DOE Review Release 08/25/2023

Site Profile for Grand Junction Facilities

ORAUT-TKBS-0060 Rev. 01
Effective Date: 08/03/2023
Supersedes: Revision 00

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
05/18/2018	00	New site profile for the Grand Junction Facilities in Grand Junction, Colorado. Incorporates formal internal and NIOSH review comments. Training required: As determined by the Objective Manager. Initiated by Mutty M. Sharfi.
08/03/2023	01	Revision initiated to incorporate resolutions to Advisory Board comments. These changes address unclear medical X-ray language and incorrect thorium DAC. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by John M. Byrne and authored by Mutty M. Sharfi.

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ACRONYMS AND ABBREVIATIONS

ac	acre
AEC	U.S. Atomic Energy Commission
ALI	annual limit on intake
ARA	Airborne Radioactivity Area
AWE	Atomic Weapons Employer
CEP	Controls for Environmental Pollution
cm	centimeter
DAC	derived air concentration
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
DOL	U.S. Department of Labor
D&D	decontamination and decommissioning
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
GJAO	Grand Junction Area Office
GJF	Grand Junction Facilities
GJO	Grand Junction Office
GJOO	Grand Junction Operations Office
GJPO	Grand Junction Projects Office
GJRAP	Grand Junction Remedial Action Project
Hp(10)	personal dose equivalent at 10 millimeters depth in tissue
Hp,slab(10)	personal dose equivalent (slab phantom) at 10 millimeters depth in tissue
hr	hour
ICRP	International Commission on Radiological Protection
INEEL	Idaho National Engineering and Environmental Laboratory
INL	Idaho National Laboratory
L	liter
lb	pound
LOD	limit of detection
m	meter
MDA	minimum detectable amount
mg	milligram
mi	mile
mL	milliliter
MPC	maximum permissible concentration
mR	milliroentgen
mrem	millirem
NIOSH	National Institute for Occupational Safety and Health
NTS	Nevada Test Site
NURE	National Uranium Resource Evaluation
NYOO	New York Operations Office

ORAU	Oak Ridge Associated Universities
ORAUT	ORAU Team
pCi	picocurie
R	exposure
REECo	Reynolds Electrical & Engineering Company
REMS	Radiation Exposure Monitoring System
RTC	Riverview Technology Corporation
SEC	Special Exposure Cohort
SNL	Sandia National Laboratories
SRDB Ref ID	Site Research Database Reference Identification (number)
t	ton
TBD	technical basis document
TLD	thermoluminescent dosimeter
UMTRA	Uranium Mill Tailings Remedial Action Project
U.S.C.	*United States Code*
WL	working level
WLM	working level month
yd	yard
yr	year
µCi	microcurie
§	section or sections

1.0 INTRODUCTION

Technical basis documents (TBDs) 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 U.S. 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), such as changing scientific understanding of operations, processes, or procedures involving radioactive materials. These documents may be used to assist NIOSH staff in the evaluation of Special Exposure Cohort (SEC) petitions and the completion of individual dose reconstructions under Part B of the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA).

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 term "AWE facility" is defined in EEOICPA to mean "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 *United States Code* (U.S.C.) § 7384l(5). On the other hand, a DOE facility is defined as "any building, structure, or premise, including the grounds upon which such building, structure, or premise is located—(A) 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 (B) with regard to which the [DOE] has or had—(i) a proprietary interest; or (ii) 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). The DOE determines whether a site meets the statutory definition of an AWE facility and the U.S. Department of Labor (DOL) determines if a site is a DOE facility and, if it is, designates it as such.

Under EEOICPA, a Part B cancer 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., a "covered employee with cancer"). After DOL determines that a claim meets the eligibility requirements under Part B of EEOICPA, DOL transmits the claim to NIOSH for a dose reconstruction. EEOICPA provides, among other things, guidance on eligible employment and the 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. 42 U.S.C. § 7384l(11). Also under EEOICPA, the types of exposure to be included in dose reconstructions for DOE employees are those radiation exposures incurred in the performance of duty. As such, NIOSH includes all radiation exposures received as a condition of employment at DOE facilities in its dose reconstructions for covered employees, which may include radiation exposures related to the Naval Nuclear Propulsion Program at DOE facilities, if applicable. This is because NIOSH does not determine the fraction of total measured radiation exposure at a DOE facility that is contributed by the Naval Nuclear Propulsion Program at the DOE facility during a specified period of time for inclusion in dose reconstruction.

NIOSH does not consider the following types of exposure as those incurred in the performance of duty as a condition of employment at a DOE 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, and
- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons.

1.1 PURPOSE

This site profile provides methods for dose reconstruction for the Grand Junction Facilities (GJF) in Grand Junction, Colorado.

1.2 SCOPE

Section 1.3 provides information on classes of GJF workers that have been added to the SEC. Section 2.0 describes facilities and operations at the site. Sections 3.0 through 6.0 discuss occupational medical, environmental, internal, and external dose, respectively.

GJF personnel performed a lot of offsite work. Exposures incurred while performing work at locations other than GJF are not discussed in this site profile.

1.3 SPECIAL EXPOSURE COHORT

March 23, 1943, to January 31, 1975
The Secretary of the U.S. Department of Health and Human Services has added the following class of employees at GJF, formerly known as Grand Junction Operations Office (GJOO), to the SEC [Sebelius 2011, p. 3]:

> *All employees of the Department of Energy, its predecessor agencies, and its contractors and subcontractors who worked at the Grand Junction Operations Office from March 23, 1943 through January 31, 1975, for a number of work days aggregating at least 250 work days, occurring either solely under this employment or in combination with work days within the parameters established for one or more other classes of employees in the SEC.*

NIOSH has determined that it lacks sufficient information to reconstruct doses associated with radon and internal exposures from March 23, 1943, to January 31, 1975, to unmonitored GJF workers during this period [NIOSH 2011a]. In addition, NIOSH has determined that it lacks sufficient information to reconstruct doses associated with external exposures from 1943 through 1959 to unmonitored GJF workers [NIOSH 2011a].

February 1, 1975, to December 31, 1985
The Secretary has also added the following class [Burwell 2015, p. 3]:

> *All employees of the Department of Energy, its predecessor agencies, and its contractors and subcontractors who worked at the Grand Junction Facilities site in Grand Junction, Colorado, during the period from February 1, 1975, through December 31, 1985, for a number of work days aggregating at least 250 work days, occurring either solely under this employment or in combination with work days within the parameters established for one or more other classes of employees in the Special Exposure Cohort.*

NIOSH has determined that it lacks sufficient information to reconstruct doses from nonradon internal exposures from February 1, 1975, to December 31, 1985, to unmonitored GJF workers [NIOSH 2015].

Dose reconstruction guidance in this site profile for periods before January 1, 1986, is presented to provide a technical basis for partial dose reconstructions for nonpresumptive cancers not covered in the SEC classes. Although NIOSH found that it is not possible to bound the total dose for the classes, it intends to use internal and external monitoring data that might become available for an individual claim (and that can be interpreted using its existing dose reconstruction processes or procedures).

Therefore, partial dose reconstructions for individuals who were employed at GJF before January 1, 1986, but who do not qualify for inclusion in the SEC, may be performed using these data as appropriate.

2.0 SITE DESCRIPTION

The Manhattan Engineer District purchased the GJF in 1943. The GJF (Figure 2-1) is about 0.6 mi south and west of populated areas of the City of Grand Junction, Colorado. The site occupies 56.4 ac. Access to the occupied portions of the facility is restricted by security personnel and a fence. There are 35 structures of various types on the facility. Beyond the fence are vehicle parking lots to the east and an earthen dike along the Gunnison River to the west and north. The facility is bordered on the east by the Union Pacific Railroad right-of-way [Wastren 2001, p. 15].

A refinery was operated on site from 1943 to 1946 to treat and concentrate uranium oxide from "green sludge," a byproduct of vanadium production in the area. Approximately 1,180 t of uranium oxide and a comparable amount of vanadium concentrate were produced and shipped off site for further refining. Wastes from this refinery included dust losses, a few hundred tons of alumina cake, and liquid discharges [Wastren 2001, p. 15].

In late 1947, the U.S. Atomic Energy Commission (AEC) established the Colorado Raw Materials Office on the site to manage the domestic uranium procurement program. This office was responsible for the receipt, sampling, and analysis of uranium and vanadium concentrates AEC purchased from ore processing operations in the western United States. AEC operated a uranium concentrate Sample Plant and assay laboratory on site until 2003. Between 1948 and 1971, a total of approximately 172,500 t of uranium oxide and 14,500 t of vanadium oxide passed through the facility in steel drums. The remaining stockpiled vanadium and uranium concentrates were shipped off site in 1965 and 1975, respectively [Wastren 2001, p. 15].

A research program was conducted to test experimental uranium ore milling techniques in a small pilot mill from 1953 to 1954 near the present location of Building 46 and in a larger pilot mill on the southern end of the facility from 1954 to 1958. At the end of the program, some of the mill buildings and their support facilities were converted to other uses. The mill operations were the primary source of contaminated materials. Approximately 17,000 yd^3 of mill tailings and other residue remained on site. Significantly greater quantities of soil were contaminated due to windblown erosion and runoff and because tailings were used in the reconstruction of the dike along the Gunnison River and other site construction activities. Some contaminated equipment was buried on site, and some contaminated lumber and steel were reused in construction. Smaller amounts of contamination resulted from the sampling and stockpiling of uranium concentrate (yellowcake, U_3O_8) in the years after milling operations.

Tailings from the nearby commercially operated Climax Mill had been used for construction and as fill in the Grand Junction area. The Grand Junction Remedial Action Program (GJRAP) was funded to address this issue. GJF assisted in the cleanup of 600 nearby properties in the Grand Junction area from 1972 to September 30, 1988. While this work was off site, soil samples were prepared and analyzed in onsite facilities. Exposures associated with the offsite cleanup and collection of these samples are not discussed in this site profile. However, exposures associated with the onsite analysis of these samples are discussed in this site profile.

From 1974 to 1984, GJF supported the National Uranium Resource Evaluation (NURE) Program, which was a nationwide uranium modeling effort. During this program mainly non-ore samples (e.g., drilling cores) were collected from offsite locations. The samples were returned to the site for processing. Some of the samples were crushed to the proper size, blended, and other procedures in the sample preparation area, Building 7A, before analysis in the Analytical Chemistry Laboratory,

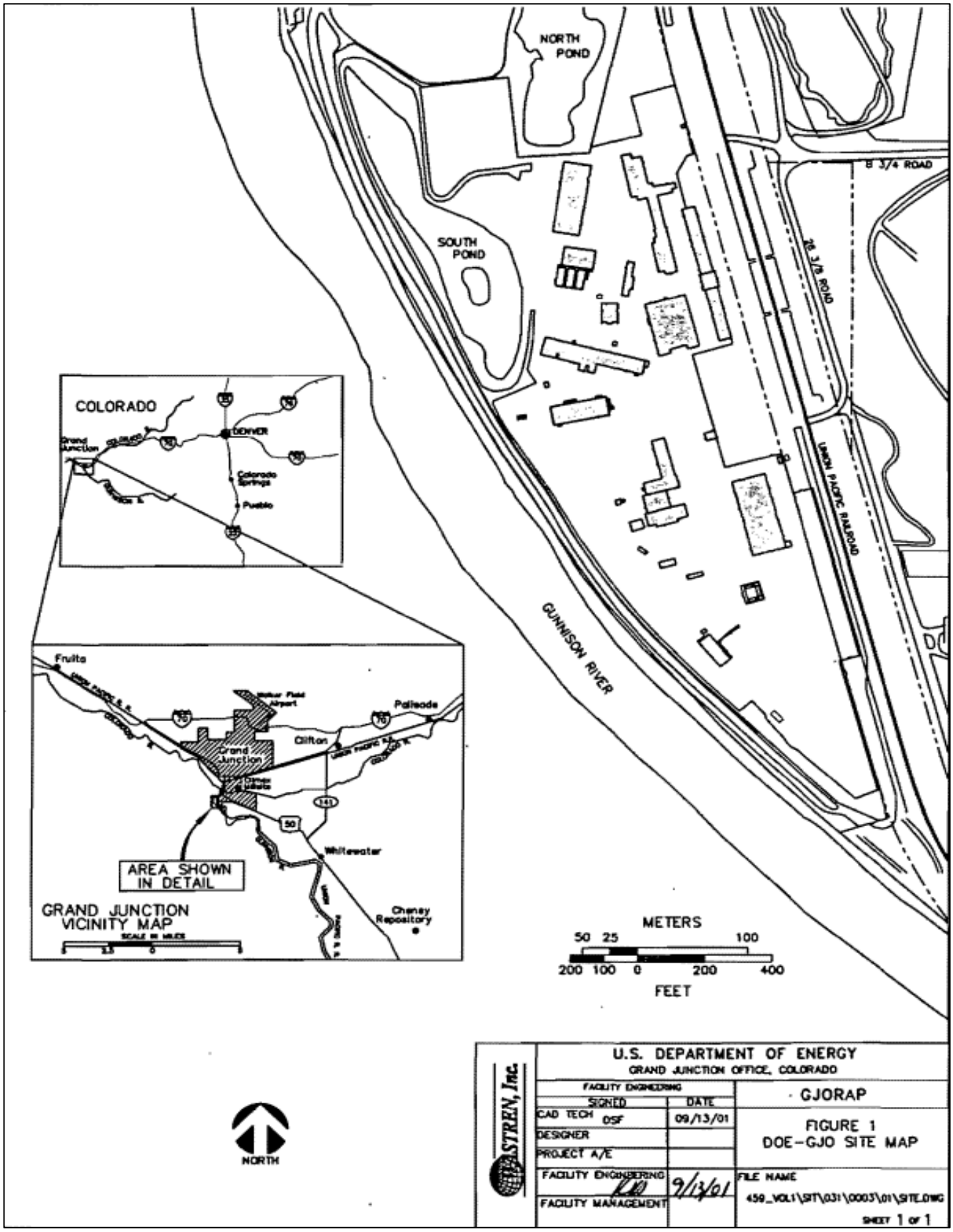

Figure 2-1. Map and layout of GJF [Wastren 2001, p. 14].

Building 20. The sample preparation activities presented the greatest potential for internal exposures after the end of concentrate sampling and storage in January 1975.

Instrument calibration models to support the NURE program as well as remediation programs, consisting of concrete mixed with radioactive materials, were constructed at GJF over its history. The models were in the form of pads and boreholes. Although ^{232}Th would have been present as a contaminant in tailings and, to a lesser extent, in the yellowcake processed and stored there, it was not routinely processed at GJF. In the 1975 to 1987 timeframe, ^{232}Th was handled sporadically in relatively small quantities to develop field calibration sources for uranium ore exploration and environmental remediation. The amount of ^{232}Th present in the calibration models was orders of magnitude less than the tons of uranium ore, concentrate, and tailings that were handled on site.

Starting in 1978, GJF participated in the Uranium Mill Tailings Remedial Action (UMTRA) program to cleanup commercial mill sites and vicinity properties. Again, the work was off site with onsite analysis and support. In addition, GJF supported the remediation work at the Monticello site in Utah, a government-owned mill that was technically not part of the UMTRA program. Though these projects would have included GJF employees who might have monitoring data specifically associated with these projects, any exposures directly attributed to these projects are not discussed in this site profile.

At the start of the Grand Junction Projects Office Remedial Action Project remediation of the site in 1986, there were approximately 33.3 ac of open land and 24 ac where, over time, approximately 61 buildings and smaller structures existed [Wastren 2001, p. 22]. Most were constructed in the 1940s and 1950s, but some prefabricated buildings were added more recently. Most of the buildings and structures known to have been contaminated have been either remediated or demolished [DOE 2006]. Figure 2-2 shows a timeline of major projects and operations, and Table 2-1 summarizes contaminated building histories.

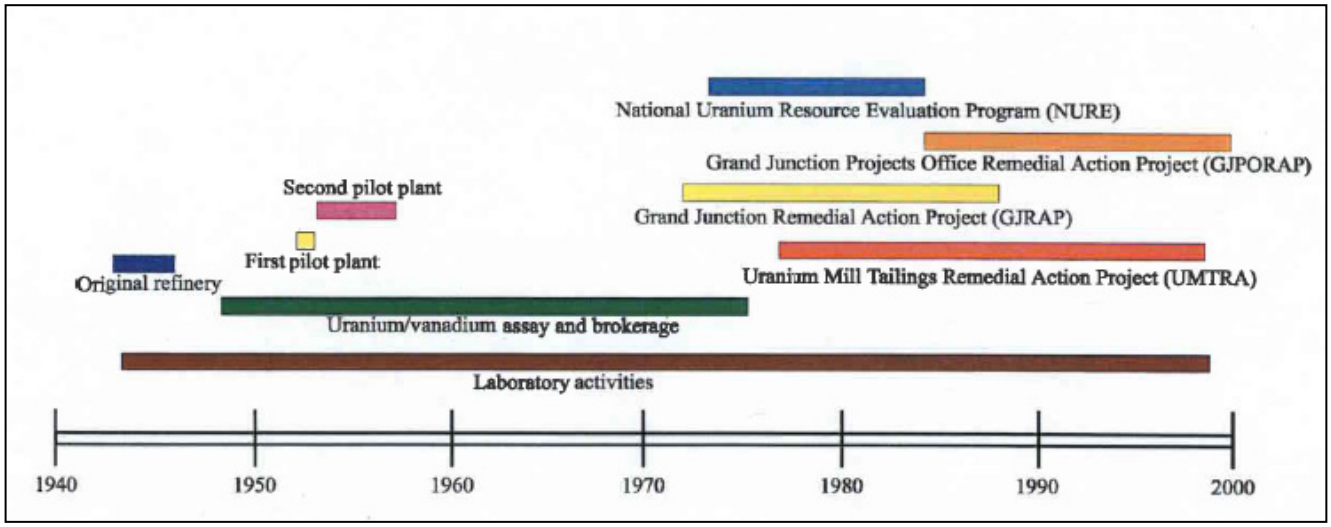

Figure 2-2. Timeline of major projects and operations [Forbes and Egidi 1997].

DOE transferred site ownership to Riverview Technology Corporation (RTC) on September 30, 2001. However, DOE continues to lease portions of the site, provide some ongoing remediation services, and conduct the Long-Term Surveillance and Maintenance Program. In December 2001, ownership of the remaining 8 ac was transferred to the U.S. Army Reserve [DOE 2016]. As of 2001, only Building 20 remained contaminated. In April 2006, DOE demolished Building 20 and remediated the contamination beneath it [DOE 2006].

Table 2-1. History of contaminated buildings and structures.[a,b]

Building	Constructed	History	Remediated	Demolished
1	1943	Originally a boiler house for the refinery. Later housed the steam boilers and a backup generator for the facility.	Not applicable	1996
2	1944	Originally a shower facility and warehouse. Later used for telecommunications and offices. Currently DOE offices.	1997	Not applicable
6	1953	Originally a bench-scale pilot mill. Subsequently used as a laboratory building and office space.	Not applicable	1992
7	1952, remodeled 1956, 1978 1984	Originally a sampling plant and materials staging area. Later used as offices, laboratories, and storage areas. Remediated in two phases and transferred to U.S. Army Reserve.	1999	Not applicable
7A	1956	Sample plant and sample preparation area from 1956 until March 2001. Demolished in June 2001 during Phase III of Building 7 remediation.	Not applicable	2001
12/12A	1953	Built as an engineering office building. Used as an office building and training facility. Approved for deferred remediation of a contaminated former mill slab present under the south wing until the building is no longer required. Currently DOE offices.	2000	Not applicable
18	1975	Training facility. Also used for office space and storage of supplies and equipment.	Not applicable	2001
20	1951, expanded 1956	Analytical chemistry laboratory. Operations ended December 2003. GJF tried to find a commercial tenant for the facility but eventually abandoned the idea. Released for unrestricted use before demolition.	2000	2006
28	1954	Originally built as a maintenance and repair facility for vehicles, heavy equipment, and electrical equipment. Also used as a site support building with offices and maintenance shops. Remediated and transferred to RTC business incubator.	1999	Not applicable
31	1954	Former large pilot plant building built to house the acid-leach circuit. Subsequently used for storage including uranium and vanadium concentrates.	Not applicable	1992
31A	1954	Built as an analytical chemistry laboratory and office building. Later used as a physics and radon laboratory with associated offices.	Not applicable	1998
32	1954	Chemical storage area and warehouse. Later used for seed storage, core preparation and viewing, and radon research. Currently used as a DOE environmental laboratory. A final release survey will be required in affected areas after laboratory operations cease.	2000	Not applicable
33	1954	Former large pilot plant building. Built as a mill operations building. Used for storage after mill operations ceased.	Not applicable	1998
34	1954	Former large pilot plant building. Built as the boiler house. Later used for storage.	Not applicable	1996

Building	Constructed	History	Remediated	Demolished
35	1954	Former large pilot plant building. Built as the uranium ore and yellowcake feed preparation and sample plant.	Not applicable	1998
36	1945	Originally a paint shop for the small pilot plant. Relocated in 1954 and used as a uranium concentrate drying area for the large pilot plant. Subsequently used for concentrate storage and later for general storage.	Not applicable	1996
37	Unknown	Former scale house for truck scale.	Not applicable	1992
39	Unknown	Metal shed that housed pumps and valves that controlled the fuel supply from the emergency reserve tanks to the facility backup generator and boiler plant.	Not applicable	1992
42	1955	Former hazardous and mixed waste storage building. Assembled and expanded on three occasions from structures located elsewhere on site. Waste was transferred to Building 61C in June 2000.	Not applicable	2000
44	1956	Former storage shed for gas cylinders.	Not applicable	1994
46	1977	Former cafeteria reconfigured with a sample preparation area for Building 20 after Building 7A was closed (March 2001). Activities ended September 2004. Transferred to RTC after final survey.	1999, final survey 2005	Not applicable
52	1956	Former radioactive source storage shed.	Not applicable	1994
62	Unknown	Bag house for Building 7A sampling plant.	Not applicable	2001
938	1954–1955, 1981	Former Buildings 9, 9A, and 38. Office space for exploration geologists and mill support personnel. Later used as offices and conference rooms for DOE contractor personnel. Presently DOE offices.	2000	Not applicable
3022	1953	Former Buildings 30, 22, and 22A. Formerly sedimentation and electronics laboratories, warehouse, and storage space. Used for core storage and logging vehicle support after buildings were joined in 1982. Later converted to facility maintenance, supply, and procurement warehouse. Building 30 portion of remediation completed 01/28/99. Transferred to RTC.	1999, 2000	Not applicable

a. Source: DOE [2006].
b. RTC = Riverview Technology Corporation.

In June 2006, DOE issued a report indicating the rest of the site was released with some institutional controls in place to deal with ground water and surface water containing contaminants in concentrations exceeding regulatory limits. In addition, portions of the subgrade structures and soil beneath Building 12 still contain uranium and radium contamination. The contamination beneath Building 12 was left in place to preserve the structural integrity of the building. Surveys indicate that the contamination at Building 12 does not pose any increased health risk to occupants. All exterior land areas have been remediated and released for unrestricted use. Lastly, the borehole containing radium foil used for calibrating down-hole logging instrumentation was decommissioned but not

removed. A metal plaque marks the borehole's location and provides a warning not to disturb [DOE 2006].

3.0 OCCUPATIONAL MEDICAL DOSE

From 1943 to 1946, annual chest and pelvic X-rays were taken of all employees [Ruhoff 1943]. For 1947 to 1992, X-rays were taken off site at a doctor's office or the Community Hospital in Grand Junction [Grand Junction Office (GJO), no date a]. However, for a short period between 1962 and 1969, an office of the U.S. Public Health Service brought a portable X-ray unit to GJF three or four times a year and stayed for about a week to X-ray employees [GJO, no date a].

Dose reconstructors should assume the following:

- Preemployment, annual, and postemployment posterior-anterior chest and anterior-posterior pelvis X-rays prior to 1947.

- Preemployment, annual, and postemployment chest X-rays between 1962 and 1969. Because the view geometry is not known and the X-rays were from a portable X-ray machine, assign the more favorable to the claimant technique between posterior-anterior and photofluorographic.

  Note: When assigning post-1962 photofluorographic doses, assume that the photofluorographic doses in ORAUT-OTIB-0006 for the 1943 to 1962 timeframe remain unchanged for the post-1962 timeframe [Oak Ridge Associated Universities (ORAU) Team (ORAUT) 2019].

- For all other years, X-ray dose is not applicable because X-rays were performed off site at a noncovered facility [ORAUT 2017a].

X-ray doses should be assigned in accordance with ORAUT-OTIB-0006, *Dose Reconstruction from Occupational Medical X-Ray Procedures* [ORAUT 2019].

4.0 OCCUPATIONAL ENVIRONMENTAL DOSE

Accounting for onsite ambient and environmental exposures separately is unnecessary because they are already accounted for in the assessment of unmonitored internal and external worker dose. Unmonitored doses are discussed in Sections 5.0 and 6.0.

In addition, no evidence exists that ambient exposure was subtracted from the monitored dose, so no adjustment is needed to account for ambient dose.

5.0 OCCUPATIONAL INTERNAL DOSE

5.1 INTERNAL SOURCES OF EXPOSURE

Per the SEC determinations, unmonitored intakes cannot be reconstructed before 1986 and unmonitored radon exposures cannot be reconstructed before February 1975. Limited monitoring data are available during these periods. Starting in 1986, available monitoring data are sufficient to perform dose reconstruction for unmonitored workers. During this period, the GJF performed support work for other DOE programs and performed remediation of the GJF buildings and grounds. The principal exposures at the time were to uranium and associated decay products; there was also limited exposure to thorium.

Based on the methods described in this site profile, only two potential intake rates should be applied to unmonitored workers after the end of the SEC period in 1985 and until 1989. Unmonitored worker exposures should be based either on work performed at the Sampling Plant or on work associated with decontamination and decommissioning (D&D) activities for the period from 1988 to 1990. After 1990, all unmonitored worker exposures should be limited based on regulatory requirements in DOE Order 5480.11, *Radiation Protection for Occupational Workers* [DOE 1988]. Therefore, job location is not used in this dose reconstruction approach.

5.1.1 Uranium

Uranium and associated decay products were the principal radiological source of concern at the GJF during mill operation in the 1940s and 1950s. Uranium was also the principal concern from 1948 to 1971 when the site received and sampled 347 million lb of uranium. The last of those materials was shipped off site by January 1975. After 1975, uranium continued to be a source of exposure due to contamination from previous operations and support work for other programs including remediation of the GJF buildings and grounds.

5.1.2 Thorium

Thorium-232 is not a major contaminant of concern for the overall GJF [DOE 1996, p. 24]. However, ^{232}Th was handled during development of the instrument calibration sources or models. This work was performed in the Sample Preparation Laboratory. The main sources of exposure were crushing and grinding operations.

Thorium-230 was present as a contaminant of the uranium ore. Most of the radionuclides (other than uranium) remained insoluble during leaching and left the mill (pilot plant) with the solid tailings [Sears 1976]. As this implies, ^{230}Th would have been depleted in the concentrates and enhanced in the mill tailings in relation to uranium.

5.1.3 Radium

Radium-226 was present as a decay product of the uranium ore and assumed to be in equilibrium with ^{234}U. Most of the radionuclides (other than uranium) remained insoluble during leaching and left the mill (pilot plant) with the solid tailings [Sears 1976]. As this implies, ^{226}Ra was depleted in the concentrates and enhanced in the mill tailings in relation to uranium.

5.1.4 Radon

Radon would have been present in areas and buildings that processed or handled uranium or in buildings built on tailing piles. As such, radon and its progeny could have presented an inhalation hazard to workers. In addition, GJF operated a radon calibration chamber; see Section 5.3.5 for additional information.

5.1.5 Thoron

Thoron would have been present in the Sample Preparation Laboratory that processed and handled thorium. As such, thoron and its progeny could have presented an inhalation hazard to workers.

5.1.6 Assessment of Source Terms

Tables 5-1 and 5-2 list the isotopic intake fractions for various source materials processed at the GJF Sample Plant after 1985, which apply to all GJF workers. Before 1986, only the radionuclides that

were monitored, via bioassay, can be assessed because not enough information exists to determine source term isotopic intake fractions.

Table 5-1. Alpha intake fractions for radionuclides in uranium ore and tailings, after 1985.[a,b]

Source	U-238	U-234	Th-230	Ra-226	Po-210
East tailings	0.0884	0.0884	0.2753	0.2839	0.2639
Vanadium tailings	0.0623	0.0661	0.2964	0.3077	0.2675
Climax ore	0.2084	0.2072	0.2046	0.1991	0.1808

a. Source: Donivan and Chessmore [1987].
b. Calculations provided in ORAUT [2023].

Table 5-2. Gross alpha intake fractions for radionuclides in thorium ore, after 1985.[a]

Th-232	Ra-228[b]	Ac-228[b]	Th-228	Ra-224
0.333	0.333	0.333	0.333	0.333

a. Source: UT-Battelle [2014].
b. These beta emitters are included because they provide a measurable contribution to the overall dose.

The main use of thorium ore was to create calibration pads. These pads were designed to assist in the calibration of aircraft or vehicles with mounted portable spectrometers. Table 5-3 provides a list of pads GJF constructed after 1985 with the approximate construction period.

Table 5-3. Thorium ore use, 1986 to 1988.[a,b]

Designation	Description	Period
Relocatable pad TL1	Portable spectrometer and scintillation surface pad	1986–1987
Relocatable pad TL2	Portable spectrometer and scintillation surface pad	1986–1987
Relocatable pad TL3	Portable spectrometer and scintillation surface pad	1986–1987
Relocatable pad TL4	Portable spectrometer and scintillation surface pad	1986–1987
Relocatable pad TH1	Portable spectrometer and scintillation surface pad	1986–1987
Relocatable pad TH2	Portable spectrometer and scintillation surface pad	1986–1987
Relocatable pad TH3	Portable spectrometer and scintillation surface pad	1986–1987
Relocatable pad TH4	Portable spectrometer and scintillation surface pad	1986–1987
Soil-based U disequilibrium & mixed U-Th	Reference materials	1986–1988

a. Source: UNC Geotech [1987].
b. Estimated exposure time is 1 month for each item in the table. This exact month of exposure during the listed years is unknown.

Based on interviews [ORAUT 2014a,b,c], the grinding, crushing, and blending operations for a pad were normally completed within 30 calendar days. Ore grinding and crushing, the main sources of exposure, would have been completed in much less time than a full month. However, a full month of exposure to thorium ore for each pad is considered a bounding assumption. The exact construction dates for the pads are unknown; they occurred sometime between 1986 and 1988. Therefore, from 1986 to 1988, assume thorium to be the source term for any gross alpha intake rate for the first 9 months of potential exposure, but not to exceed 1 month in 1988. After then, only the uranium ore source term should be assumed. This results in the exposure assessment most favorable to the claimant.

Sample Plant demolition occurred in 2001 [GJO 2001]. For this event, the isotopic ratios for thorium ore should also be considered and the exposure more favorable to the claimant between uranium and thorium ore should be assigned.

All radionuclides should be assessed in accordance with ORAUT-OTIB-0060, *Internal Dose Reconstruction* [ORAUT 2018]. Limited information is available on the chemical forms for uranium and thorium. Therefore, the most favorable solubility for uranium and thorium should be assumed.

5.2 IN VITRO BIOASSAY

When the Grand Junction site was established, it was recognized that bioassay might be required for personnel directly exposed to special materials [Ruhoff 1943]. Urine samples appear to have been analyzed for total uranium by fluorometric methods and reported in mg/L.

The Sample Plant was shut down in 1971 [GJO, no date b, p. 4], and by January 1975 the remaining drums of uranium concentrate on the site were shipped out. While analytical laboratory operations continued, the source term for most workers was then reduced to residual building and environmental contamination. The onsite analytical laboratory did not accept high-activity samples, and the workers were not required to be in a bioassay program [ORAUT 2010a].

Samples collected from workers across the site after 1975 were for both on- and offsite work. Therefore, for a given worker, these samples might have been collected for monitoring exposures not discussed in this site profile. Regardless, exposures should be assumed to be onsite covered exposures unless offsite exposures can be differentiated. Urine and fecal samples collected in 1984, 1986, and from 1990 to 1998 were generally analyzed by alpha spectroscopy. The samples were typically analyzed for $^{234/235/238}$U, but often included ^{230}Th and ^{226}Ra.

For part of this period there was a prejob sampling program, and many of the samples were collected for this purpose. In the early 1990s, the collected prejob/baseline samples were discarded after about 1 year if the worker had not been exposed to greater than 10% of the derived air concentration (DAC) [ORAUT 2017b].

Before 1986, source term information on radionuclides associated to uranium could not be determined. These radionuclides are covered under the SEC. Therefore, when assessing bioassay results before 1986, only the intake associated with the bioassay results can be assessed. For 1986 and beyond, the source term information in Section 5.1.6 should be used.

The site revised its *Internal Radiation Dosimetry Program* procedure in 1991 [Chem-Nuclear Geotech 1991] to comply with DOE Order 5480.11 [DOE 1988]. Baseline (or prejob), routine, and termination (or postjob) bioassay samples were required for all radiation workers working in an Airborne Radioactivity Area (ARA). For workers assigned to areas where mill tailings were present, routine (bioassay) samples were required monthly. In addition, no subcontractors or visitors were allowed to enter an ARA if they were not participating in the Internal Radiation Dosimetry Program.

From 1993 to 1994, several GJF employees were involved in nonintrusive radiological field assessment activities at Sandia National Laboratories (SNL). These employees submitted samples for bioassay analysis to the SNL Internal Radiological Dosimetry Program while working at SNL. Some of these samples were analyzed by Controls for Environmental Pollution (CEP) [Renberger 1995]. In cases where CEP analyzed bioassay samples, these samples should not be used and the worker should be considered unmonitored. The only other samples sent to CEP were some waste characterization samples, but the results failed quality assurance and were deemed unusable [Rodinella 1994].

If an assessment of bioassay data is needed, contact the Principal Scientist for AWEs for assistance.

5.2.1 Detection Limits

During the early years, the uranium urinalysis procedure used the fluorometric fusion process, which fused uranium from raw urine with sodium fluoride and measured the fluorescence created by ultraviolet light. This method provided a measure of the total amount of elemental uranium in the sample. The minimum detectable amount (MDA) was not formally established in the early periods (as

evidenced by a records search). However, the values in the bioassay data sheets are reported at levels as low as 0.001 mg/L in urine. Guidance from other sites (e.g., the Feed Materials Production Center) using the fluorometric fusion process indicates an effective MDA as being near 0.014 mg/L [ORAUT 2017c].

By the early 1980s, dosimetry records indicate that isotopic analysis was being performed. Little information has been identified on the procedure for the analyses. However, footnotes in the bioassay reports from UNC Geotech [GJOO 1985–1987] and Lockheed-Martin Idaho Technologies Center [GJOO 1998–1999] state that results greater than 3 times the total or overall error indicate detection.

If no MDA is provided, then assume that the MDA is 3.29 times the reported total or overall error [ORAUT 2022].

5.2.2 Uranium Enrichment

There is limited information on the enrichment level of uranium over time throughout the site. Therefore, a generic enrichment level is difficult to determine. If bioassay data is provided in mass units and no information can be identified on the enrichment levels the employee worked with, then the bioassay data should be assessed as natural uranium with activity of 684 pCi/mg [NIOSH 2011b] based on the large amount of natural uranium processed over the site's history.

5.3 UNMONITORED INTERNAL EXPOSURE APPROACH

5.3.1 Air Monitoring

Early on, air samples were taken during visits or inspections by AEC. Eventually, the GJF organizations acquired their own sampling and analytical capabilities. Commonly, gross alpha counts were made by scintillation detectors and interpreted as uranium activity. In a few cases, an additional analysis was made for radium. In 1967 and 1968, 16 measurements of ^{222}Rn were made within the Grand Junction compound as a part of a large study of radon from tailings [Sill 1968, p. 14; Public Health Service 1969, p. 12]. In December 1985, three high-volume air samplers were installed to collect environmental onsite air data. The air concentrations of uranium, ^{230}Th, and ^{226}Ra were then reported in the annual environmental reports [Sewell and Spencer 1987; UNC Geotech 1989, 1990a; DOE 1991, 1992, 1993, 1994]. Radon measurements are available in these reports. The annual atmospheric releases of radioactive materials are available for most years from 1992 through 2001. These reports indicated that very low levels were released; therefore, the on- and offsite environmental concentrations would have been relatively low.

Air sample data from before the start of D&D in 1989 are scarce. Before 1989, the most radiologically hazardous onsite work appears to have taken place in the Sample Plant. A 1980 environmental monitoring report stated that the Sample Plant prepared approximately 1,000 samples per month, but that most were exploratory samples of low radioactivity rather than of uranium ores. It indicated that the principal environmental problem was the dust from grinding and crushing. The report also mentions air sampling in the Sample Plant during July 1980 while ore samples were being prepared. The most concentrated sample contained 0.0046 mg/m^3 of uranium [Korte and Thul 1981]. The report indicates that the relevant American Conference of Governmental Industrial Hygienists standard at the time was 0.2 mg/m^3 of uranium. The report also states that very high-grade uranium or thorium ore (5% to 10% U_3O_8 or ThO_2) was handled occasionally in preparing calibration models. This operation could produce dust that exceeded the uranium-in-dust standard.

A 1986 memorandum, "Summary of MPC-Time Weighted Exposure for the First Quarter," provides air monitoring results for three workers grinding uranium mill tailings [Rothman 1986]. The results from

these samples are in units of maximum permissible concentration-hours (MPC-hr) per quarter. These data are supported by bioassay data taken during the work [GJOO 1985–1987].

In March 1990, *Technical Basis for Bioassay Sampling for Sample Preparation Plant and Grand Junction Vicinity Property Workers* provided a set of air monitoring data for the Sample Preparation Laboratory [UNC Geotech 1990b, p. 9]. The data consist of isotopic air concentration measurements for ^{210}Po, ^{226}Ra, ^{230}Th, ^{210}Pb, ^{238}U, and ^{210}Bi.

For D&D from 1989 to 2001, numerous air monitoring results are available including breathing zone samples. For example, the remediation of Building 7, which was contaminated during use for sample preparation, was divided into three phases (areas). There were 60 area measurements and 15 personnel measurements made in Building 7 during Phase III [Grand Junction Projects Office (GJPO) 1991–2001a]. Most of these measurements were made after a 1994 contamination incident caused by a water leak and during removal of contaminated concrete in 1999. Five hundred and sixty-nine air sample measurement results are available for onsite D&D work after 1988 including both general area and breathing zone samples [GJPO 1980–1998, 1986–2000, 1990–1991, 1990–1992, 1990–2000, 1991–2000, 1991–2001b, 1992–1996, 1993–1997, 1997]. These samples indicate that air concentrations were well controlled during these activities (generally less than 10% of the DAC or action level in use).

5.3.2 Sample Preparation and Analytical Chemistry Operations

After the SEC period (i.e., starting January 1986), sample preparation is considered the highest onsite exposure scenario. Grinding, crushing, and preparation of these samples occurred at the Sample Plant in Building 7A. In March 2001, sample preparation operations were moved to Building 46. Analytical chemistry operations ended in late 2003. Analytical chemistry operations in Building 20 were related to, but less hazardous than, sample grinding, crushing, mixing, and other preparation in a ventilated, unenclosed area. The chemical digestions of rock and soil samples in Building 20 took place in hoods that were necessary due to the use of strong acids.

When samples potentially containing ore and/or tailings were prepared for the NURE and GJRAP programs, intake rates were calculated by the site based on the GJF quarterly limit of 520 MPC-hr. Rothman [1986] is an example of MPC time-weighted exposures for the first quarter of 1986 for three Sample Preparation Laboratory workers grinding uranium mill tailings. Based on a review of the available limited air and bioassay data, there is no indication that a worker might exceed the quarterly limit of 520 MPC-hr. The maximally exposed [redacted] received [redacted] MPC-hr of exposure to soluble ^{230}Th uncorrected for respiratory protection. The results from these samples were compared to the allowable number of MPC-hr [Rothman 1986]. NIOSH considers these data to be representative of grinding and crushing tailings in the Sample Preparation Laboratory because they were collected over an entire quarter. Therefore, the GJF quarterly limit of 520 MPC-hr is considered a bounding limit for exposure. In addition, workers in the Sample Preparation Laboratory were routinely issued respirators. However, no credit should be given for protection associated with respirators. This assumption is favorable to claimants as it results in maximizing the assigned potential exposure.

For dose reconstruction, GJF workers were divided into categories:

- Operator. Workers who operated the process equipment and directly handled radioactive material.

- Laborer. Workers who were assumed to be routinely in close contact with radioactive material. This includes maintenance workers, laboratory workers, geologists, etc.

- Supervisor. Workers who were periodically in areas where radioactive material resided. This includes supervisory staff, engineers, radiological safety personnel, etc.

- Administrative. Workers who were assumed to have minimal exposure. This includes administrative, security, and office personnel.

All job categories are used as generic titles, and the merits of each individual claim should be considered when determining which category to apply to an individual worker.

Daily intake rates (Table 5-4) were calculated for Operators and Laborers assuming a worker received the MPC-hr limit every quarter. Thorium-230 was used as the limiting radionuclide (which is consistent with the calculation in Rothman [1986]). The limiting MPC for soluble ^{230}Th was 2.00×10^{-12} µCi/mL [DOE 1981], which is what would have been used to control exposures. Values for the Supervisor and Administrative categories were scaled at one-half and one-tenth, respectively, of the Operator and Laborer values.

Table 5-4. Sample Plant gross alpha inhalation and ingestion intake rates by job category (pCi/calendar day), 1986 to 1990.[a,b]

Job category[c]	Inhalation	Ingestion
Operator/Laborer	13.68	0.274
Supervisor[d]	6.84	0.137
Administrative[e]	0.68	0.014

a. Source: Calculations provided in ORAUT [2023].
b. All intakes assigned as a constant distribution. Intakes after 1990 are covered in Section 5.3.4 based on implementation of DOE Order 5480.11 [DOE 1988].
c. All job categories are used as generic titles, and the merits of each individual claim should be considered when determining which category to apply to an individual worker.
d. Supervisor dose is assumed to be one-half of the Operator/Laborer dose [NIOSH 2011b].
e. Administrative dose is assumed to be one-tenth of the Supervisor dose [NIOSH 2011b].

5.3.3 Decontamination and Decommissioning

GJF officially began D&D in 1984, but before 1988 or 1989 the initial activities were surveys with minimal work that actually disturbed surfaces. Most of the D&D projects were short term, occurring over a few months. All available D&D air sample data were used to determine the 95th-percentile air concentration (2.66×10^{-12} µCi/mL [ORAUT 2023]) of the lognormal distribution for the entire D&D period [GJPO 1972–1999; 1980–2000a,b; 1985–1999; 1986–2000; 1990; 1990–1992; 1990–2000; 1991–2000; 1991–2001a,b,c; 1992–1996; 1993–1999; 2001]. This resulted in the estimate of the workforce's exposure, which is favorable to claimants, in Table 5-5.

Table 5-5. D&D gross alpha inhalation and ingestion intake rates (pCi/calendar day), 1988 to 1990.[a,b]

Job category[c]	Inhalation	Ingestion
Operator/Laborer	17.5	0.350
Supervisor[d]	8.75	0.175
Administrative[e]	0.87	0.017

a. Source: Calculations provided in ORAUT [2023].
b. All intakes assigned as a constant distribution. Intakes after 1990 are covered in Section 5.3.4 based on implementation of DOE Order 5480.11 [DOE 1988].
c. All job categories are used as generic titles, and the merits of each individual claim should be considered when determining which category to apply to an individual worker.
d. Supervisor dose is assumed to be one-half of the Operator/Laborer dose [NIOSH 2011b].
e. Administrative dose is assumed to be one-tenth of the Supervisor dose [NIOSH 2011b].

5.3.4 Implementation of DOE Order 5480.11

The 1990 technical basis for bioassay sampling [UNC Geotech 1990b] lays out the implementation of DOE Order 5480.11 [DOE 1988] for monitoring workers. The 1990 technical basis for bioassay sampling specifies that bioassay would be collected if exposure indicated that a worker could be exposed during the year to inhalation intakes exceeding 0.1 of the annual limit on intake (ALI). This is implemented in GJF Procedure 3.8, *Internal Radiation Dosimetry Program*, which indicates that any worker working in any area posted as an ARA (area with the potential to exceed 10% of a DAC) should be routinely monitored [Chem-Nuclear Geotech 1991]. The 10% of a DAC requirement in Procedure 3.8 is analogous with the 1990 GJF technical basis requirement of 0.1 ALI = 200 DAC-hr = 2,000 hr at 10% DAC. The GJF used its workplace monitoring program in the 1990s to identify any potential source of airborne radioactivity.

Any radiation workers tasked to work in an ARA were required to provide a baseline (or prejob), routine, and termination (or postjob) bioassay sample. For workers entering an ARA, routine bioassay samples were required monthly. In addition, no subcontractors or visitors were allowed to enter an ARA if they did not participate in the Internal Radiation Dosimetry Program [Chem-Nuclear Geotech 1991]. Special bioassays might have been required if an exposure event occurred (e.g., facial contamination) or if air sampling revealed unexpectedly high airborne concentrations [Chem-Nuclear Geotech 1991].

Based on interviews with a health and safety staff member [ORAUT 2017b], this process was implemented by 1991. Therefore, starting in 1991, it is assumed that any unmonitored (no bioassay monitoring) routine radiation worker would not have exceeded 0.1 ALI in a given year. Job categories that fall into routine radiation workers are Operators and Laborers. These workers routinely worked in contamination areas.

All other workers that did not routinely work in a contamination area should be considered nonradiation workers. These workers have been included in the Administrative worker job category, which includes administrative, security, and office personnel. According to the 1990 technical basis for bioassay sampling [UNC Geotech 1990b], if the results of the workplace monitoring program indicated a potential for intakes greater than 0.02 ALI to have occurred, individual worker monitoring (i.e., followup bioassay samples) should be initiated. Therefore, 0.02 ALI should be considered bounding for unmonitored nonradiation workers such as those in the Supervisor and Administrative job categories. This ALI was confirmed by a health and safety staff member [ORAUT 2017b]. Therefore, ambient airborne radioactivity levels are considered low and bounded by the assignment of 0.02 ALI per year.

The 1990 technical basis for bioassay sampling reiterates that the controlling radionuclide was ^{230}Th [UNC Geotech 1990b]. The DAC for Class Y ^{230}Th was 7.00 × 10^{-12} µCi/mL [DOE 1988]. Table 5-6 provides the calculated intake rates for unmonitored workers based on these limits.

Table 5-6. Gross alpha inhalation and ingestion intake rates (pCi/calendar day), after 1990.[a,b,c]

Job category[d]	Inhalation	Ingestion
Operator/Laborer[e]	4.60	0.092
Supervisor/Administrative worker[f]	0.92	0.018

a. Source: Calculations provided in ORAUT [2023].
b. All intakes assigned as a constant distribution.
c. Intakes are assumed to be uranium ore or tailings for all years other than 2001. Sample Plant demolition occurred in 2001 [GJO 2001]. For this event, the isotopic ratios for thorium ore should also be considered and the exposure more favorable to the claimant between uranium and thorium ore should be assigned.
d. All job categories are used as generic titles, and the merits of each individual claim should be considered when determining which category to apply to an individual worker.
e. Based on 10% of a DAC for 2,000 hours resulting in 200 DAC-hr or 0.1 ALI per year.
f. Based on 2% of a DAC for 2,000 hours resulting in 40 DAC-hr or 0.02 ALI per year.

5.3.5 Radon and Thoron

By February 1975, the last of the drums containing uranium concentrate had been shipped off site, but the ^{226}Ra in surface contamination, in soils, and under and around the buildings remained relatively constant until remediation of the outdoor areas. Radon in buildings was studied extensively during D&D (1989 to 2001). There were indoor radon progeny measurements for most of the buildings including 300 measurements in 1985 in some of the former Pilot Plant buildings. Only Building 34 [Henwood and Ridolfi 1986, p. 36], the former boiler building for the large Pilot Plant, exceeded 0.02 working level (WL) (averaged over 100 hours). This building had been used to store ore and yellowcake and was not routinely occupied [Grand Junction Area Office (GJAO) 1984, p. 2].

In 1990, the site implemented and participated in the DOE radon study that included all occupied buildings on site at that time. The study's measurements were representative of the highest radon levels in those portions of the buildings fit for occupancy [DOE 1990, p. 19]. Analysis of these data indicates that the median concentration was 2.2 pCi/L or 0.011 WL assuming a typical indoor equilibrium factor of 0.5 [U.S. Environmental Protection Agency 1992]. Only three buildings had activity levels greater than the U.S. Environmental Protection Agency recommended action level of 4 pCi/L or 0.020 WL [UNC Geotech 1990c]: Building 26 (4.5 pCi/L), Building 30B (5.7 pCi/L), and Building 32 (4.9 pCi/L) [DOE 1990]. These three buildings were reassessed in 1997 and 1998 after remediation, and all measured less than 1.6 pCi/L or 0.008 WL [Wastren 1997; Egidi and Green 1999; GJO 1980–2000]. These remediated radon levels are lower than the average indoor radon levels in Mesa County [Map of radon zones, no date]. Therefore, no radon exposure should be assigned for the postremediation period.

GJF made routine calibrations on thoron instruments [George 1992; Pearson 1990], which indicates site personnel were capable of detecting routine thoron levels. However, no direct thoron measurement could be identified. Therefore, thoron levels were assumed to be equivalent to radon. This is considered bounding because the thoron source term was much less than that of the radon source term; that is, there was less thorium on site than radium or uranium. Therefore, it is unlikely that the thoron air concentration would have exceeded the radon air concentration. Radon and thoron exposure rates are in Table 5-7 and apply to all GJF workers.

Table 5-7. Radon and thoron exposure rates, February 1975 to December 1998.[a,b]

Source	Year	Concentration (pCi/L)	WL	WLM/yr[c]
Radon	1975–1998	5.7	0.0285	0.335
Thoron[d]	1975–1998	5.7	0.760	8.941

a. Source: Calculations provided in ORAUT [2023].
b. Rates not applicable after 1998 as buildings were reassessed after remediation and released.
c. WLM = working level month; assigned as a constant distribution.
d. Thoron WLM exposures should be assessed based on guidance in DCAS-TIB-011, *Dose Conversion Factors for Radon WLM* [NIOSH 2018].

In addition, GJF operated a radon calibration chamber. The radon calibration chamber was used for calibrating, testing, and evaluating both radon and radon progeny measuring instruments. The chamber was an environmentally controlled cylindrical vessel through which air containing radon was circulated [Langner and Nelson 1985]. Based on interviews with a health and safety staff member [ORAUT 2017b], the chamber was posted as an ARA when in use. During use, access to the chamber was controlled with double entry locking doors and no personnel were allowed in the chamber. GJF Procedure 3.8, *Internal Radiation Dosimetry Program*, indicates that for radon workers "...entry logs shall be maintained... the log shall indicate the date, time in and out, and concentration of the airborne contaminant" [Chem-Nuclear Geotech 1991, p. 8]. Any exposure from radon while working around the radon calibration chamber was calculated as working level month (WLM) and should be provided in a workers exposure file [ORAUT 2017b]. A review of internal radon doses for 1989 and 1990 indicated that the worker's exposures were less than 10 mrem annual effective dose equivalent [UNC Geotech 1991; King 1991]. In addition, a review of worker exposures in 1994 indicated that the largest committed effective dose equivalent received in a year was 3 mrem and the largest derived WLM was 0.0022 WLM [RUST Geotech 1995]. This supports the assumption that the unmonitored exposures in Table 5-7 are considered bounding for the workers associated with the radon calibration chamber.

5.3.6 Summary of Unmonitored Internal Exposure Rates

Before 1986 for particulates, and before 1975 for radon and thoron, no unmonitored internal exposures should be assessed in accordance with SEC-00175 [NIOSH 2011a, 2015]. Only exposures associated with bioassay data for the individual should be assessed.

Gross alpha inhalation and ingestion intake rates by job category for all GJF workers are in Tables 5-4 through 5-6 for the period after 1985. Between 1988 and 1990, the more favorable to claimant intake between Tables 5-4 and 5-5 should be assigned. These are default intakes for workers who have no bioassay data. Dose reconstructions must also consider any available bioassay data for a worker. Section 5.1.6 provides the isotopic source terms to apply to these gross intake rates; the most favorable to claimant mixture should be assumed. In addition, all workers should be assigned the radon and thoron exposures from the rates in Table 5-7 for the period from February 1975 to 1998.

During certain years, the unmonitored approach periods overlap for various job categories. Therefore, where little or no information is available to determine the appropriate exposure scenario, the assumption more favorable to the claimant should be used. All radionuclides should be assessed in accordance with ORAUT-OTIB-0060 [ORAUT 2018].

5.4 INCIDENTS

After January 1975, there are two reports of interest [Chem-Nuclear Geotech 1993; King 1994]. In 1992, there was a spill of yellowcake during disposal of what was thought to be UMTRA Project soil samples. [redacted] individuals were involved, and initial 24-hour urine samples and followup samples were collected. A formal investigation indicated that one of the samples (from [redacted] who was

involved but not contaminated), had been contaminated with material that was not involved in the spill. The identities of the individuals involved are not given in the report, but can be determined from [redacted].

In a second incident in 1994, a water leak occurred during conversion of old yellowcake processing areas into office space that contaminated the spaces below. Fecal samples were collected. There was no significant activity in the samples. The names of the individuals involved are given [redacted].

In general, the worker exposure history file from DOE should include incident reports.

6.0 OCCUPATIONAL EXTERNAL DOSE

In accordance with the SEC determinations, unmonitored external exposures cannot be reconstructed before 1960 [NIOSH 2011a, 2015]. If pre-1960 monitoring data exists then it should be included in the assessment if there is sufficient information available to assess it.

6.1 SOURCES OF EXPOSURE

The radiation source (other than X-ray procedures) for external exposure at Grand Junction was primarily uranium. External exposures were (1) the result of direct radiation exposure from handling and working with uranium ore and tailings and (2) submersion in the contaminated dust cloud [NIOSH 2011a, p. 32].

Photon exposure was from uranium, ^{226}Ra, and uranium progeny. There were high-energy beta radiation exposures for workers in close proximity to the ore that contributed to shallow dose. Neutron radiation was also present from ^{252}Cf, americium-beryllium sources, and neutron generators (e.g., a linear accelerator) in some periods. Well logging involved a low potential for photon and neutron exposure [NIOSH 2011a, p. 38; ORAUT 2010b, p. 6].

6.2 MONITORING PROGRAM

Early in GJF history, some workers were provided with film badges [GJPO 1952; AEC 1952–1953]. The New York Operations Office (NYOO) fiscal year 1953 film badge summary showed the beta/gamma results for 757 individuals [AEC 1953, pp. 28–31].

Film badge use restarted in 1957 [AEC 1957; GJOO 1957]. Memoranda from January 3 and 8, 1957, address the concern that radioactive dust can accumulate on film badges, and wrapping the dosimeters in thin film was offered as a solution to the surface contamination problem [Harris 1957]. Fourteen film badges were initially sent from the NYOO to GJF for use for a 2-week period. The first set indicated exposure to gamma radiation, and GJF was advised to continue the use of film dosimeters.

In a March 1958 letter to NYOO, GJF requested discontinuation of the film badge program until further notice due to the lack of measured exposure [AEC 1958, p. 2]. A note on top of the NYOO Film Badge Report for the March 31 and April 7, 1958 period states that it is the last batch [AEC 1958, p. 3]. However, film badge service appears to have been restarted and more film badge results are available through 1959 [GJOO 1959].

In the *Summary of Whole Body Radiation Exposures to External Penetrating Radiation Accumulated During the Year* for 1960 from the Chicago Operations Office, [redacted] Lucius Pitkin workers were monitored. The remaining 389 workers (138 Lucius Pitkin and 251 AEC) were not monitored [AEC 1961, p. 30].

In the *Summary of Whole Body Radiation Exposures to External Penetrating Radiation Accumulated During the Year* for 1961 from the Chicago Operations Office, 47 workers (29 Lucius Pitkin and 18 AEC) were reported to have been monitored with film badges and Cambridge self-reading dosimeters [AEC 1962, p. 40]. The remaining 304 workers (114 Lucius Pitkin and 190 AEC) were not monitored. The footnotes indicate that the film badges were worn by Lucius Pitkin workers at the Sample Plant and in the Electronics Laboratory and by AEC employees working with a neutron source.

The *Grand Junction Project Summary* from Reynolds Electrical & Engineering Company (REECo) indicates that the GJF dosimetry service was provided by REECo from 1967 to 1981 [REECo 1991, p. 2]. No GJF dosimeter specifications are available during this period; therefore, a surrogate site is required. Because REECo operated the Nevada Test Site (NTS), it is reasonable to assume that the dosimeter technical information from NTS is an applicable surrogate for the GJF dosimeter. At NTS, REECo used a DuPont 301-4 Packet from 1960 to 1965. From 1966 to February 1971, the NTS dosimeter was a DuPont Type 556 Packet. From March 1971 through 1986, NTS switched to a Kodak Type III film dosimeter [ORAUT 2012].

The neutron dosimeter NTS used from 1961 through part of 1979 was a Kodak nuclear track emulsion, type A, film dosimeter with a monthly exchange frequency. Starting in 1979 and through 1986, REECo switched to Hankins-type albedo thermoluminescent dosimeters (TLDs) with four pairs of TLD-600 and TLD-700 (^{6}LiF and ^{7}LiF) chips in cadmium pillboxes for thermal neutron suppression. Hankins-type albedo dosimeters have high sensitivity to low-energy neutrons with decreasing response as energy increases. The exchange frequency was monthly [ORAUT 2012].

The 1980 beta/gamma dosimeter results for all the monitored workers at the Sample Plant and Chemistry Laboratory showed zero dose, and again a proposal was made to discontinue badging for those personnel unless a change in duties was anticipated [Thul 1981].

In June 1980, GJF received a REECo proposal to change the personnel dosimeters from Kodak Type III film badges to albedo TLD badges for neutron monitoring [Schiager 1980, p. 4]. The Hankins-type albedo TLD badge (in use at NTS from 1979 to 1986) used ^{6}LiF and ^{7}LiF TLD chips to respond to neutron plus beta/gamma and beta/gamma-only exposures.

Neutron doses of 10 mrem were expected to be detected routinely even though REECo did not claim a sensitivity below 30 mrem. The REECo proposal to change from Type III film dosimeters to albedo TLDs was accepted with the plan to make the change in 1980. However, film dosimeters were still in use at GJF as of September 1980 [Bendix 1980]. It has not been possible to determine when, or if, GJF actually started to use the Type III albedo TLD.

By the fourth quarter of 1981, the dosimetry service for GJF was being provided by the Idaho Operations Office, so it can be assumed to be similar to that at Idaho National Laboratory (INL) [Gesell 1982]. The dosimeter used by INL in 1981 was a commercial Harshaw system with two LiF TLDs that were 240 mg/cm^2 thick. One chip was covered by 540 mg/cm^2 (initially 350 mg/cm^2) of aluminum, and the other was under 4 mg/cm^2 of Mylar. The aluminum-covered chip provided penetrating dose at a nominal tissue depth of 1 cm.

The beta dose was calculated from the difference between the two TLD chips. Because of the thickness of the Mylar-covered chip, the beta dose was accurate only for the beta energy used in calibration. Field calibrations were used to reduce the problem of beta energy dependence [ORAUT 2011]. The reporting level of the Harshaw dosimeter for penetrating and nonpenetrating radiation was 15 mrem [Gesell et al. 1996; ORAUT 2011].

In 1986, with the advent of the DOE Laboratory Accreditation Program (DOELAP), INL changed to the four-element Panasonic 814 AS4 TLD system [ORAUT 2019]. Elements 1 and 2 with lithium borate

($Li_2B_4O_7$) phosphor elements had plastic and aluminum filtration to provide an improved measurement of deep dose equivalent and, with a thinner filter, an improved measurement of the shallow dose equivalent. Calcium sulfate ($CaSO_4$) phosphor in elements 3 and 4 provided a strong low-energy photon response [Idaho National Engineering and Environmental Laboratory (INEEL) 2001].

Each Panasonic element was 15 mg/cm^2 thick. Element 1 had filtration of 16 mg/cm^2, element 2 had 58 mg/cm^2 of plastic, element 3 had 550 mg/cm^2 of plastic, and element 4 had 50 mg/cm^2 of aluminum [INEEL 2001].

The minimum reporting level of 15 mrem was retained in the INL Panasonic Dosimetry System, but experience indicated that, for penetrating radiation, the detection limit of 10 mrem was not expected to result in false positive readings. For nonpenetrating radiation, the reporting level of 30 mrem was expected to eliminate false positive readings [Gesell et al. 1996].

The GJF badge exchange frequency in the 1990s was quarterly. The Hankins albedo neutron dosimeter was added to the badge for the workers involved with well logging and for Radiological Assistance Program team members. Only the radiation workers were monitored, not the office workers [ORAUT 2010b; UNC Geotech 1990c].

Interviews for the initial SEC evaluation report indicate TLDs were used during the NURE Program and GJRAP. A small number of employees who worked with neutron-generating equipment had neutron dosimetry, but the results were not available to review and the specific type of dosimetry is unknown [NIOSH 2011a, p. 47]. However, the technical basis for the INL personal neutron dosimeter [Gesell et al. 1996] describes a Hankins-type two-chip dosimeter. The reporting level of the INL Hankins albedo dosimeter was 15 mrem [Gesell et al. 1996, p. 19]. The technical basis for the INL personal photon/beta dosimeter states that, for those employees at INL who had the potential for exposure to neutrons, a special Panasonic dosimeter with an attached albedo dosimeter was provided [Gesell et al. 1992, p. 16].

6.3 MONITORING DATA

Exposure records are maintained at the Grand Junction office and in a database maintained by INL. A data report from INL includes personnel believed to be associated with Grand Junction through the use of INL location codes [INL 2012]. This report has data for 1982 to 1998 and contains over 15,000 records, each with a gamma and beta result. There are also occasional neutron results in these data. The persons listed in this report could include individuals involved in off-site remediation work. To be favorable to claimants, all exposures listed in this report should be assumed to have occurred on site.

Twenty-five files have been added to the Site Research Database (SRDB) from GJF that provide dosimetry files for workers alphabetically by last name: SRDB Reference Identification (SRDB Ref IDs) [redacted].

Although NIOSH found that it is not possible to bound the external dose before 1960, any external monitoring data that might become available for an individual claim during this period can be included if the information below allows for its interpretation.

6.4 LIMITS OF DETECTION AND RADIATION FIELDS

6.4.1 Photon

Exposure to photons was possible during all phases of handling and processing the natural uranium ore. Radium-226 was also a source of external exposure to workers. Other gamma-emitting uranium progeny from the ^{238}U and ^{235}U decay chains were present and contributed to photon exposure,

although the ^{235}U concentration represents only 0.0072% by weight of the isotopic composition of natural uranium while ^{238}U represents 99.27% by weight. Penetrating doses should be assessed as 100% 30- to 250-keV photons using an acute exposure rate. Table 6-1 shows the limits of detection (LODs) and exchange frequencies for photon exposures.

Table 6-1. Gamma LODs and exchange frequencies.

Period	Type	LOD	Exchange frequency	Source
1960–02/1971	Film	40 mR	Monthly	ORAUT 2012, p. 19
03/1971–1981[a]	Film	30 mR	Monthly	ORAUT 2012, p. 20
1981–1985	TLD	15 mrem	Quarterly	ORAUT 2011, pp. 21, 40
01/1986–07/1986	TLD	15 mrem	Quarterly	ORAUT 2011, pp. 21, 40
08/1986–09/1989	TLD	10 mrem	Quarterly	ORAUT 2011, pp. 21, 40
10/1989–1993	TLD	15 mrem	Quarterly	ORAUT 2011, pp. 21, 40
1994–present	TLD	10 mrem	Quarterly	ORAUT 2011, pp. 21, 40

a. For 1981, there is no documentation on when the site switched from film to TLDs. Therefore, if the type cannot be determined from the records, then the assumption that is more favorable to claimants should be made.

For dose conversion factors (DCFs) for 1960 to 1985, before DOELAP, dose reconstructors should apply the exposure (*R*) dose equivalent DCF values in accordance with OCAS-IG-001, *External Dose Reconstruction Implementation Guideline* [NIOSH 2007]. After that (1986 to 2006), doses should be considered deep dose equivalent [*Hp(10)*] and dose reconstructors should apply those DCF values in accordance with OCAS-IG-001.

6.4.2 Beta

Shallow dose should be assigned as an acute dose of 100% >15-keV electrons. Shallow measured and missed doses should be based on the dosimetry records in accordance with ORAUT-OTIB-0017, *Interpretation of Dosimetry Data for Assignment of Shallow Dose* [ORAUT 2005]. Table 6-2 shows the LODs and exchange frequencies for beta exposures.

Table 6-2. Beta LODs and exchange frequencies.

Period	Type	LOD (mrem)	Exchange frequency	Source
1960–02/1971	Film	40	Monthly	ORAUT 2012, p. 19
03/1971–1981[a]	Film	30	Monthly	ORAUT 2012, p. 20
1981–1985	TLD	15	Quarterly	ORAUT 2011, p. 40
01/1986–07/1986	TLD	15	Quarterly	ORAUT 2011, pp. 21, 40
08/1986–09/1989	TLD	30	Quarterly	ORAUT 2011, pp. 21, 40
10/1989–1993	TLD	30	Quarterly	ORAUT 2011, pp. 21, 40
1994–present	TLD	30	Quarterly	ORAUT 2011, pp. 21, 40

a. For 1981, there is no documentation on when the site switched from film to TLDs. Therefore, if the type cannot be determined from the records, then the assumption that is more favorable to claimants should be made.

6.4.3 Neutron

Neutron sources such as ^{252}Cf and neutron generators with deuterium and tritium targets were used on site by one contractor [ORAUT 2010c]. There is a reference to Grand Junction purchasing a small quantity of zetatrons (a neutron-producing device that uses a tritium target) sometime between 1991 and 1995. The same reference indicates no zetatrons at Grand Junction from 1980 to 1990 [Lutz 1995]. Neutron doses should be assessed using a chronic exposure rate as 100% 0.1- to 2-MeV neutrons and the International Commission on Radiological Protection (ICRP) Publication 60 weighting factor [ICRP 1991] of 1.9 [ORAUT 2006].

TLD badge doses should be assessed using deep dose equivalent [*Hp,slab(10)*] for all years, in accordance with OCAS-IG-001 [NIOSH 2007]. Table 6-3 shows the LODs and exchange frequencies for neutron exposures.

Table 6-3. Neutron LODs and exchange frequencies.

Period	Type	LOD (mrem)	Exchange frequency	Source
1960–1981[a]	Film	50	Monthly	ORAUT 2012, p. 21
1981–present	TLD	15	Quarterly	ORAUT 2011, p. 41

a. For 1981, there is no documentation on when the site switched from film to TLDs. Therefore, if the type cannot be determined from the records, then the assumption that is more favorable to claimants should be made.

6.5 UNMONITORED EXTERNAL EXPOSURE APPROACH

No unmonitored external exposures should be assessed for periods before 1960 [NIOSH 2011a, 2015]. Only exposures associated with dosimetry data for the individual should be assessed.

All unmonitored external doses should be assigned as a constant distribution.

6.5.1 Photon

The maximum values from the DOE annual report summaries or the 95th-percentile values from the Radiation Exposure Monitoring System (REMS) database [DOE 2010] were applied as a single exchange. Missed dose was applied to all other exchanges. These values (Table 6-4) were used to determine annual doses for the unmonitored Operator/Laborer category. Supervisor and Administrative category doses were determined by scaling.

Table 6-4. Unmonitored gamma dose (rem).[a]

Year	Operator/Laborer[b]	Supervisor[c]	Administrative[d]
1960	1.220	0.610	0.240
1961	1.220	0.610	0.240
1962	1.220	0.610	0.240
1963	1.220	0.610	0.240
1964	1.220	0.610	0.240
1965	1.220	0.610	0.240
1966	1.220	0.610	0.240
1967	1.220	0.610	0.240
1969	1.220	0.610	0.240
1970	1.220	0.610	0.240
1971	1.175	0.588	0.190
1972	1.165	0.583	0.180
1973	1.165	0.583	0.180
1974	1.165	0.583	0.180
1975	0.915	0.458	0.180
1976	0.180	0.180	0.180
1977	0.665	0.333	0.180
1978	0.665	0.333	0.180
1979	0.915	0.458	0.180
1980	1.165	0.583	0.180
1981[e]	1.165	0.583	0.180
1982[e]	1.023	0.511	0.051
1983[e]	1.023	0.511	0.051
1984[e]	1.023	0.511	0.051
1985	0.080	0.040	0.030
1986	0.054	0.027	0.025

Year	Operator/Laborer[b]	Supervisor[c]	Administrative[d]
1987	0.077	0.038	0.020
1988	0.045	0.040	0.040
1989	0.067	0.034	0.023
1990	0.067	0.033	0.030
1991	0.043	0.030	0.030
1992	0.074	0.037	0.030
1993	0.036	0.030	0.030
1994	0.033	0.020	0.020
1995	0.026	0.020	0.020
1996	0.038	0.020	0.020
1997	0.025	0.020	0.020
1998	0.087	0.043	0.020
1999	0.025	0.020	0.020
2000	0.025	0.020	0.020
2001	0.022	0.020	0.020
2002	0.031	0.020	0.020
2003	0.039	0.020	0.020
2004	0.025	0.020	0.020
2005	0.025	0.020	0.020
2006	0.022	0.020	0.020
2007	0.022	0.020	0.020
2008	0.024	0.020	0.020
2009–present	0.042	0.021	0.020

a. Calculations provided in ORAUT [2023].
b. Doses through 1980 are based on a maximum value from the DOE annual summaries. Doses after 1984 were based on the 95th percentile of the REMS data [DOE 2010] for badges with end dates in that year. Values were applied as a single exchange and missed dose was applied to all other exchanges.
c. Supervisor dose is assumed to be one-half of the Operator/Laborer dose or missed dose for all exchange frequencies [NIOSH 2011b].
d. Administrative dose is assumed to be one-tenth of the Supervisor dose or missed dose for all exchange frequencies [NIOSH 2011b].
e. Based on a maximum recorded dose for adjacent years plus missed dose based on that year's dosimetry requirements and LOD.

6.5.2 Beta

No beta dose data were found for the early years (before 1950). A beta/gamma ratio for the 1950s era data was calculated to be 1.2 [ORAUT 2023]. Using data from REMS [DOE 2010] for 1985 and later, an average beta/gamma ratio was calculated to be 1.5 [ORAUT 2023]. Because this data from after 1985 include exposure from offsite remediation activities, the beta component could be expected to be high in comparison with onsite activities. To be favorable to claimants, dose reconstructors should use the higher ratio of 1.5 to bound unmonitored shallow dose for any year in which shallow dose was not reported.

6.5.3 Neutron

There are limited data for neutron exposures from before 1985 in individual claim files. However, there are exposure data from REMS [DOE 2010] from 1985 to 2009, and there is no indication that the source term was different before then. These data were analyzed to obtain the 95th percentile, which is considered a bounding estimate for unmonitored neutron exposures to geologists (Laborer category). Those results were scaled for the other worker categories. Table 6-5 lists the unmonitored neutron doses.

Table 6-5. Unmonitored neutron dose (rem/yr).[a]

Job category	Period	Total dose
Laborer (geologist)[b]	Before 1981[c]	0.398
Laborer (geologist)[b]	1981 and after[d]	0.1455
Supervisor[e]	Before 1981	0.199
Supervisor[e]	1981 and after	0.073
Administrative[f]	Before 1981	0.020
Administrative[f]	1981 and after	0.007

a. Calculations provided in ORAUT [2023].
b. Based on 95th percentile.
c. Based on monthly exchange rate.
d. Based on quarterly exchange rate.
e. Based on one-half of the Laborer dose rate.
f. Based on one-tenth of the Supervisor dose rate.

The number of workers that had potential for neutron exposure was small due to the limited role of neutron sources at GJF [Duray 1981; REECo 1979–1981; Bendix 1981]. Therefore, the 95th percentile applies only to the Geologist/Laborer job category, and the 50th percentile applies to all other job categories.

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GLOSSARY

acute exposure
Radiation exposure to the body delivered in a short period. See *chronic exposure*.

Administrative
Category for workers who were assumed to have minimal exposure for the purpose of dose reconstruction. This includes administrative, security, and office personnel.

albedo dosimeter
Thermoluminescent dosimeter that measures the thermal, intermediate, and fast neutrons scattered and moderated by the body or a phantom from an incident fast neutron flux.

annual limit on intake (ALI)
Historical dose limit that represents the activity of a radionuclide which, taken alone, would irradiate a person, represented by Reference Man, to the limit set by the International Commission on Radiological Protection for each year of occupational exposure.

bioassay
Measurement of amount or concentration of radionuclide material in the body (in vivo measurement) or in biological material excreted or removed from the body (in vitro measurement) and analyzed for purposes of estimating the quantity of radioactive material in the body. Also called radiobioassay.

chronic exposure
Radiation dose to the body delivered in small amounts over a long period (e.g., days or years). See *acute exposure*.

decommissioning
Removal of a facility from service, usually involving decontamination of radioactivity to specified levels and often involving demolition of the facility.

decontamination
Reduction or removal of radioactive material from a structure, area, object, or person. Decontamination can occur through (1) treating the surface to remove or decrease the contamination or (2) allowing natural radioactive decay to occur over a period of time.

derived air concentration (DAC)
Annual limit of intake of a radionuclide divided by the volume of air inhaled by Reference Man in a working year (2.4×10^3 cubic meters). A DAC-hour is the exposure to a person breathing the DAC for 1 hour. See *working level*.

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 sieverts; other types of dose are in units of rad, rep, or grays.

dosimeter
Device that measures the quantity of received radiation, usually a holder with radiation-absorbing filters and radiation-sensitive inserts packaged to provide a record of absorbed dose received by an individual. See *albedo dosimeter*, *film dosimeter*, *neutron film dosimeter*, and *thermoluminescent dosimeter*.

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.

film dosimeter

Package of film for measurement of ionizing radiation exposure for personnel monitoring purposes. A film dosimeter can contain two or three films of different sensitivities, and it can contain one or more filters that shield parts of the film from certain types of radiation. When developed, the film has an image caused by radiation measurable with an optical densitometer. Also called film badge.

Laborer

Category for workers who were assumed to be routinely in close contact with radioactive material. This category includes maintenance workers, laboratory workers, geologists, etc.

internal dose

Dose received from radioactive material in the body (e.g., plutonium or uranium) that was inhaled, ingested, absorbed, or injected through a wound.

in vitro bioassay

Measurements to determine the presence of or to estimate the amount of radioactive material in the excreta or in other biological materials removed from the body.

Manhattan Engineer District

Subdivision of the U.S. Army Corps of Engineers that administered the World War II Manhattan Project to develop the first nuclear bomb. The word *Manhattan* was chosen to divert attention from the Project's real purpose. The U.S. Atomic Energy Commission assumed control of District facilities and activities in 1946.

neutron film dosimeter

Film dosimeter with a nuclear track emulsion, type A, film packet.

occupational dose

Internal and external ionizing radiation dose from exposure during employment. Occupational dose does not include that from background radiation or medical diagnostics, research, or treatment, but does include dose from occupationally required radiographic examinations that were part of medical screening.

occupational environmental dose

Dose received from radiation site-related activities (i.e., above-normal background levels) while on a site, which is often recorded by monitoring stations in specific areas or along the boundaries of facilities (e.g., plant stack emissions).

occupational medical dose

Dose from X-ray procedures performed for medical screening of workers as part of an occupational health program. Doses from X-rays used to diagnose diseases or injuries, even if incurred on the job, are not considered occupational and are therefore not eligible to be included in dose reconstruction under the Energy Employees Occupational Illness Compensation Program Act of 2000.

Operator
Category for workers who operated the process equipment and directly handled radioactive material.

source term
Description of the types and quantities of radioactive materials. The source term is usually specified as a rate of exposure or an amount of radioactivity (i.e., becquerels or curies), sometimes by specific radionuclide. Often includes distinctions in chemical and physical forms and history of the material.

Supervisor
Category for workers who were periodically in areas where radioactive material resided. This includes supervisory staff, engineers, radiological safety personnel, etc.

thermoluminescent dosimeter (TLD)
Device for measuring radiation dose that consists of a holder containing solid chips of material that, when heated, release the stored energy as light. The measurement of this light provides a measurement of absorbed dose. Thermoluminescent dosimeters replaced film dosimeters at essentially all U.S. Department of Energy sites beginning in the 1960s.

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.

U.S. Department of Energy (DOE)
Federal agency created in 1979 that assumed, from the U.S. Energy and Research Development Administration, the responsibility for development of new reactors, production and use of nuclear materials, and production of nuclear weapons by the federal government.

U.S. Department of Labor (DOL)
Agency that oversees compliance with federal labor laws and collects labor-related information. DOL is responsible for compensation decisions under the Energy Employees Occupational Illness Compensation Program Act of 2000.

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 1.3×10^5 megaelectron-volts of alpha energy; 1 working level equals 2.083×10^{-5} joule per cubic meter.

working level month (WLM)
Unit of exposure to radon progeny defined as exposure for 1 working month (170 working hours) to a potential alpha energy concentration of 1 working level; 1 working level month equals 1 working level times 170 hours, which is 0.00354 joule-hour per cubic meter. See *working level*.