective clothing, showers, and lunchroom.
3. The exposure of personnel to direct radiation.
4. The spread of contamination in the plant.
5. The concentration of radioactive dust in the air.

Medical examination requirements for Aliquippa Forge uranium workers were specified in October 1948 (Belmore 1948). The AEC staff noted on March 29, 1949, that "a complete blood count, a urine and a chest X-ray were done on all employees exposed in the rolling area before work on the AEC Project was started" (Tabershaw 1949) and "a repeat blood count and urine [medical, not radioactivity analyses] were done on all workers after a period of 6 months." The X-ray examinations were performed by Dr. W. T. Rice, who kept the films in his Rochester, Pennsylvania, office.

As of the September 1, 1948, visit, there were few health physics controls in place. Piccot (1948) noted, "workers furnish and launder their own clothes, shoes and gloves and usually change before going home. Separate lockers are not provided for clean and dirty clothes. Smoking is permitted in the mill and some men were observed smoking with their dirty gloves on. The men also eat their lunch in the vicinity of the mill." In addition, the report noted that workers were loitering or standing near uranium billets or rods, and one even sat on billets while taking a break.

In October 1948, the AEC specified "protective clothing and hygienic procedures" (Belmore 1948). Protective clothing was listed as dedicated work clothing, gloves, and shoes. The AEC recommended that Vulcan Crucible provide workers with clothing that could be kept separate from personal clothes. Workers were to be instructed to not eat or smoke with gloved hands, and to wash hands thoroughly before smoking, eating, or leaving the shift. The AEC also recommended showering at the end of the shift. No later reports were found to indicate whether the company supplied clothing, but there was indication that some workers showered and changed at the end of the shift. The available records indicate contamination controls were not strictly implemented.

Air samples were taken during the September 1948 visit; one sample (during the third pass in back of the mill) showed an air concentration as high as 1,800 times the preferred level (i.e., 50 µg/m^3). Although peak values need to be considered, the fact that work tasks and worker locations were constantly changing resulted in time-weighted exposures that were typically much lower than the peak values. The other air sampling results for September 1 and 2, 1948, showed concentrations in the range of 2.6 to 510 times the preferred level, with 15 of the 22 results less than or equal to 50 times the preferred level.

An NYOO report of an AEC visit to the Aliquippa Forge on February 15 and 16, 1949, described time-weighted radioactive dust exposures between 2.7 and 5,300 times the preferred level depending on

the type of job (AEC 1949a). A review of the February 1949 report and calculations showed that February report was in error and overstated the maximum exposure by about a factor of 10. When discussing the higher concentration, the report stated:

> *It was noted during the sampling that relatively large flakes of scale were being thrown from the rods at this operation. The above concentrations may therefore represent some number of large, non-respirable particles, and not be a true indication of exposure.*

A later summary report (AEC 1949b) stated that four workers who were directly involved in the rolling were exposed to as much as 530 times the preferred level. The summary report mentioned that the recommended ventilation system upgrade had not been installed, but that it was on order and that a temporary although inadequate system was in place.

The AEC visit of March 30, 1949, occurred after the installation of a new exhaust fan with twice the capacity of the previous fan. During this visit, the largest calculated time-weighted uranium exposure was 21 times the preferred level. A reevaluation of one worker's exposure based on a statement that one sample appeared to be unreasonably low indicates that the largest exposure might have been 57 times the preferred level. This is still indicative of a reduction of uranium air concentrations due to the improved ventilation. AEC noted during this visit that rather than rolling 112 "small" billets during a 9-hour shift, 70 "larger" billets were rolled in an 8-hour shift, which might also have contributed to the lower uranium dust concentrations (Breslin 1949). The AEC record indicates that there were no rolling operations after March 1949 and that only cleanup operations were taking place (Kelley 1949).

The purpose of the April 24, 1949, AEC visit was to survey the contamination from previous rollings. The visit resulted in recommendations for the cleanup of the mill. The visit of July 21, 1949, evaluated the effectiveness of the recommended decontamination. During these two visits (Belmore 1949a, 1949b), AEC took direct measurements of surface contamination using a Zeuto but did not collect smear samples. (A Zeuto is a portable ionization chamber. The early models were used to measure alpha contamination; some models also measured beta and gamma radiation.)

Based on the time-weighted information AEC collected on February 15 and 16, 1949 (AEC 1949a) and on March 30, 1949 (Breslin 1949), this evaluation assumed 10-hour workdays before March 30, 1949, and 8-hour workdays thereafter. Table 2-2 lists the assumed number of workdays and uranium rolling days in each period.

Table 2-2. Number of assumed workdays and uranium rolling days.

Start	End	Nonuranium rolling workdays	Rolling days	Calendar days
07/23/1948	12/31/1948	116	50	162
01/01/1949	03/29/1949	63	30	88
03/30/1949	12/31/1949	198	90	277
01/01/1950	02/28/1950	42	20	58

The analyses for this exposure matrix divided the workers into three groups. Exposures to workers who do not fit in the following three groups are designated to an "unknown" category, for which dose reconstruction information is included in the internal and external exposure sections of this document:

- Group I
  - Hook Man (Front Hooker, Back Hooker)
  - Drag-Down Operator (Buggy Man)
  - Rougher
  - Finisher

  - Shear Man
  - Shear Man Helper
  - Heater (Furnace Man)
  - Heater Helper (Furnace Man Helper)
  - Mill Roller
  - Catcher
  - Hot Sawyer
  - Hot Sawyer Helper
  - Rod Stamper
  - Quencher

- Group II

  - Shipping and Receiving
  - Checker
  - Rod Weigher

- Group III

  - Guard
  - Technical Supervisor
  - Office Workers

While different tasks in the mill resulted in differences in exposures (AEC 1949a), it is not known if each worker always performed the same task within a group, or if workers temporarily worked in locations where higher or lower exposures occurred. Workgroup exposure assignments are based on data that are suggestive of worker exposures and further modified by uncertainty parameters to ensure that the reconstructed dose distributions capture the larger exposures. Depending on the organ of interest and the ancillary data on a specific claim, additional considerations might be appropriate.

The analyses assumed:

- Group I workers were involved primarily with heating, rolling, finishing, and quenching of uranium. They spent the largest part of their time in the general mill area near the furnace and rollers.

- Group II workers worked primarily with the finished uranium rods and spent the largest part of their time in the rod storage area and boxcar.

- Group III workers were not engaged directly in the processing of uranium. They probably had lower internal and external exposures than the other groups, with the possible exception of the guards, who might have spent time near the boxcar and the uranium storage areas.

In July of 1949, a survey was performed to determine forge cleanup requirements (Belmore 1949c). Additional AEC assessments and surveys were made throughout the cleanup process. Although AEC noted that the cleanup personnel had no monitoring equipment, the assessments concluded that a sufficient job of cleanup had been done (Eisenbud 1950; Belmore 1950).

The Formerly Utilized Sites Remedial Action Program (FUSRAP) began in 1976. Perry (1993) stated:

> *A radiological survey in 1978 identified contamination (primarily uranium-238) in and around onsite buildings. The site was designated for further remediation under FUSRAP, and the small operation was shut down and the building evacuated.*

Because ^{238}U is the predominant isotope by mass in natural uranium and is more easily identified than the other isotopes, the 1978 survey report might have been referring to natural uranium, which consists of approximately equal activities of ^{234}U and ^{238}U and a smaller amount of ^{235}U. Reported ^{238}U quantities might include all of the uranium activity or just part, depending on actual analysis techniques and reporting procedures.

Radioactive contamination was found during the survey of May 2 to 8, 1978, on the dirt floor, concrete floor, steel floor plates, and the overhead beams above the furnaces that were used in the uranium processing (Wynveen et al. 1982). The actual date of building evacuation is unknown and is assumed to have occurred on May 31, 1978, after the FUSRAP survey.

In August 1983, the Aliquippa Forge site was designated for remedial action under FUSRAP (DOE 1996a). In December 1987, storage activities began in Building 3. Interim remedial actions were taken from October to December 1988 to enable additional restricted use of Building 3 for expansion of a small forging operation (Baublitz 1988; Harbert 1989; DOE 1996a). Controlled areas were established to prevent access to contamination (Seay 1988; DOE 1996a). The exact date of reoccupation is unknown, but is assumed to have occurred as early as December 1, 1987. As of May 17, 1993, the buildings were no longer in use, although the actual last date of use is not clear. This analysis assumed that a second period of residual exposure occurred from December 1, 1987, to May 17, 1993. Final remedial activities occurred from about June 1993 to September 1994 (Abelquist 1995; DOE 1996a). A final survey and decontamination were performed in 1995 (DOE 1996a). A DOE notice of certification was published in October 1996 in the *Federal Register* (61 FR 55981).

Because recycled uranium was not available to contracted AEC facilities until after March 1952 (DOE 2001), this exposure analysis did not consider it.

3.0 ESTIMATION OF INTERNAL EXPOSURE

The primary source of internal radiation exposure at Aliquippa Forge was uranium dust from the manipulation and oxidation of uranium metal during the rolling and related processes. There is no indication that uranium rolled at Vulcan Crucible was enriched, so the analysis assumed natural uranium enrichment.

Human and animal studies have indicated that oxides of uranium can be very insoluble (ICRP 1995), indicating absorption type S. Other in vitro dissolution studies of compounds at uranium facilities have shown that oxides of uranium exhibit moderate solubility (Eidson 1994; Heffernan et al. 2001) suggesting absorption type M. In vitro dissolution tests on oxides produced from uranium metal during depleted uranium armor penetrator tests have indicated multicomponent dissolution rates, with 25% of uranium dissolving with a half-time of less than or equal to 0.14 days and 75% dissolving with a half-time of 180 days. Because there was no specific information on the solubility of aerosols at the forge, this analysis assumed that both types M and S were available. The selection of absorption type should depend on the organ of interest. Dose reconstructions should assume International Commission on Radiological Protection (ICRP) Publication 66 default parameters for particle deposition (ICRP 1994).

The uranium fusion photofluorimetry urinalyses performed by the University of Rochester and the AEC NYOO were similar to those performed at the Fernald Plant. The default detection threshold for uranium urinalysis is 14 µg/L, based on the Fernald reevaluation of its uranium fluorimetry urinalysis minimum detectable activity (MDA) in 1993 (Blalock 1993).

Individual uranium urinalysis data are available for some forge workers (AEC 1949c). For unmonitored workers or unmonitored periods, this document analyzes air monitoring data for use in reconstructing internal doses.

3.1 URANIUM AIR SAMPLING

Air sampling was performed at Aliquippa Forge during some of the uranium rolling (AEC 1949b; Breslin 1949). The air samples consisted of collection on filters of radioactive particulate from breathing zones, general areas, processes, and effluents. The measured alpha activity on the filter was used to determine airborne alpha activity concentrations. The AEC matched these air concentration determinations with information about worker categories, locations, tasks, and time at each location or task. For some tasks and locations, multiple samples were collected; the mean count rate was calculated and used to calculate an average air concentration.

The AEC used the information on work tasks with the measured air concentration to determine an average air concentration weighted by time and summed these weighted average air concentrations to determine a daily weighted average air concentration for specified job categories. These air concentration results are further analyzed here to determine group geometric means (GMs). The daily weighted average air concentrations were weighted further by the AEC-reported number of workers who were exposed at a given concentration. The GMs of the workgroups' daily weighted average air concentrations were calculated. The geometric standard deviations (GSDs) of both the job category concentrations and the workgroup concentrations were determined to provide an indication of the distribution of the data. The latter GSD includes consideration of the number of people in each category in the AEC study. This analysis assumed that, because data are limited and rigorous analyses to determine distribution type are not likely to be meaningful, a lognormal distribution could represent the time-weighted exposures and the subsequently derived annual organ doses.

The report on the February 1949 rolling shows time-weighted air concentrations (based on measurements at the plant) before the upgrade of the ventilation system. The report on the March 1949 rolling (Breslin 1949) shows the time-weighted air concentrations after the upgrade. During spot checks of the February 1949 air concentrations, this analysis revealed a mathematical error for the Hook Man's daily weighted air concentration, which resulted in a change from the 36,800 dpm/m^3 to 38,200 dpm/m^3. An error was also found for the February result for Roughers, but the change was small and correction of the error would have slightly reduced the exposure, so it was ignored. The March report noted that "one unsubstantiated sample of unusually low concentration" probably resulted in an "erroneous" daily weighted average air concentration for the Hook Man. To remedy this, the March 30 average ratio of the second-to-first rolling pass air concentrations was determined. This ratio, 19.2 to 1, was used to modify the low air concentration result. The two sets of data from February and March 1949 were then used to estimate the air concentrations to determine internal exposures by workgroup. Table 3-1 lists the GMs and GSDs for the job category and the workgroups' daily time-weighted average air concentrations.

To be favorable to claimants, the analysis of intakes based on air concentrations assumed that uranium rolling took place between July 23, 1948, and February 28, 1950. It also assumed that 10 days of every month were spent rolling uranium because the AEC required Vulcan Crucible to be prepared to spend 2 consecutive weeks of every 5 consecutive weeks performing AEC work (AEC 1948). Rolling did not occur after March 1949, and data to estimate exposure directly from

cleanup operations were not available. The analysis assumed that the internal exposure rates during cleanup would not have exceeded the internal exposure rates during rolling operations with the improved ventilation.

Table 3-1. Daily time-weighted average air concentration information.

By job category			
Group and air sample collection date	**Group I, 02/15/1949**	**Group I, 03/30/1949**	**Group II and III 02/15/1949**
Number of categories	9	9	6
GM (dpm/m^3)	2,210	545	484
GSD	5	3.2	2
By workgroup			
Group and air sample collection date	**Group I, 02/15/1949**	**Group I, 03/30/1949**	**Group II and III 02/15/1949**
Number of workers	15	9	10
GM (dpm/m^3)	2,610	479	608
GSD	5.3	3	1.8

The breathing rate is based on the default for light work in ICRP Publication 66 (ICRP 1994, Table 6, p. 23). The intakes, in picocuries, were calculated by dividing the GM of a workgroup's time-weighted air concentration by 2.22 dpm/pCi and multiplying this result by the breathing rate and the assumed number of exposed hours at the given concentration. Aliquippa Forge internal organ doses were assumed to be lognormally distributed, and the GSDs for the calculated internal organ doses were assumed to be 5.3. The primary bases for selecting a GSD of 5.3 for all internal organ dose calculations was to simplify and expedite dose reconstructions and to encompass the largest distribution from the air sampling data. Several assumptions included in the intake and dose reconstruction are likely to be overestimating assumptions, which increases the estimate of the median intakes. This overestimation of the median, combined with the assumed GSD of 5.3, is believed to be sufficiently large to describe the organ dose distributions.

Tables 3-2 and 3-3 list estimated annual inhalation intakes during rolling that were assigned to workers in each category. Because air concentrations were not available for Groups II and III in March 1949, the March-to-February ratio of the Group I GM air concentration (4 to 1) was used to estimate a Group II and III air concentration for March 30, 1949.

Table 3-2. Inhalation exposures during rolling operations for Group I workers.[a]

Work period	**Number of months**	**Number of potential AEC workdays**	**Air concentration (pCi/m^3)**	**Breathing rate (m^3/hr)**	**Hours worked per day**	**Intake (pCi)**
07/23/1948–03/29/1949	8	80	1,180	1.2	10	1.13E+6
03/30/1949–02/28/1950	11	110	216	1.2	8	2.28E+5
Total	N/A	N/A	N/A	N/A	N/A	**1.36E+6**

a. N/A = not applicable.

Table 3-3. Inhalation exposures during rolling operations for Group II and III workers.[a]

Work period	**Number of months**	**Number of potential AEC workdays**	**Air concentration (pCi/m^3)**	**Breathing rate (m^3/hr)**	**Hours worked per day**	**Intake (pCi)**
07/23/1948–03/29/1949	8	80	274	1.2	10	2.63E+5
03/30/1949–02/28/1950	11	110	68.5	1.2	8	7.23E+4
Total	N/A	N/A	N/A	N/A	N/A	**3.35E+5**

a. N/A = not applicable.

There was a potential for internal exposure to resuspended material from the AEC work during non-AEC operations. To estimate exposure from resuspended materials, this analysis assumed that surfaces in the building became contaminated by deposition of uranium dust during rolling operations.

The level of contamination was determined by multiplying the largest air concentrations, listed in Table 3-2, by the indoor deposition velocity and the assumed deposition time. Indoor deposition velocity is dependent on the physical properties of the room (such as air viscosity and density, turbulence, thermal gradients, and surface geometry). It is also dependent on the physical properties of the aerosol particles (such as diameter, shape, and density). In this case, these characteristics are not known, so the terminal settling velocity was calculated for an aerosol with the ICRP Publication 66 default particle size distribution of 5-µm activity median aerodynamic diameter (ICRP 1994). The calculated terminal settling velocity was 7.5×10^{-4} m/s, which is within the range of measured deposition velocities (2.7×10^{-6} to 2.7×10^{-3} m/s) in various studies (Biwer et al. 2002).

The calculated surface contamination level from airborne dusts during the uranium rolling from July 23, 1948, to February 28, 1950, was 5.35×10^{6} pCi/m^2 (119,000 dpm/100 cm^2). To be favorable to claimants, the analysis assumed that all of the surface contamination was present for the entire period of AEC operations. Using a resuspension factor of 1×10^{-6}/m (Abu-Eid et al. 2002), the air concentration due to resuspension would have been 5.35 pCi/m^3. Table 3-4 lists the assumed annual inhalation intake from resuspension of deposited material. The intakes in Table 3-4 are added to the intakes in Table 3-2 or Table 3-3 before calculation of annual organ dose (see Table 3-6).

Table 3-4. Annual inhalation exposure during non-AEC operations due to resuspension of deposited uranium dust.[a]

Work period	Hours per day	Workdays per work period	Breathing rate (m^3/hr)	Resuspended air concentration (pCi/m^3)	Intake (pCi)
07/23/1948–03/29/1949	10	179	1.2	5.35	1.15E+4
03/30/1949–02/28/1950	8	240	1.2	5.35	1.23E+4
Total	N/A	N/A	N/A	N/A	**2.38E+4**

a. N/A = not applicable.

When inhalation intakes are calculated from air concentrations, ingestion intakes must also be considered. NIOSH (2004) states that the daily ingestion rate in picocuries can be estimated by multiplying the daily air concentration in picocuries per cubic meter by a factor of 0.2 for an 8-hour workday. For a 10-hour workday, the multiplier would be 0.223. The daily ingestion rates during AEC uranium work were estimated from the air concentrations in Table 3-2, which are larger than the concentrations in Table 3-3. The daily ingestion intakes from resuspended uranium were estimated from Table 3-4. The ingestion intake rates were multiplied by the number of exposed workdays at the calculated levels and summed. The ingestion intakes in Table 3-5 apply to workers in Groups I, II, and III.

Table 3-5. Estimated amount of uranium ingested (pCi) (based on Tables 3-2 and 3-4).[a]

Work period	Days of uranium rolling	Uranium ingestion rate (during uranium rolling) (pCi/d)	Non-uranium rolling workdays	Uranium ingestion rate (during normal operation) (pCi/d)	Intake (pCi)
07/23/1948–03/29/1949	80	2.62E+02	99	1.19	2.12E+4
03/30/1949–02/28/1950	110	4.32E+01	130	1.07	4.89E+3
Total	N/A	N/A	N/A	N/A	**2.62E+4**

a. N/A = not applicable.

3.2 OCCUPATIONAL INTERNAL DOSE RECONSTRUCTION ASSUMPTIONS AND SUMMARY

The assumed uranium photofluorimetry urinalysis MDA is 14 µg/L.

The assumed operational exposure period was from July 23, 1948, to February 23, 1950. The uranium-rolling period was over by March 31, 1949, and the analysis assumed that the exposure after that time was due to cleanup activities, which might have resulted in changing uranium intake rates for some workers. If limited bioassay data are used to calculate intakes, the assignment of the exposure period needs to be considered carefully, because assuming that bioassay results are collected during periods of elevated exposure, when the result is actually collected days or months after the period of elevated exposure, could result in underestimation of intake. For individuals unlikely to have been involved in cleanup, but who have positive bioassay results, it is reasonable to set the intake period to the period of uranium rolling operations (July 23, 1948, through March 30, 1949) and to add an additional intake based on the Table 3-6 intakes for the period after the last bioassay.

Table 3-6. Internal exposure summary for operational period July 23, 1948, to February 28, 1950.

Group I and unknown				
Start	**End**	**Intake route**	**Absorption type**	**Intake (pCi/d)**
07/23/1948	03/29/1949	Inhalation	M, S	4,610
07/23/1948	03/29/1949	Ingestion	(a)	85.1
03/30/1949	02/28/1950	Inhalation	M, S	731
03/30/1949	02/28/1950	Ingestion	(a)	14.6
Groups II and III				
Start	**End**	**Intake route**	**Absorption type**	**Intake (pCi/d)**
07/23/1948	03/29/1949	Inhalation	M, S	1,120
07/23/1948	03/29/1949	Ingestion	(a)	85.0
03/30/1949	02/28/1950	Inhalation	M, S	267
03/30/1949	02/28/1950	Ingestion	(a)	14.6

a. Choose same f_1-value as used for inhalation per NIOSH (2004).

For unmonitored workers or unmonitored periods, Table 3-6 lists intake rate assumptions for natural uranium. The intake mode is chronic. The dose distribution is assumed to be lognormal with a GSD of 5.3.

4.0 ESTIMATION OF EXTERNAL EXPOSURE

Individual external dosimetry results for Aliquippa Forge workers are not available. If results are found, dose reconstructors should consider those results in the evaluation of external dose.

For dose reconstruction, this analysis assumed there was a potential for external exposure from five sources:

- Submersion in air contaminated with uranium dust,
- Exposure from contaminated surfaces,
- Exposure to electrons from the surface of the uranium billets and rods, and
- Exposure to photons from the uranium billets and rods, and
- Exposure to an annual diagnostic X-ray.

The majority of photons from natural uranium metals have energies in the range of 30 to 250 keV. Solid uranium objects provide considerable shielding of the lower energy photons and harden the spectrum, which causes the majority of photons from a solid uranium object, such as a billet or a rod, to have energies greater than 250 keV. While solid uranium sources have a hardened photon spectrum, exposure to a thin layer of uranium on a surface results in a larger fraction of exposure to lower energy photons. To be favorable to claimants, the analysis assumed workers were exposed to

photon energies in the range of 30 to 250 keV. Nonpenetrating dose from natural uranium consists primarily of electrons with energies above 15 keV. For consistent presentation, exposure or dose is reported as either penetrating or nonpenetrating and is assumed to be associated with photons with energies of 30 keV or greater, and with photons with energies less than 30 keV or with electrons, respectively.

4.1 SUBMERSION AND CONTAMINATION EXPOSURES

In a survey at Simonds Saw and Steel, the AEC suspended 20 film badges about 5 ft from the floor in the rolling mill for 192 hours "to determine the long term direct [external] radiation to individuals" (AEC 1949d). When the badges were retrieved, they were covered with radioactive dust from the plant, which probably resulted in an overestimate of the true area radiation levels. The maximum results were reported as 5.6 mR/hr beta and 0.34 mR/hr gamma. The results of these measurements were assumed to be representative of the general levels of external exposure from submersion in air and contaminated surfaces at Aliquippa Forge. This analysis assumed that the data distribution was lognormal. The calculated GMs were 1.3 mR/hr with a GSD of 2.3 for the nonpenetrating radiation and 0.26 mR/hr with a GSD of 1.2 for the penetrating radiation. This assumption does not appear to be inconsistent with the reported Zeuto (portable ionization chamber) beta and gamma readings at Simonds Saw and Steel of 2 mR/hr or less for most areas (AEC 1949d), some of which appear to be contact readings. The beta reading was assumed to be related to the nonpenetrating dose, and the gamma reading was assumed to be related to the penetrating dose. These assumed exposures during operational years are listed in Table 4-3. The analysis assumed all workers were exposed to penetrating and nonpenetrating radiation from submersion in air and contamination for each workday for 10 hr/d before March 30, 1949, and 8 hr/d thereafter.

4.2 URANIUM BILLET AND ROD EXPOSURES

Another assumption was that workers received a deep dose from photon exposure to the uranium billets and rods. According to reports, the AEC work involved rolling uranium billets 4 to 5 in. in diameter and 15 to 28 in. long. The billets were rolled into rods approximately 1.5 in. in diameter and 20 ft long. Monte Carlo N-Particle (MCNP) calculations determined the photon (including bremsstrahlung) dose rate at the surface, 1 ft, and 1 m from a 5-in.-diameter by 28-in.-long cylindrical billet and a 1.405-in.-diameter by 20-ft-long rod. Table 4-1 lists calculated photon dose rates for the uranium billet and rod.

Table 4-1. Calculated photon dose rates for uranium billet and uranium rod.

Distance from source	Billet dose rate (mrem/hr)	Rod dose rate (mrem/hr)
Surface	7.74	5.09
1 ft	0.703	0.285
1 m	0.108	0.0883

The analysis assumed Group I workers were exposed primarily to the billet dose rate and that Group II workers were exposed primarily to the rod dose rate. It also assumed that the dose rate at 1 ft was the median dose rate and the dose rate at the surface was the upper 95th percentile.

The annual penetrating dose rates in Table 4-2 were calculated by multiplying the median photon dose rates by the number of rolling days per year and the number of work hours (10 hr/d before March 30, 1949, and 8 hr/d thereafter).

Shallow doses from the uranium billets and rods were estimated using the measurements in Table 4-3. These measurements were taken during an AEC survey in September 1948 (Belmore 1948).

This analysis estimated the shallow dose for Group I by assuming that the median dose rate was 5 mrem/hr and that the upper 95th-percentile dose rate was 10 mrem/hr, giving a GSD of 1.5. For Group II, the assumed median dose rate was 5 mrem/hr and the assumed upper 95th-percentile dose rate was 20 mrem/hr, giving a GSD of 2.3. These exposure rates were multiplied by the assumed number of uranium rolling hours in the period.

Table 4-2. External exposure summary for operational period, July 23, 1948, to February 28, 1950.[a,b,c]

All workers from submersion and area contamination						
Exposure type	**Exposure or dose rate**	**Basis, photon DCF**	**Exposure time assumption**	**Year**	**Annual exposure**	**GSD**
Penetrating	0.26 mR/hr	Film badge, exposure	2,000 work-hr/yr	1948	0.302 R	1.2
				1949	0.576 R	1.2
				1950	0.087 R	1.2
Nonpenetrating	1.3 mR/hr	Film badge, exposure	2,000 work-hr/yr	1948	1.508 R	2.3
				1949	2.878 R	2.3
				1950	0.437 R	2.3
Group I from uranium billets						
Exposure type	**Exposure or dose rate**	**Basis, photon DCF**	**Exposure time assumption**	**Year**	**Annual exposure**	**GSD**
Penetrating	0.703 mrem/hr	MCNP calculation, dose equivalent [*Hp(10)*]	3 hr/rolling-day	1948	0.105 rem	4.2
				1949	0.253 rem	4.2
				1950	0.042 rem	4.2
Nonpenetrating	5 mrep/hr	Instrument measurement, N/A	3 hr/rolling-day	1948	0.750 rem	2.7
				1949	1.800 rem	2.7
				1950	0.300 rem	2.7
Group II and unknown from uranium rods						
Exposure type	**Exposure or dose rate**	**Basis, photon DCF**	**Exposure time assumption**	**Year**	**Annual exposure**	**GSD**
Penetrating	0.285 mrem/hr	MCNP calculation, dose equivalent [*Hp(10)*]	7 hr/rolling-day	1948	0.100 rem	5.7
				1949	0.239 rem	5.7
				1950	0.040 rem	5.7
Nonpenetrating	5 mrem/hr	Instrument measurement, N/A	7 hr/rolling-day	1948	1.750 rem	2.3
				1949	4.200 rem	2.3
				1950	0.700 rem	2.3

a. Medical X-rays were taken off site; no occupational medical dose is to be assigned (ORAUT 2011).
b. Lognormal distribution in the Interactive RadioEpidemiological Program (IREP).
c. N/A = not applicable.

Table 4-3. Direct radiation measurements from September 1948.[a]

Group I	
Location of measurement	**Dose rate (mrep/hr)[b]**
Contact with floor next to the quench tank where oxide scale collected	8
Contact with floor in front of rolls where oxide scale collected	5–10
Same location but 18 in. high	2–5
Group II	
Location of measurement	**Dose rate (mrep/hr)[b]**
4 ft above a pile of rods in the boxcar	20
5 ft from the end of a pile of rods next to the door of the boxcar	5
2 ft from the end of the same pile	13

a. Belmore (1948).
b. A rep is an obsolete unit of dose equivalence (roentgen-equivalent-physical) approximately equal to a rem.

Table 4-3 lists these doses for Group I and II workers. The analysis assumed that Group III workers were unlikely to be in close contact with the rods and billets for extended periods; it also assumed that air and surface external exposures account for the external exposures.

4.3 OCCUPATIONAL MEDICAL DOSE

According to memorandums from September 20, 1948, and March 29, 1949 (Piccot 1948, Tabershaw 1949), X-ray procedures were taken off site at a physician's office in Rochester, Pennsylvania. Therefore, per guidance in ORAUT-OTIB-0079, *Guidance on Assigning Occupational X-Ray Dose Under EEOICPA for X-Rays Administered Off Site* (ORAUT 2011), no occupational medical dose should be assigned.

4.4 MISCELLANEOUS INFORMATION RELATED TO EXTERNAL DOSE

This section includes external dose information that might be of interest for specific dose reconstructions, but that this analysis did not consider generically because of its limited applicability or because of limited information.

In September 1948, Piccot (1948) noted that some workers were smoking while wearing dirty gloves and one worker was observed sitting on billets during a break. These activities are not directly considered in the external dose evaluations. They were observed early in the Vulcan Crucible uranium rolling operations and might have been limited occurrences.

During the 1949 decontamination activities, an AEC inspector noted (Belmore 1949a):

> *There were 15 pairs of shoes in two steel drums in the storeroom of the plant. The soles of the shoes gave an average reading of 14,000 alpha d/m and 1.3 mr/hr beta-gamma. The leather tops of the shoes showed an average reading of 5,000 alpha d/m and less than* [0.4] *mr/hr beta-gamma. Inside the shoes there were negligible alpha and beta-gamma readings.*

4.5 OCCUPATIONAL EXTERNAL DOSE RECONSTRUCTION ASSUMPTIONS AND SUMMARY

Table 4-2 above summarizes occupational external doses during uranium operations at Aliquippa Forge.

5.0 ESTIMATION OF RESIDUAL EXPOSURE

After the end of AEC rolling operations, a July 1949 survey was performed. The survey indicated that the maximum air dust concentration, taken during normal operations in the furnace area, was 5.9 µg/m^3 or 8.94 dpm/m^3 (assuming a specific activity of 1.516 dpm/µg for natural uranium) (Belmore 1949b).

Vulcan Crucible received essentially pure uranium metal (no radium) for processing. This is confirmed by the 1978 Argonne National Laboratory survey (Wynveen et al. 1982), which showed radon levels varying between 0.11 and 0.27 pCi/L (0.0.0011 to 0.0027 working level assuming 100% equilibrium), which are within the normal range of atmospheric radon content of 0.1 to 0.5 pCi/L (Eisenbud 1987, p. 417). The building was reportedly evacuated in 1978 (Perry 1993); this is assumed to have occurred on May 31, 1978, after the Argonne National Laboratory survey.

The Aliquippa Forge site was included in the DOE FUSRAP in August 1983. In December 1987, Bechtel National, Inc. (BNI) surveyed Aliquippa Forge for the purpose of allowing the use of portions of Building 3 for storage. Interim remedial activities were conducted by BNI in 1988 by removing contaminated materials and equipment and placing a barricade around the remaining contaminated area (Adams and Payne 1992b, p. 12). DOE noted that access to the contaminated areas was not allowed (Seay 1988).

In 1992 and 1993, areas in and adjacent to Buildings 3 and 8 were further characterized (Abelquist 1994; Adams and Payne 1992a, 1992b). The maximum reported exposure rate at 1 m was 0.014 mR/hr (Adams and Payne 1992a). The maximum removable surface contamination was 350 dpm alpha/100 cm^2.

To calculate internal exposure from residual activity, the analysis assumed that all buildings had a postoperational air concentration of 8.94 dpm/m^3 at the end of July 1950. A source term depletion rate was calculated based on a starting air concentration in 1950 along with the air concentration calculated based on the 1992 survey data (ORAUT 2012). The 1992 calculated air concentration of 0.35 dpm/m^3 was based on applying a resuspension factor of 1×10^{-5} m^{-1} (Abu-Eid et al. 2002) to the maximum removable surface contamination of 350 dpm alpha/100 cm^2. Using these two air concentrations, a source term depletion rate of 2.08×10^{-4} d^{-1} was calculated. The ingestion intake rate in Table 3-6 (14.6 pCi/d) was used as the ingestion rate for the start of the residual period. The estimated daily inhalation and ingestion intake rates to residual radioactivity from AEC operations at the site (Table 5-1), were calculated by assuming that workers were exposed for 2,000 hr/yr.

To reconstruct external exposure to residual radioactivity, the maximum reported exposure rate of 0.014 mR/hr (Adams and Payne 1992a) was back-extrapolated using the source term depletion rate calculated from the internal data. The nonpenetrating exposure rate was determined by assuming that the ratio of nonpenetrating to penetrating exposure rates for submersion and contamination external exposures during the operational exposure period (5 to 1), provided a reasonable estimate of the ratio of nonpenetrating to penetrating exposure rate during the residual exposure period. The estimated annual penetrating and nonpenetrating external exposures to residual radioactivity from AEC operations at the site (Table 5-1) were calculated by assuming that workers were exposed for 2,000 hr/yr.

Table 5-1. Annual internal and external exposure to residual radioactivity.[a]

Year	Inhalation[b] (pCi U/d)	Ingestion[c] (pCi U/d)	Penetrating[d] (rem/yr)	Nonpenetrating[d] (rem/yr)
3/1950-12/1950[e]	26.492	14.600	0.578	2.890
1951	24.847	13.693	0.651	3.253
1952	23.012	12.682	0.603	3.013
1953	21.312	11.745	0.558	2.790
1954	19.738	10.878	0.517	2.584
1955	18.281	10.075	0.479	2.393
1956	16.931	9.331	0.443	2.216
1957	15.680	8.641	0.411	2.053
1958	14.522	8.003	0.380	1.901
1959	13.450	7.412	0.352	1.761
1960	12.456	6.865	0.326	1.631
1961	11.536	6.358	0.302	1.510
1962	10.684	5.888	0.280	1.399
1963	9.895	5.453	0.259	1.295
1964	9.165	5.051	0.240	1.200
1965	8.488	4.678	0.222	1.111
1966	7.861	4.332	0.206	1.029
1967	7.280	4.012	0.191	0.953
1968	6.743	3.716	0.177	0.883
1969	6.245	3.441	0.164	0.818
1970	5.783	3.187	0.151	0.757
1971	5.356	2.952	0.140	0.701
1972	4.961	2.734	0.130	0.649
1973	4.594	2.532	0.120	0.601
1974	4.255	2.345	0.111	0.557
1975	3.941	2.172	0.103	0.516
1976	3.650	2.011	0.096	0.478
1977	3.380	1.863	0.089	0.443
1978	3.131	1.725	0.082	0.410
1979	2.899	1.598	0.076	0.380
1980	2.685	1.480	0.070	0.352
1981	2.487	1.371	0.065	0.326
1982	2.303	1.269	0.060	0.302
1983	2.133	1.176	0.056	0.279
1984	1.976	1.089	0.052	0.259
1985	1.830	1.008	0.048	0.240
1986	1.695	0.934	0.044	0.222
1987	1.569	0.865	0.041	0.205
1/1988-10-1988	1.454	0.801	0.038	0.190
11/1988-12/1988[f]	145.4	80.1	0.038	0.190
1989	1.346	0.742	0.035	0.176
1990	1.247	0.687	0.033	0.163
1991	1.155	0.636	0.030	0.151
1992	1.069	0.589	0.028	0.140
1/1993-5/1993	0.990	0.546	0.026	0.130
6/1993-12/1993[f]	724	33.5	0.026	0.130
1/1994-9/1994[f]	724	33.5	0.024	0.120
10/1994-12/1994	0.917	0.506	0.024	0.120
1995	0.850	0.468	0.022	0.111

a. All exposures are assigned as a constant distribution.
b. Absorption types M and S are possible.
c. Choose same f_1-value as used for inhalation per NIOSH (2004).
d. External doses should be assessed using Exposure (R) dose conversion factors (DCFs).
e. The operational period ended on 02/28/1950. Therefore, the residual period is extended from 1951 back to 03/01/1950. Annual external dose rates are prorated for the period from 03/1950 to 12/1950.
f. See text for explanation of cleanup activities.

In addition to general exposure from residual contamination, two cleanup efforts (in 1988 and 1993 to 1994) were performed that could result in additional exposure. The 1988 effort was limited in Building 3 and occurred in November and December of 1988. Vacuums were fitted with high-efficiency particular air (HEPA) filters to clean the floors and walls. Contaminated bricks and soil were removed as necessary. In addition, respiratory protection equipment was used to reduce the likelihood of inhaling contaminated particulates. Further, workers were required to wear lapel air monitors that were analyzed every 24 hours. The lapel air data was not available for this analysis. The prejob estimates for the 1988 cleanup efforts were about 0.0034 pCi/m^3 for about 150 hours (ANL 1988). There is air data from the cleanup in 1993 and 1994 at Aliquippa Forge (TMA/Eberline 1993). The air concentration for vacuuming tasks was 1 to 2 orders of magnitude greater than the other tasks and general area numbers. Therefore, for the 1988 cleanup effort, a bounding assumption of 100 times the estimated residual air concentration was used to estimate internal exposure. These intake rates apply only to November and December of 1988.

The decontamination techniques in 1993 and 1994 were much more aggressive than in 1988. In addition to HEPA vacuuming, which was the main method in 1988, mechanical shot blasting, concrete saws, and jack-hammering were employed (DOE 1996b). The maximum air concentration during the 1993 to 1994 cleanup was 1.1×10^{-10} µCi/mL. This air concentration was for a 3.75-hour job, recorded on a lapel air sampler, and without accounting for the worker's use of respiratory protection doing decontamination work on the west furnace (DOE 1996b). Using this air concentration as a bounding estimate of the decontamination and decommissioning work, the calculated intake rates were 724 pCi/d for inhalation and 33.5 pCi/d for ingestion. These intake rates apply only from June of 1993 to September of 1994.

6.0 ATTRIBUTIONS AND ANNOTATIONS

All information requiring identification was addressed via references integrated into the reference section of this document.

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GLOSSARY

absorption type
Categories for materials according to their rate of absorption from the respiratory tract to the blood, which replaced the earlier inhalation clearance classes. Defined by the International Commission on Radiological Protection, the absorption types are F: deposited materials that are readily absorbed into blood from the respiratory tract (fast solubilization), M: deposited materials that have intermediate rates of absorbtion into blood from the respiratory tract (moderate rate of solubilization), and S: deposited materials that are relatively in the respiratory tract (slow solubilization). Also called solubility type.

activity median aerodynamic diameter
Diameter of a unit density sphere with the same terminal settling velocity in air as that of the aerosol particle whose activity is the median for the entire aerosol.

alpha radiation
Positively charged particle emitted from the nuclei of some radioactive elements. An alpha particle consists of two neutrons and two protons (a helium nucleus) and has an electrostatic charge of +2.

anterior-posterior (AP)
Physical orientation of the body relative to a penetrating directional radiation such that the radiation passes through the body from the front to the back.

atomic weapons employer (AWE) [42 U.S.C. § 7384l(5)]
Entity other than the United States, that—(A) processed or produced, for use by the United States, material that emitted radiation and was used in the production of an atomic weapon, excluding uranium mining and milling, and (B) is designated by the Secretary of Energy as an atomic weapons employer for purposes of the [Energy Employees Occupational Illness] compensation program.

beta radiation
Charged particle emitted from some radioactive elements with a mass equal to 1/1,837 that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is a positron.

biological half-life
Time required for the body or an organ to eliminate, by biological processes, one half of the amount of an ingested substance.

bremsstrahlung
Electromagnetic radiation released as a result of inelastic scattering of a moving charged particle within the nucleus of an atom. X-rays produced in a typical medical X-ray tube frequently originate from inelastic scattering of accelerated electrons in the anode material.

breathing rate
Amount of air a person breathes in a specified time. In relation to health physics for workers, rates typically vary from light (1.2 cubic meters per hour) to heavy (1.7 cubic meters per hour) as defined by the International Commission on Radiological Protection.

contamination
Radioactive material in an undesired location including air, soil, buildings, animals, and persons.

counts per minute (cpm)
Unit of measurement on a radiation meter in which a count indicates a detected ionization event.

disintegrations per minute (dpm, d/m)
Measure of radioactivity equal to the number of nuclear disintegrations in a mass per minute; 1 dpm equals 1/60 becquerel.

dose
In general, the specific amount of energy from ionizing radiation that is absorbed per unit of mass. Effective and equivalent doses are in units of rem or sievert; other types of dose are in units of roentgens, rads, reps, or grays.

electron-volt (eV)
Unit equal to the energy of one electron moving through a potential difference of 1 volt (1.602×10^{-19} joules). The common units in nuclear physics and radiology are kiloelectron-volts (thousands) and megaelectron-volts (millions).

exposure
(1) In general, the act of being exposed to ionizing radiation. See *acute exposure* and *chronic exposure*. (2) Measure of the ionization produced by X- and gamma-ray photons in air in units of roentgens.

favorable to claimants
In relation to dose reconstruction for probability of causation analysis, having the property of ensuring that there is no underestimation of potential dose, which often means the assumption of a value that indicates a higher dose than is likely to have actually occurred in the absence of more accurate information. See *probability of causation*.

gamma radiation
Electromagnetic radiation (photons) of short wavelength and high energy (10 kiloelectron-volts to 9 megaelectron-volts) that originates in atomic nuclei and accompanies many nuclear reactions (e.g., fission, radioactive decay, and neutron capture). Gamma photons are identical to X-ray photons of high energy; the difference is that X-rays do not originate in the nucleus.

high-efficiency particulate air (HEPA) filter
Dense filter that removes contaminants from air flows before return to the working environment or discharge to the outside air (exhaust).

Interactive RadioEpidemiological Program (IREP)
Computer program that uses a person's calculated annual organ doses and other information (e.g., gender, age at diagnosis, and age at exposure) to calculate the probability of causation of a specific cancer for a given pattern and level of radiation exposure.

probability of causation
For purposes of dose reconstruction for the Energy Employees Occupational Illness Compensation Act, the percent likelihood, at the 99th percentile, that a worker incurred a particular cancer from occupational exposure to radiation.

rad
Traditional unit for expressing absorbed radiation dose, which is the amount of energy from any type of ionizing radiation deposited in any medium. A dose of 1 rad is equivalent to the absorption of 100 ergs per gram (0.01 joules per kilogram) of absorbing tissue. The rad has

been replaced by the gray in the International System of Units (100 rads = 1 gray). The word derives from radiation absorbed dose.

radioactivity

Property possessed by some elements (e.g., uranium) or isotopes (e.g., ^{14}C) of spontaneously emitting energetic particles (electrons or alpha particles) by the disintegration of their atomic nuclei.

radon (Rn)

Radioactive gaseous element with atomic number 86. Radon is a decay product (progeny) of other radioactive elements such as thorium and radium.

rem

Traditional unit of radiation dose equivalent that indicates the biological damage caused by radiation equivalent to that caused by 1 rad of high-penetration X-rays multiplied by a quality factor. The sievert is the International System unit; 1 rem equals 0.01 sievert. The word derives from roentgen equivalent in man; rem is also the plural.

rep

Historical quantity of radiation (usually other than X-ray or gamma radiation) originally defined as 83 ergs absorbed per gram in the body and redefined in the 1940s or early 1950s as the amount that would liberate the same amount of energy (93 ergs per gram) as 1 roentgen of X- or gamma rays. Replaced by the gray in the International System of Units; 1 rep is approximately equal to 8.38 milligray. The word derives from roentgen equivalent physical.

roentgen (R, sometimes r)

Unit of photon (gamma or X-ray) exposure for which the resultant ionization liberates a positive or negative charge equal to 2.58×10^{-4} coulombs per kilogram (or 1 electrostatic unit of electricity per cubic centimeter) of dry air at 0°C and standard atmospheric pressure. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher energy photons (generally greater than 100 kiloelectron-volts).

U.S. Atomic Energy Commission (AEC)

Federal agency created in 1946 to assume the responsibilities of the Manhattan Engineer District (nuclear weapons) and to manage the development, use, and control of nuclear energy for military and civilian applications. The U.S. Energy Research and Development Administration and the U.S. Nuclear Regulatory Commission assumed separate duties from the AEC in 1974. The U.S. Department of Energy succeeded the U.S. Energy Research and Development Administration in 1979.

uranium (U)

Heavy, metallic, and radioactive element with atomic number 92. Most natural uranium as found in ores is ^{238}U with trace levels of other isotopes. Uranium-235 (0.7% of natural uranium) is fissile by itself and used in nuclear weapons as well as reactors. Uranium-238 (99.3% of natural uranium) is fissionable by fast neutrons and used in nuclear reactors. Natural uranium contains a minute amount of ^{234}U.

working level (WL)

Unit of concentration in air of the short-lived decay products of ^{222}Rn (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) and ^{220}Rn (^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po) defined as any combination of the short-lived radioactive progeny of radon or thoron in 1 liter of air, without regard to the degree of equilibrium, that results in the ultimate emission of 130,000 megaelectron-volts of alpha energy; 1 WL equals 2.083×10^{-5} joules per cubic meter.