DOE Review Release 09/26/2023

Site Profile for Ames Laboratory

ORAUT-TKBS-0055 Rev. 04
Effective Date: 09/18/2023
Supersedes: Revision 03

Subject Expert(s): Jackson R. Ellis

Document Owner Approval:	Signature on File Jackson R. Ellis, Document Owner	Approval Date:	09/15/2023
Concurrence:	Signature on File John M. Byrne, Objective 1 Manager	Concurrence Date:	09/15/2023
Concurrence:	Signature on File Scott R. Siebert, Objective 3 Manager	Concurrence Date:	09/15/2023
Concurrence:	Vickie S. Short Signature on File for Kate Kimpan, Project Director	Concurrence Date:	09/15/2023
Approval:	Signature on File Timothy D. Taulbee, Associate Director for Science	Approval Date:	09/18/2023

**FOR DOCUMENTS MARKED AS A TOTAL REWRITE OR REVISION,
REPLACE THE PRIOR REVISION AND DISCARD / DESTROY ALL COPIES OF THE PRIOR REVISION.**

☐ New ☒ Total Rewrite ☐ Revision

PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
06/22/2007	00	Approved new Site Profile for Ames Laboratory. Incorporates formal internal and NIOSH review comments. Adds Glossary and Attributions and Annotations section. There is no change to the assigned dose and no PER is required. Training required: As determined by the Task Manager. Initiated by Jerome B. Martin.
08/20/2008	00 PC-1	Approved page change revision made to include SEC-00075 on pages 10 and 11 in Section 1.3 where Sections 1.3.1, 1.3.2 and Table 1-2 were added. NIOSH required language was revised on pages 9 and 10 in Section 1.1. Added reference on page 74. Incorporates formal internal review comments. As a result of formal internal review, editorial changes were made on the following pages: 8 in Acronym and Abbreviations Section; 11 (Table 1-2), 25 (Table 4-1), 30 (Table 4-2), 32 (Table 4-6), 34 (Table 5-1), 36 (Table 5-2 and 5-3), 48 (Table 5-6), 51 (Table 6-1), in Sections 1.3, 4.2, 4.4, 4.7, 5.0, 5.1, 5.4, and 6.2. SEC changes occurred on pages 11 (Table 1-1), 32, 33, 37-39 (Table 5-4), 40, 41, 46 (Table 5-5), 49 (Table 5-7), 50, 57, 60, 61 (Table 6-4), 63 (Figure 6-2) in Sections 1.3, 4.7, 5.0, 5.1, 5.2, 5.3, 5.5, 6.1, and 6.3. Incorporates formal NIOSH review comments on page 2 (Publication Record), 30 (Table 4-2), 41, 48 (Table 5-6), and 74 in Sections 4.4, 5.2, 5.4, and Reference Section. References were updated on pages 10, 11, 19, 29, 30, 32, 33, 37, 40, 41, 46, 47, 50-52, 57-62, 64, 65, 70, 74-76 in Sections 1.3, 2.3, 4.4, 4.7, 5.0, 5.1, 5.2, 5.4, 6.1, 6.2, 6.3, 6.4, 7.0, and Reference Section. No sections were deleted. Training required: As determined by the Task Manager. Initiated by Karen S. Kent.
12/18/2009	01	Approved revision to add lateral chest doses for all periods, skin doses for various parts of the body, and an explanation of terminology. Sections 3.0 and 3.1 were modified as a result of these changes. Tables 3-1 through 3-6 were modified and Tables 3-7 and 3-8 were added. The definition of occupational medical dose was revised, and three reference titles were changed. Wording in Section 6.2.1 about external uranium dose was modified. Revision made to add unmonitored doses before 1953. Section 6.2.1 reworded to remove OTIB-0004 discussion and add new methodology. Section 6.3.1 was modified to include two eras of unmonitored doses. Figure 6-2 was altered to reflect the new unmonitored dose methodology for doses before 1953. Table 5-1 was separated into three tables. Changes were made to Table 5-7 (now 5-8) to clarify and correct intake values. Wording was added to Section 1.3 to caution the Dose Reconstructor on when to label the DR as a partial DR. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite or the document. Training required: As determined by the Objective Manager. Initiated by Jackson R. Ellis.

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
01/14/2011	02	Revision initiated to include SEC-00166. Section 1.3.3 and Table 1-3 added. Section 2.1.6 updated to note the end of hot cell operations in the Research Building. Paragraph added in Section 5.0 to discuss SEC-00166. Section 5.1.1.3 updated with internal intake information from SEC-00166. Table 5-4 and 5-8 updated with updated intake rates. Section 5.4.1 updated to remove statement that intakes from the Research Building hot cell would be negligible. Removed A&A point. Added SEC-00166 to the reference section as NIOSH 2010. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Jackson R. Ellis.
01/03/2012	03	Revision initiated to include SEC-00185. Section 1.3.4 was added. Section 1.3 edited to update partial dose reconstruction information and to introduce new SEC. Sections 1.3.1 and 1.3.2 were edited to show inclusion of all workers in those SECs. Expansion of class was inserted in sections of the document as necessary. Section 5.4.1 edited to state environmental doses should be applied to certain Research Building workers. Battelle 2006a was updated to Battelle 2011 and Battelle 2006b was cancelled and replaced with other references. Changes were made to several sections and tables in Sections 5.1 and 6.3. Section 6.3.1.2 was updated to reduce missed dose component of beta doses in Table 6-7. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Jackson R. Ellis.
09/18/2023	04	Revision initiated to incorporate SEC-00245. Section 1.3 edited to update partial dose reconstruction information and to introduce SEC-00245. Section 4.4 deleted per SEC. Section 5.1.1.4 deleted. Section 5.2 edited to remove thorium intakes prior to 1990 per SEC. Section 5.3.1 updated to present improved example tritium bioassay records. Section 5.3.2 edited to start tritium exposures in 1990 per SEC. Section 5.3.3 deleted to remove tritium unmonitored exposures per SEC. Sections 5.4.1 and 5.4.2 revised to remove fission product intakes per SEC. Summary table edited to incorporate revisions and deletions discussed above. Section 6.3.1 was edited to remove unmonitored doses prior to 1955 per SEC. Section 6.4 edited to extend exposure to organ dose factor to 1985, in line with NVLAP certification. Section 7 was updated to assign A&A citations to current project personnel. Brought into compliance with ORAUT-PROC-0031 as specified during discussions with NIOSH. Section 4.5 updated to include uranium intakes based on residual contamination and subsequent reduction per Battelle-TBD-6000 and ORAUT-OTIB-0070. Thorium ingestion intakes added based on NUREG/CR 6755. Incorporates additional formal NIOSH review comments. Sections 4.1 and 5.1 edited to incorporate environmental uranium intakes as documented in NIOSH Response to SC&A Review of the Ames Site Profile Document Regarding Uranium Internal Exposures white paper. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of a focused revision. Training required: As determined by the Objective Manager. Initiated by John M. Byrne and authored by Jackson R. Ellis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

A&A	attribution and annotation
AEC	U.S. Atomic Energy Commission
ALRR	Ames Laboratory Research Reactor
AWE	Atomic Weapons Employer
BNL	Brookhaven National Laboratory
BRH	Bureau of Radiological Health
C.F.R.	*Code of Federal Regulations*
Ci	curie
cm	centimeter
d	day
D&D	decontamination and decommissioning
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
dpm	disintegrations per minute
DR	dose reconstruction
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
F	fast (absorption type)
ft	foot
g	gram
GM	geometric mean
GSD	geometric standard deviation
Hp(10)	personal dose equivalent at 10 millimeters depth in tissue
HPS	Health Physics Services
hr	hour
ICN	ICN Dosimetry Service
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
in.	inch
IREP	Interactive RadioEpidemiological Program
ISU	Iowa State University
keV	kiloelectron-volt, 1,000 electron-volts
kg	kilogram
kV	kilovolt
L	liter
m	meter
M	moderate (absorption type)
MDA	minimum detectable amount
MDL	minimum detection level
MeV	megaelectron-volt, 1 million electron-volts
mg	milligram

mi	mile
mL	milliliter
mo	month
mR	milliroentgen
mrad	millirad
MRD	minimum recordable dose
mrem	millirem
mrep	millirep
MTR	Materials Test Reactor
MW	megawatt
n	neutron
NCA	Nucleonic Corporation of America
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
NTA	nuclear track emulsion, type A
NVLAP	National Voluntary Laboratory Accreditation Program
OPOS	one person–one statistic
ORAU	Oak Ridge Associated Universities
ORAUT	ORAU Team
pCi	picocurie
PER	program evaluation report
R&D	research and development
s	second
S	slow (absorption type)
SEC	Special Exposure Cohort
SLAC	Stanford Linear Accelerator Center
SRDB Ref ID	Site Research Database Reference Identification (number)
t	ton
TBD	technical basis document
TLD	thermoluminescent dosimeter
U.S.C.	*United States Code*
yr	year
β	beta
γ	gamma
µCi	microcurie
µg	microgram
§	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 2010a]:

- 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 information about operations at Ames Laboratory that pertains to radiation exposures for monitored or unmonitored workers. The laboratory began as several buildings on the grounds of the Iowa State College, which later became Iowa State University (ISU). This document uses ISU for either.

1.2 SCOPE

Section 2.0 provides a description of the site and operations that pertain to possible radiation exposures and discusses radiation source terms. Section 3.0 provides guidance for the determination of occupational medical dose. Section 4.0 provides guidance for the determination of dose to workers outside radiological facilities due to releases of radioactive materials to the environment as well as radiation emitted by facilities, reaching the surrounding areas. Section 5.0 provides guidance for the determination of intakes of radionuclides inside facilities. Section 6.0 provides guidance for the determination of external doses from measured doses and for periods for which records of measured doses are missing. Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 7.0.

1.3 SPECIAL EXPOSURE COHORT

The Secretary of the U.S. Department of Health and Human Services has designated five classes of employees at Ames Laboratory as additions to the SEC:

January 1, 1942 (later revised to August 13, 1942; see below) through December 31, 1954

Department of Energy (DOE) employees or DOE contractor or subcontractor employees who worked at the Ames Laboratory in one or more of the following facilities/locations: Chemistry Annex 1 (also known as "the old women's gymnasium" and "Little Ankeny"), Chemistry Annex 2,[1] Chemistry Building (also known as "Gilman Hall"), Research Building, or the Metallurgical Building (also known as "Harley Wilhelm Hall") from January 1, 1942 through December 31, 1954 for a number of work days aggregating at least 250 work days, or in combination with work days within the parameters (excluding aggregate work day requirements) established for one or more classes of employees in the SEC, and who were monitored or should have been monitored [Leavitt 2006, p.3].

January 1, 1955, through December 31, 1970

Sheet metal workers, physical plant maintenance and associated support staff (including all maintenance shop personnel), and supervisory staff who were monitored or should have been monitored for potential internal radiation exposures associated with the maintenance and renovation activities of the thorium production areas in Wilhelm Hall (a.k.a. the Metallurgy Building or "Old" Metallurgy Building) at the Ames Laboratory from January 1, 1955, through December 31, 1970, for a number of work days aggregating at least 250 work days or in combination with work days within the parameters established for one or more other classes of employees in the Special Exposure Cohort [Leavitt 2007, p. 3].

January 1, 1955, through December 31, 1960

All employees of the Department of Energy, its predecessor agencies, and its contractors and subcontractors who worked in any area of the Department of Energy facility at the Ames Laboratory from January 1, 1955 through December 31, 1960, for a number of work days aggregating at least 250 work days, occurring either solely under this

[1] This document refers to these facilities as Physical Chemistry Annex 1 and Physical Chemistry Annex 2.

employment, or in combination with work days within the parameters established for one or more other classes of employees in the Special Exposure Cohort [Sebelius 2010, p.3].

August 13, 1942, through December 31, 1970

All Department of Energy (DOE) employees, its predecessor agencies, and its contractors and subcontractors who worked in any area of the Ames Laboratory at Iowa State University during the periods from August 13, 1942 through December 31, 1970, 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 classes of employees included in the Special Exposure Cohort [Sebelius 2011, p. 3].

January 1, 1971, through December 31, 1989

All employees of the Department of Energy, its predecessor agencies, and their contractors or subcontractors who worked in any area of the Ames Laboratory in Ames, Iowa, during the period from January 1, 1971, through December 31, 1989, 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 included in the Special Exposure Cohort [Azar 2018, p. 3].

The first two classes covered two separate groups of employees based on work location and job description [NIOSH 2006, 2007a]. However, NIOSH determined that the information available about worker job description, work location, or movement about the site was insufficient to determine if an employee worked in the affected areas [NIOSH 2010b]. In 2011, the Secretary designated a fourth class that encompassed all previous periods and included all Ames employees (including predecessor agencies, contractors, and subcontractors). In addition, the class was revised to change the covered period's start date from January 1, 1942, to August 13, 1942, the start of the Manhattan Engineer District, known later as the Manhattan Project [NIOSH 2011a]. The Secretary subsequently designated a fifth class that extended the covered period to include January 1, 1971, through December 31, 1989 [NIOSH 2017].

Although NIOSH found that it is not possible to reconstruct radiation doses completely for all the evaluated classes, it intends to use any internal and external monitoring data that might become available for an individual claim (and that can be interpreted using existing dose reconstruction processes or procedures). Therefore, partial dose reconstructions for individuals employed at Ames Laboratory from August 13, 1942 through December 31, 1989, but who do not qualify for inclusion in the SEC, can be performed using these data as appropriate.

This site profile provides internal and external exposures that might coincide with work periods that fall within the class periods. There are varying types of exposures that can be applicable to dose reconstructions during the class periods for employees who do not qualify for inclusion in the SEC. The feasibility findings for all SEC class periods were evaluated, with consideration of how latter designations affect earlier designations, and an overall covered period approach to dose reconstruction was developed [Rutherford 2022a,b]. Table 1-1 provides sources of exposure and periods for which dose reconstruction is feasible.

Exposures that are listed as feasible in Table 1-1 are discussed in later sections of this site profile. Exposures from other sources or nuclides not included in Table 1-1 are infeasible. After 1990, there are no SEC restrictions, as the SEC period ends December 31, 1989. Exposures after 1989 are covered in later sections of this document.

Table 1-1. Feasibility findings for SEC classes, August 13, 1942, through December 31, 1989.

Internal dose[a]

Source of exposure	Dates reconstruction is feasible
Uranium	08/13/1942–12/31/1970
All other nuclides	None
Environmental (except fission products)	08/13/1942–12/31/1989

External dose[a]

Source of exposure	Dates reconstruction is feasible
Co-exposure dose	01/01/1955–12/31/1989
Environmental	08/13/1942–12/31/1989
Occupational medical X-ray	Not applicable

a. Any internal and external monitoring data that might become available for an individual claim (and that can be interpreted using existing dose reconstruction processes or procedures) can be used for dose reconstruction as described in the internal and external sections below.

2.0 SITE DESCRIPTION

The Ames Laboratory site consists of several buildings at ISU in Ames, Iowa. The precursor to the Ames Laboratory was the Ames Project, which was established in 1942 in a contract between the Metallurgical Laboratory at the University of Chicago and the former Iowa State College (now ISU) [Fulmer 1947]. Ames Laboratory was established by the U.S. Atomic Energy Commission (AEC) in May 1947 [Karsjen 2003]. The site played a key role in the production of strategic nuclear materials for the Manhattan Project and the AEC.

Early in 1942, before the beginning of the Manhattan Project, the most pressing problem was the preparation of large amounts of pure uranium metal [Ames 1960a]. Faculty members in the Chemistry Department at ISU with expertise in rare earth metallurgy were called on to develop a method to purify uranium and reduce its cost of production [Ames 1960a]. By November 1942, successful methods had been developed and approximately one-third of the uranium in the Chicago pile was supplied by the Ames Project [Karsjen 2003]. The Ames Project was asked to turn its process over to industry and, in the meantime, to produce as much pure uranium as possible. Between mid-1942 and August 1945, more than 1,000 t of pure uranium metal was supplied to the Manhattan Project [Ames 1960a].

Once the potential need for thorium metal was recognized, the Ames Project began to develop methods for purifying thorium in 1943. By late 1944, a large-scale process for thorium metal production was developed; between 1950 and April 1953, when thorium production was turned over to industry, Ames produced more than 65 t of pure thorium metal and thorium compounds [Ames 1960a].

In addition to the early uranium and thorium metal production operations, personnel at Ames Laboratory handled several other radionuclides and operated an 80-MeV synchrotron, a 5-MW research reactor, and several radiation-generating machines. Each of these radiation sources is described in the following sections.

2.1 FACILITIES

The original buildings at ISU for the Ames Project included Physical Chemistry Annex 1, the Chemistry Building (now Gillman Hall), and the Physics Building (now Physics Hall) [Ames 1967]. In 1944, a new building, Physical Chemistry Annex 2, was constructed to house operations to recover uranium from scrap material [Fulmer 1947].

In November 1945, the buildings used by the Ames Project were designated as the Institute for Atomic Research. In May 1947, AEC established a major research facility at Ames known as Ames Laboratory [Ames 1962a], which operated as an integral part of the Institute for Atomic Research. Four additional buildings were constructed: the Metallurgy Building (now Wilhelm Hall), the Research Building (now Spedding Hall), the Office and Laboratory Building that connected the Chemistry and Physics Buildings, and the Synchrotron Building (now the Spangler Geotechnical Laboratory) [Ames 1962a]. The Metals Development Building was added in 1960 [Ames 1960a]. Construction of a 5-MW heavy-water-moderated research reactor began in 1962, and operations began in 1965. The Technical and Administrative Services Facility was added to connect the Research Building (Spedding Hall) and the Chemistry Building (Gilman Hall); this facility includes only offices. The locations of Ames Laboratory buildings on the ISU campus are shown in Figure 2-1. The locations of the reactor facilities (now known as the Applied Science Complex) and the Synchrotron Building are shown in Figure 2-2.

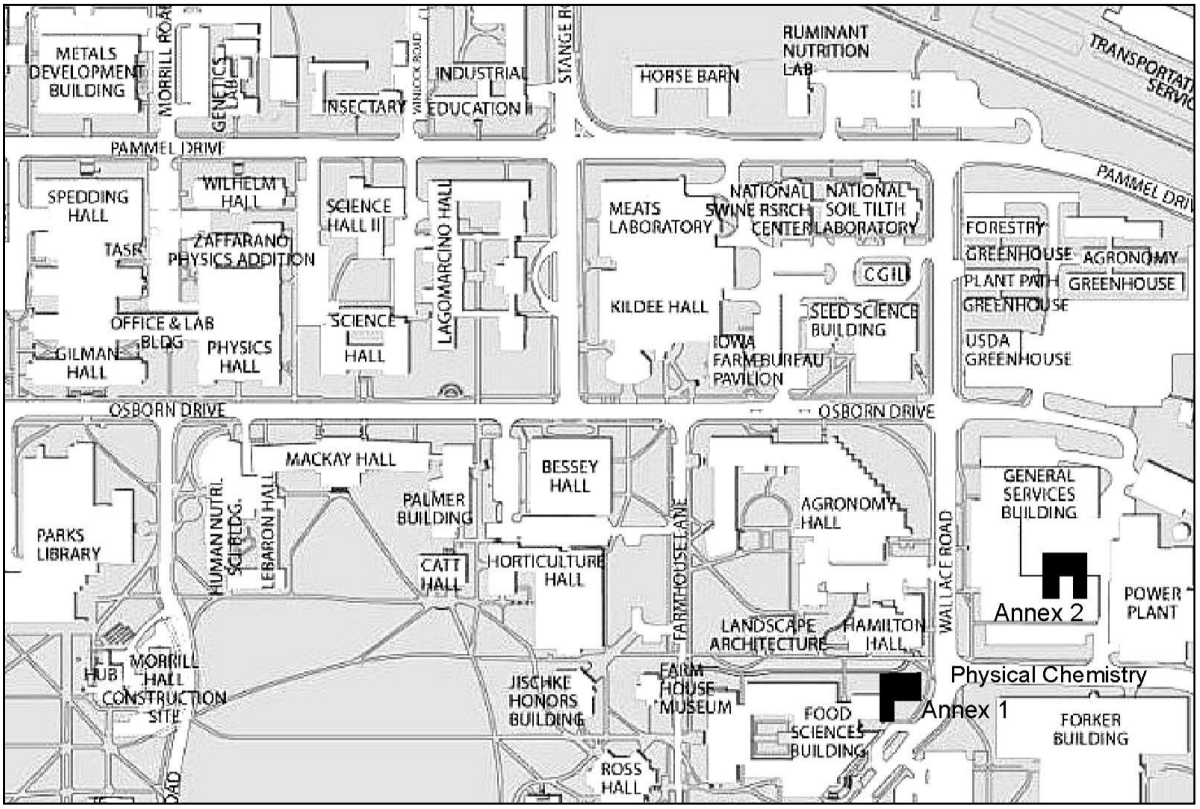

Figure 2-1. ISU campus map showing locations of laboratory buildings including former sites of Physical Chemistry Annex 1 and Annex 2 [ISU 2006].

To avoid confusion between the historical building names and the current names as shown in Figures 2-1 and 2-2, the following section headings provide the historical name first and the current name in parentheses.

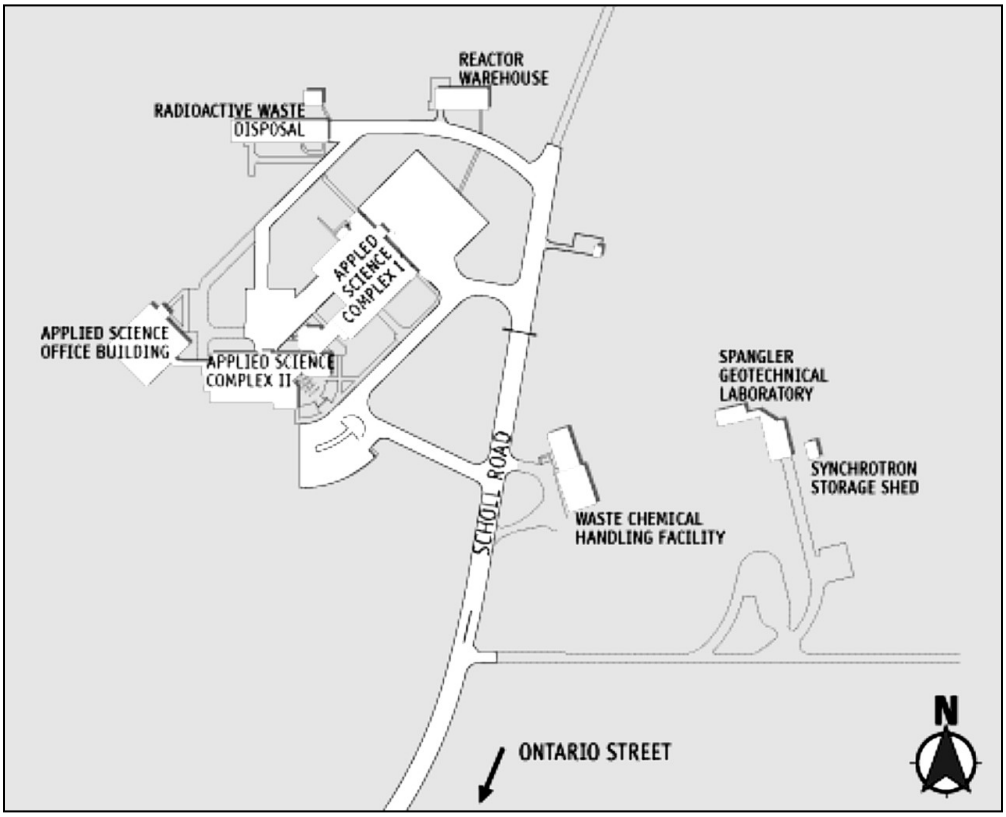

Figure 2-2. ISU campus map showing locations of reactor facilities and Synchrotron Building [ISU 2006].

2.1.1 Physical Chemistry Annex 1

The production of uranium metal was conducted in Physical Chemistry Annex 1, an old wooden structure east of the Dairy Industries building and west of Wallace Road. Uranium operations began there in mid-1942 and ended on August 5, 1945, when the uranium purification process was transferred to industry. More than 1,000 t of pure uranium and more than 300 t of uranium scrap were produced during this period [Karsjen 2003]. In 1943, an open porch area was enclosed (to control dusty operations) and additions were constructed to accommodate increases in uranium production [Payne 1992]. Beginning in 1943, the building was also used to produce thorium metal until the processing equipment was transferred to the new Metallurgy Building in 1949 or 1950 [Ames 1960a]. Physical Chemistry Annex 1 was torn down in 1953 [Karsjen 2003]. The building site was decontaminated, surveyed in May 1976, and designated acceptable for future construction [Voss 1979a, p. 2].

2.1.2 Chemistry Building (Gilman Hall)

The initial Ames Project work was conducted in the Chemistry Building in early 1942. The process for purifying uranium metal and the methods and equipment to increase production were developed in this building. Uranium production operations were moved to Physical Chemistry Annex 1 in mid-1942, while other uranium research continued in the Chemistry Building such as determination of uranium properties, studies of uranium corrosion, development of protective coatings for uranium, and development of uranium alloys and compounds [Fulmer 1947]. Other research in the Chemistry Building involved development of pure thorium metal, thorium alloys and compounds, yttrium metal, cerium metal, and beryllium metal [Ames 1962a]. Analytical work centered on plutonium chemistry and the radiochemistry of the separation of fission products from uranium and plutonium, which was

conducted in the “hot laboratory” between 1942 and 1951 [Ames 1960a]. The Chemistry Building was decontaminated and surveyed in May 1976 [Voss 1979a, p. 2].

2.1.3 Physics Building (Physics Hall)

Research and development (R&D) to support other work at Ames Laboratory was conducted in the Physics Building. Analytical equipment was developed, including three beta-ray spectrometers, a bent crystal X-ray spectrometer, a kevatron, X-ray and neutron diffraction spectrometers, scintillation and conduction crystal spectrometers, X-ray and electron diffraction machines, and an electron microscope [Ames 1951, 1962a]. Nuclear fission was studied to identify the individual fission fragments, the energies involved, and the ionized state of the emitted particles [Ames 1951]. Research was conducted to determine the stopping power and shielding properties of various solid materials [Ames 1951]. Personnel of the Physics Department operated the 80-MeV synchrotron, which is described below [Ames 1962a]. In 1968, an addition to the Physics Building was completed. The Physics Building Addition (also known as Physics Hall Addition) was a 44,000-square foot building constructed to house the graduate research program and the advanced undergraduate teaching laboratories of the ISU Physics Department [Ames 1968].

2.1.4 Physical Chemistry Annex 2

Physical Chemistry Annex 2 was a brick fireproof structure built east of Wallace Road in early 1944 to house uranium recovery from scrap uranium metal turnings from other Manhattan Project sites. Operations in this building through December 1945 produced more than 300 t of recovered uranium metal [Fulmer 1947]. Operations ended in 1953 when the building was converted to a plumbing shop; it was razed in 1972 [Struss and Hawkins 1986]. The area where the building stood was covered with concrete and served as a parking lot and loading zone. The area was surveyed in May 1979 [Voss 1979a]. Part of the General Services Building now covers part of the former building site (see Figure 2-1).

2.1.5 Metallurgy Building (Wilhelm Hall)

The Metallurgy Building, constructed by the AEC, was completed in October 1949 [Ames 1951]. The building housed research aimed at development of special metals and alloys used in nuclear energy projects. Zircaloy was initially developed at Ames Laboratory as part of a basic study of the zirconium-tin alloy phase diagram [Ames 1962a]. The subject of reactor coolants was studied along with the heat-transfer properties of various metals and alloys [Ames 1951]. Equipment available for research, development, and production in metallurgy included many types of furnaces, high-vacuum systems, pyrometric devices, fabricating and testing machines, metallographs, X-ray diffractometers, and ultrasonic, spectrographic, dilatometric, and other instrument types for examination and study of metals and alloys. A glovebox line in the Metallurgy Building was used to study the behavior of plutonium in molten metal systems [Ames 1962a].

Thorium production and research activities were moved from Physical Chemistry Annex 1 to the Metallurgy Building in 1949, and work on thorium continued until 1953. Poor contamination control practices and poor ventilation contributed to contamination of the building. However, contamination levels have been reduced by mitigation, decontamination, remodeling, and renovation projects. Contamination still exists in many interspatial areas of the building and in some relatively inaccessible areas [Hokel et al. 1998].

2.1.6 Research Building (Spedding Hall)

The Research Building was constructed by the AEC and occupied in early 1951 [Ames 1951]. Many metals, including rare earths, were investigated for mechanical, chemical, electrical, and other

properties and were studied by experimental techniques that probed the inner structures and forces of the materials [Ames 1962a]. Research facilities in the building included a 150-kV accelerator that produced 14-MeV neutrons; a glovebox line for radiochemistry experiments; a hot canyon and hot cell with steel shielding, lead glass windows, and manipulators for work with highly radioactive materials; and an electron microprobe analyzer. The hot canyon was two stories high with the lower level in the basement adjacent to the hot cell. Research activities included electron beam welding, the study of the electronic structure of metals, and the separation, preparation, and measurement of properties of rare earth metals. The initial research on liquid metal coolants was done at Ames Laboratory in an engineering sodium test loop used in corrosion, fluid-flow, and heat transfer studies with liquid sodium [Ames 1967]. Work in the hot cell continued until 1982.

Ames Laboratory had a Texas Nuclear Model 9900 neutron generator located in the Research Building. The neutron generator used tritium targets with activities ranging from 5 to 10 Ci. [Voss 1971].

2.1.7 Office and Laboratory Building

The Office and Laboratory Building connects the Chemistry and Physics Buildings and houses the administrative offices of the Ames Laboratory, the special research laboratories used jointly by chemists and physicists, and a large physical sciences reading room [Ames, no date].

2.1.8 Synchrotron Building (Spangler Geotechnical Laboratory)

The Synchrotron Building was constructed in 1949 on a 200-acre tract northwest of the campus that was set aside for special use by the Institute for Atomic Research [Ames 1962a]. The synchrotron room housed two electron accelerators that could project electrons up to 80 MeV onto a target, which produced high-energy gamma rays that interacted with nuclei to release neutrons, protons, and alpha particles [Ames 1967]. The accelerators were operated from a control room where there was a safety gate that prohibited access to the synchrotron room when the beam was on [Ames 1967]. In many cases, the products of these reactions were radioactive and were used in research in nuclear physics and radiochemistry [Ames 1967]. In addition, the synchrotron was used to probe nuclear structures and to provide radionuclides for nuclear spectroscopy [Ames 1962a]. Operations at the Synchrotron Building ended in June 1971; the equipment was decommissioned in the early 1990s.

2.1.9 Metals Development Building

Ames Laboratory facilities were expanded in 1960 to include the Metals Development Building. Its missions were to conduct process development research on larger-than-laboratory scale and to evaluate commercial feasibility of the developed processes. One major process was the production of very pure metals; small quantities of these metals were to be used elsewhere as standards. The building contained a complete pilot plant with facilities for each step of the metal production process from ore treatment to metal fabrication or analysis [Ames 1960a]. Equipment in the building included electron microscopes, an electron microprobe, metallography apparatus, liquid-liquid extraction apparatus, extrusion presses for producing rods and tubes, and rolling machines for making sheet metal [Ames 1967].

2.1.10 Ames Laboratory Research Reactor (Applied Science Complex)

Construction of the 5-MW, heavy-water-moderated Ames Laboratory Research Reactor (ALRR) began in 1961; the reactor was first operated in February 1965 [Ames 1967; Voigt 1981]. The reactor and its support facilities were about 1.5 mi northwest of the ISU campus on a 200-acre site used by the Institute for Atomic Research [Ames 1967]. The reactor fuel was 93%-enriched ^{235}U contained in 24 fuel assemblies in a hexagonal arrangement in a core 30 in. across and 25 in. high [Voigt 1981].

The reactor shielding was an irregular decahedral prism shape with a thermal column on one face and nine faces with beam tubes from which radiation beams (primarily neutrons) could be extracted and directed to experimental areas around the reactor [Ames 1967; Voigt 1981]. Other tubes and thimbles provided access to the reactor core for irradiation experiments. Research activities included radiation damage studies, determination of the crystalline structure of solids, determination of mechanical properties of reactor materials, and analysis of the decay products of nuclear fission. The experimental equipment featured an online isotope separator that received fission products directly from the operating reactor, separated them by weight, and analyzed them by isotope. Other research equipment included a neutron diffractometer used to determine the physical properties of solids and a hot cell for handling spent reactor fuel [Ames 1967]. Operation of the reactor resulted in airborne tritium concentrations in occupied spaces of the building [Voigt 1981]. A routine tritium bioassay program was part of the radiation safety program at the reactor [Voss 1971]. Operation of the reactor ended in December 1977 and decontamination and decommissioning (D&D) of the facilities was completed in 1981. At the time operations ended, the heavy-water coolant contained approximately 1.7 Ci/L of tritium [Voigt 1981].

2.2 OPERATIONS

Two major operations at Ames Laboratory resulted in radiation exposure to the staff: the production of large quantities of pure uranium (1942 to 1945) and the production of thorium metal (1943 to 1953). Several smaller operations contributed to staff exposure to radiation.

2.2.1 Uranium Metal Operations

The initial Ames process for production of uranium metal was based on the chemical reduction of uranium tetrafluoride (UF_4) by calcium metal. Finely ground UF_4 was mixed with granulated calcium metal and the mixture was poured into a refractory-lined container. A fuse wire buried in the charge was electrically heated to initiate the reaction, which continued until both uranium metal and calcium fluoride were in the molten state. The more dense uranium collected at the bottom of the container, where it was allowed to cool to room temperature, after which it was removed for casting. The uranium metal was cast by placing it in a graphite crucible, heating it in a vacuum, and allowing the liquid metal to flow into a graphite mold for specific shapes [Fulmer 1947]. Although more complex, the uranium production process was improved by replacing the calcium reagent with magnesium metal [Fulmer 1947].

Most of the uranium metal production operations were conducted in Physical Chemistry Annex 1, which had poor contamination control and poor ventilation [Friedell 1942]. Workers in this building were likely to have received intakes of uranium between 1942 and 1945 and thorium between 1943 and 1950 as well as external exposures to beta and gamma radiation. These exposures are estimated in Sections 5.0 and 6.0. Effluents from the building were not monitored, and local environmental contamination by uranium compounds was likely. Uranium and thorium contamination of the ground surface around Annex 1 required removal and offsite disposal of the contaminated soil [Payne 1992]. No other records could be found that addressed the disposal of contaminated waste or the control and monitoring of air and liquid effluents.

A substantial amount of uranium scrap material was produced, which was processed in Physical Chemistry Annex 2 from early 1944 to December 1945 [Fulmer 1947]. Radiation exposures to workers in this building during this period were similar to the uranium exposures in Physical Chemistry Annex 1, and are estimated in Sections 5.0 and 6.0. Local environmental contamination around Annex 2 was assumed to be similar to that around Annex 1 (see Section 4.1).

2.2.2 Thorium Metal Operations

The uranium metal production method was adjusted between August 1943 and August 1944 to produce thorium metal [Fulmer 1947]. Thorium tetrafluoride (ThF_4) was mixed with calcium metal with a zinc chloride booster to produce a thorium-zinc alloy with a 96% yield of thorium metal. The alloy was heated under vacuum in a graphite crucible to distill off the zinc. Casting of thorium metal was difficult because of its high melting point and its reactive properties. Beryllium oxide crucibles had to be used; melting the thorium in a crucible the size and shape of the desired ingot proved to be a more reliable method of casting, although it often did not separate well from the slag and oxide. Castings were improved in late 1946 by pouring molten thorium into graphite molds [Fulmer 1947]. Production of thorium metal and thorium compounds continued until April 1953 when thorium production operations were turned over to industry [Ames 1960a].

The purified feed material for the thorium production operation was prepared by dissolving thorium nitrate in nitric and oxalic acids, precipitating the thorium oxalate, drying the precipitate in trays, hydrofluorinating the precipitate to ThF_4, and crushing the ThF_4 to a fine powder [Fulmer 1947]. This process was used throughout thorium production operations.

Thorium production operations, which were conducted in Physical Chemistry Annex 1 after uranium operations ended in 1945, continued until 1949 or 1950 when the operation and equipment were moved to the new Metallurgy Building (Wilhelm Hall) [Ames 1960a]. Workers in Annex 1 were likely to have intakes of thorium and external exposures to beta and gamma radiation. These exposures are estimated in Sections 5.0 and 6.0. Effluents from the building were not monitored, and local environmental contamination by thorium compounds was likely. Thorium production operations in the Metallurgy Building improved with better ventilation, but personnel exposures and environmental contamination continued to be unquantified until 1953 because of a lack of monitoring and inadequate records.

A summary of AEC activities at Ames Laboratory during the period from 1942 to 1954 is presented in Table 2-1.

Table 2-1. Timeline of activities, 1942 to 1954.

Operation	Period[a]	Building	Activity
Uranium metal production	02/1942–08/1942	Chemistry (Gilman Hall)	Process development
Uranium metal production	08/1942–12/1942	Chemistry	Production
Uranium metal production	09/1942–08/1945	Annex 1	Production
Uranium scrap recovery	Late 1943–early 1944	Chemistry	Process development
Uranium scrap recovery	Early 1944–12/1953	Annex 2	Production
Uranium metal casting	09/1942–08/1945	Annex 1	Production
Thorium metal production	08/1943–06/1946	Annex 1	Process development
Thorium metal production	06/1946–late 1949	Annex 1	Production
Thorium metal production	Early 1950–04/1953	Metallurgy (Wilhelm Hall)	Production
Studies of plutonium properties	06/1943–12/1947	Chemistry & Metallurgy	Research
Plutonium/fission product separations	Summer 1943–12/1954	Chemistry & Research (Spedding Hall)	Research and hot cell work
Thorium metal casting	06/1946–late 1949	Annex 1	Production
Thorium metal casting	Early 1950–04/1953	Metallurgy	Production
Studies of uranium and thorium properties	Early 1942–12/1954	Chemistry	Research
Development of analytical procedures	Early 1943–12/1954	Chemistry	Research
Annex 1 demolition	1953	Annex 1	Demolition

a. Exact start and end dates vary depending on the reference. Listed dates are the most common or consensus.

2.2.3 Other Operations

Methods for routine analysis of fission products were developed at Ames Laboratory. These activities resulted in the discovery of the previously unidentified isotopes ^{33}P, ^{144}Pm, ^{125}Sb, and five isotopes of ruthenium and rhodium. Research on the parent-progeny relationship of $^{90}Sr/Y$ was conducted. Pioneering research in applications of alpha and beta spectroscopy and mass spectroscopy to identify specific radionuclides was part of the development of laboratory methods. A process for separating ^{233}U from thorium was developed.

2.3 SOURCE TERMS AND PERSONNEL MONITORING

Ames Laboratory staff were exposed to radiation sources through several pathways including environmental effluents, radioactive intakes, and external radiation dose.

Environmental effluents from the early Ames Laboratory buildings were unmonitored and uncontrolled. Radioactive effluents near these buildings could have exposed workers to unmonitored occupational environmental doses. An accidental release of thorium waste materials to the sanitary sewer system occurred in 1951 [Voss 1979a]. This release, which could have contributed to the occupational environmental dose received by workers who were involved in the incident response, is addressed in Section 4.4.

Uranium and thorium metal production involved several dusty operations that resulted in work area contamination and potential worker inhalation and ingestion. The principal sources of surface contamination and airborne dust were the processes of grinding uranium tetrafluoride into a fine powder, transferring the powder from the grinder, and mixing and loading the powder charge into the reduction crucibles. Because the uranium had been separated from radium and its decay products, ^{222}Rn was not a potential inhalation concern. The principal sources of thorium surface contamination and airborne dust were the processes of preparing and drying the fine powder and mixing and loading the powder charge into the reduction crucibles [Fulmer 1947].

There were frequent small explosions and fires associated with the uranium and thorium production operations. Payne [1992] cited as many as six small fires in a single day; these fires contributed to work area contamination and potential airborne radioactive material exposures. No records were found to indicate that air sampling or contamination control was associated with these fires.

Personnel protection for potentially dusty operations included the use of laboratory-provided clothing and gloves as well as restrictions on eating and smoking in areas where radioactive materials were handled. Although respiratory protection measures such as gas masks and dust masks were provided, their use was not enforced before about 1952. Showers were recommended for workers at the end of each day, but records indicated that not all workers complied with this recommendation [Klevin 1952; Payne 1992].

Many other radioactive materials were handled in Ames Laboratory buildings before routine monitoring for radiation exposures began in about 1952. Because the bioassay program was minimal and records are sparse, intakes that might have occurred before 1953 have been estimated. When reactor operations started in 1965, a routine tritium bioassay program was started. Tritium intakes can be more reliably estimated from that time forward. Occupational internal dose is addressed in Section 5.0.

The uranium and thorium metal production operations resulted in beta and gamma radiation exposures to workers. Beta radiation was the dominant external source of radiation associated with unshielded sources of uranium such as uranium metals production, scrap recovery, and machining processes. The significance of beta emissions from thorium depends on the state of equilibrium with

the ^{232}Th parent, which is a factor of the time elapsed since the thorium process feed material was separated [NIOSH 2006]. Photon exposure rates as high as 22 mR/hr were reported for a thorium storage area, which suggests that this raw material for the thorium production process was not newly separated [Klevin 1952].

Only two film badge results were identified for 1944 with results in units of "average roentgens/8-hour day during week" [Tybout 1944, p. 7]. Before 1952, only pencil dosimeters were used in Ames Laboratory facilities and the records are sparse. The use of film badges began in late 1952; records from 1953 and 1954, along with workplace measurements, have been used to estimate earlier radiation doses. Records of external radiation exposures received from 1955 to the present are given in Section 6.0 for evaluation of occupational external dose.

3.0 OCCUPATIONAL MEDICAL DOSE

Occupational medical exposures are included in dose reconstruction only for medical examinations obtained at covered facilities [Oak Ridge Associated Universities (ORAU) Team (ORAUT) 2017]. The X-ray equipment for occupational medical examinations of Ames Laboratory staff was at the Iowa State Student Health Center/College Hospital [Voss 1957], which is not a covered facility under EEOICPA. Therefore, no occupational medical doses should be included in dose reconstruction.

4.0 OCCUPATIONAL ENVIRONMENTAL DOSE

Occupational environmental dose refers to the dose received by workers on the site but outside facilities (i.e., buildings). These doses can be internal or external depending on the characteristics of the individual radionuclides. Radionuclides at Ames Laboratory included uranium, plutonium, thorium, and small amounts of others used in the R&D program [Fulmer 1947]. Tritium, argon, and krypton were released at the ALRR. These radionuclides are addressed in the following sections.

Occupational environmental dose was not measured (direct radiation dosimeters) until 1953, when workers were badged [ORAUT 2006a,b], and it was not calculated from environmental media concentrations until 1962. Sources of potential environmental exposures (releases to the environment) were not measured until 1962 [Voss 1963, p. 7].

Different activities were carried out during distinct periods of Ames Laboratory history. Occupational environmental doses are, therefore, addressed below for each of these periods and their activities. A significant release of radioactive materials to the environment from Ames Laboratory facilities is addressed in Section 4.4.

4.1 URANIUM AND THORIUM PRODUCTION, 1942 TO 1953

Uranium production occurred in Physical Chemistry Annex 1 (see Figure 2-1) from mid-1942 to August 5, 1945 [Karsjen 2003]. Uranium scrap recovery occurred in Physical Chemistry Annex 2 (see Figure 2-1) from early 1944 to December 1945, and some operations continued until 1954. Thorium production occurred first in Physical Chemistry Annex 1 from 1943 to 1949 when the operation moved to the new Metallurgical Building (Wilhelm Hall; see Figure 2-1). The operation in the Metallurgical Building continued until April 1953. Like Annex 1 and Annex 2, there was no on- or offsite designation for this facility. Workers, students, and college personnel moved freely by and around the building. No measurements were made of the particulate or gaseous effluents from the buildings or of the radiation levels outside the buildings [Ames 1962b, 1962–1964].

Workers conducted their assignments inside the facilities, and there were no specific assignments outside the facilities. That is, input materials arrived at the facilities and were processed, and products

were shipped from the facilities. Workers did not move between the facilities on campus and there was no transportation of materials among the facilities on campus [Ames 1962a].

Uranium exposures were developed from bioassay data during uranium operations as described in Section 5.1. The environmental exposure intakes during the production period (1942 to 1953) are from Table 5-4 in Section 5.1.4 and are repeated in Table 4-8 in Section 4.6.

Thorium environmental doses were derived from contamination surveys of operating areas. No documents were found that stated the room and hood ventilation stacks on the facilities had filters. Concentrations of dust were measured in the operation rooms [Voss 1979b]. To estimate a bounding dose outside the facilities, it was assumed that losses of 0.1% of the thorium as dust in a facility were emitted continuously and dispersed from ground level by local and regional meteorological conditions (see Figure 4-1) [Voss 1982] and a standard Gaussian atmospheric dispersion computer model [Napier et al. 2004]. When resuspension is included, the daily intake rate is 0.07 pCi/d for each of ^{232}Th, ^{228}Th, and ^{228}Ra. This applies to Annex 1 for June 1943 to 1949 and to the Metallurgy Building for 1950 to April 1953. These are upper bound intake rates, so the distribution is constant [Napier 2007].

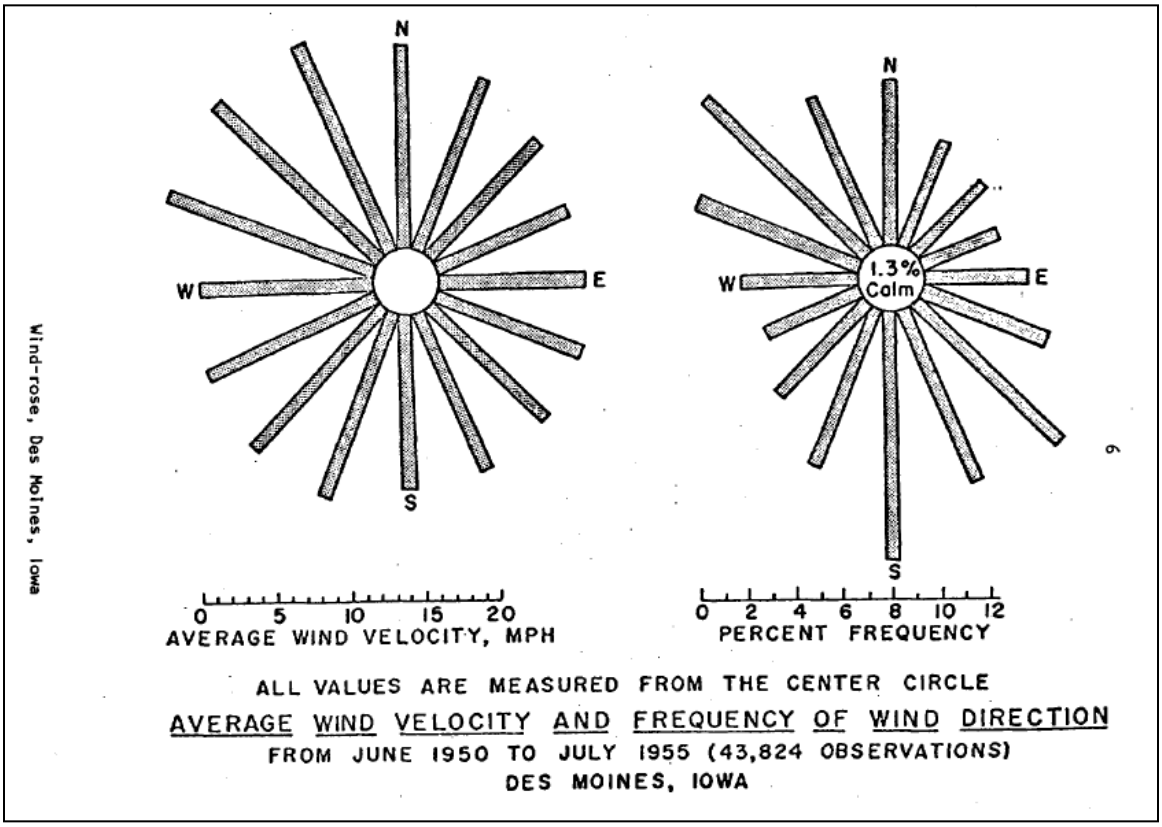

Figure 4-1. Wind rose for Des Moines, Iowa, 1950 to 1955 [Voss 1982].

4.2 SYNCHROTRON OPERATIONS, 1949 TO 1971

Synchrotron operations occurred in what is now called the Spangler Geotechnical Laboratory from 1949 to June 1971 (see Figure 2-2). Unlike the uranium and thorium facilities, this facility was fenced, which provided a defined exclusion area outside the building. Dosimeters were not provided to anyone at the facility until late 1952 [ORAUT 2006c]. There were small research amounts of radioactive materials that were generated during operations, and negligible particulate or gaseous effluents were released from the building. This information is consistent with the site profile for the Stanford Linear Accelerator Center (SLAC) [ORAUT 2007], which found that the environmental dose

from accelerator effluents was less than 1 mrem/yr and negligible. No routine measurements of direct gamma or neutron radiation were made outside the buildings, but a detailed survey of the facility, including fence line gamma dose rates, was made on May 16, 1961, during a special synchrotron operation. The results of that survey are listed in Table 4-1 [Ames 1961a, p. 8].

Table 4-1. Survey of fence line gamma dose rates around the synchrotron facility with the beam directed west.[a]

Location	Dose rate (mrem/hr)[b]
1	0.75–1
2	3.5
3	7
4	6
5	5.5
6	7
7	4.75
8	3.5
9	2.6
10	1.5
11	2
12	2
13	1.8
14	1.8
15	1.8
16	1.8
17	1.6
18	1.5
19	1.5
20	1.75
21	1.6
22	1.6
23	1.5
24	0.75–1
25	4.5

a. Source: Ames [1961a, p. 8].
b. Background reading in the beam direction (see locations 3 to 6) before turning on the beam was 0.5 to 1.0 mrem/hr.

The fence line gamma dose rates measured in the radiation survey [Ames 1961a, p. 8] were worst case and were produced with the maximum beam current on a target and direction that would produce maximum dose rates at the fence line [1]. This condition was most unusual in relation to typical research studies because it produced radiation levels in the normally occupied parts of the Synchrotron Building that were clearly hazardous to staff (tens of milliroentgen per hour) [Ames 1961a, p. 5]. Dosimeter results for synchrotron personnel verified that the machine was not operated in this condition for significant periods (during the May 16, 1961, survey or at any other time) [ORAUT 2006c].

The synchrotron was operated part time by Physics Department faculty and graduate students. The typical research schedule would have been weekdays and evenings plus occasional weekends, which was estimated at a maximum of 3,000 hr/yr. Much of this time would have been occupied with experiment setup, maintenance, system startup, etc., so the maximum operating time would have

been about 2,000 hr/yr [2]. Most of this operating time would have been dedicated to various material property studies that involved electron beams, beam currents, and targets that produced gamma fields outside the building that were at least a factor of 10 (and more likely a factor of 100) less than the survey dose rates in Ames [1961a, p. 5] [3].

A topographical map that was part of the 1961 radiation survey [Ames 1961a, p. 13] indicates the Synchrotron Building was surrounded by hills that would have protected nearby buildings from a direct beam. Therefore, the primary source of environmental exposures from this facility would have been skyshine from the synchrotron. The Waste Chemical Handling Facility (see Figure 2-2) was not built until 1980, so the area was not affected by synchrotron operations between 1949 and 1971. The ALRR (now the Applied Science Complex) was and is about 750 ft from the nearest part of the Synchrotron Building, and construction or operations at the two facilities overlapped, at a maximum, from 1962 to 1971. Skyshine from both heavy particles and photons decreases at rates equal to or greater than the reciprocal of the square of the distance ($1/r^2$) from accelerator facilities [National Council on Radiation Protection and Measurements (NCRP) 2003]. If it is conservatively assumed that all the radiation field measured in the 1961 survey was from skyshine, the dose rate at the ALRR would have been less than 0.13 mrem/hr during the worst-case operation and less than 0.013 mrem/hr during routine operations. On the main campus of the University, the dose rate would have decreased to less than about 0.00025 mrem/hr during routine operations.

It is favorable to claimants to use the environmental external dose from synchrotron operations at the ALRR for full-time exposure (2,000 hr/yr) for all locations at 25 mrem/yr for the period from 1949 to 1971.

4.3 AMES LABORATORY RESEARCH REACTOR OPERATIONS, 1965 TO 1977

The ALRR began operations in February 1965 and continued through December 1977 [Ames 1967; Voigt 1981]. The facility was and is surrounded by a fence about 700 ft from the reactor building that designates what is on and off the site (see Figures 2-2 and 4-2). From review of dosimetry records, it seems evident that all workers inside the ALRR fence were provided dosimeters. However, not all dosimetry records list names. Therefore, not all workers at the ALRR have recorded doses. In addition, environmental doses from gaseous effluents from the operating reactor were not monitored. However, environmental doses to the public from airborne releases were calculated and reported [Voss 1975, 1976, 1977]. The only air monitoring station near the reactor was on the roof of the reactor building as shown in Figure 4-3.

Environmental Monitoring at Ames Laboratory: Calendar Year 1974 was the first annual report to provide gamma spectroscopy of environmental media samples [Voss 1975]; subsequent annual reports [Voss 1976, 1977] provided similar results. The average release estimates from these reports were used to determine the estimated environmental dose to offsite workers from gaseous releases from reactor operations. From the effluent data, it was shown that the contribution to radioactivity in air from ALRR operations consisted principally of ^{41}Ar and tritium [Voss 1975, 1976, 1977]. An atmospheric dispersion model, which used annual average meteorological data for Ames and an exposure model, was used to determine external dose rates from the ^{41}Ar and inhalation intake estimates for the tritium [Napier et al. 2004; Napier 2006].

At the fence line location with the highest dose from gaseous effluents, the average annual dose to a person for the entire year (8,760 hours) was estimated to be 4.2 mrem from ^{41}Ar during the years of reactor operation. A worker at this location full time would not have been exposed for more than 2,080 hr/yr, which would result in a submersion dose of about 1 mrem/yr.

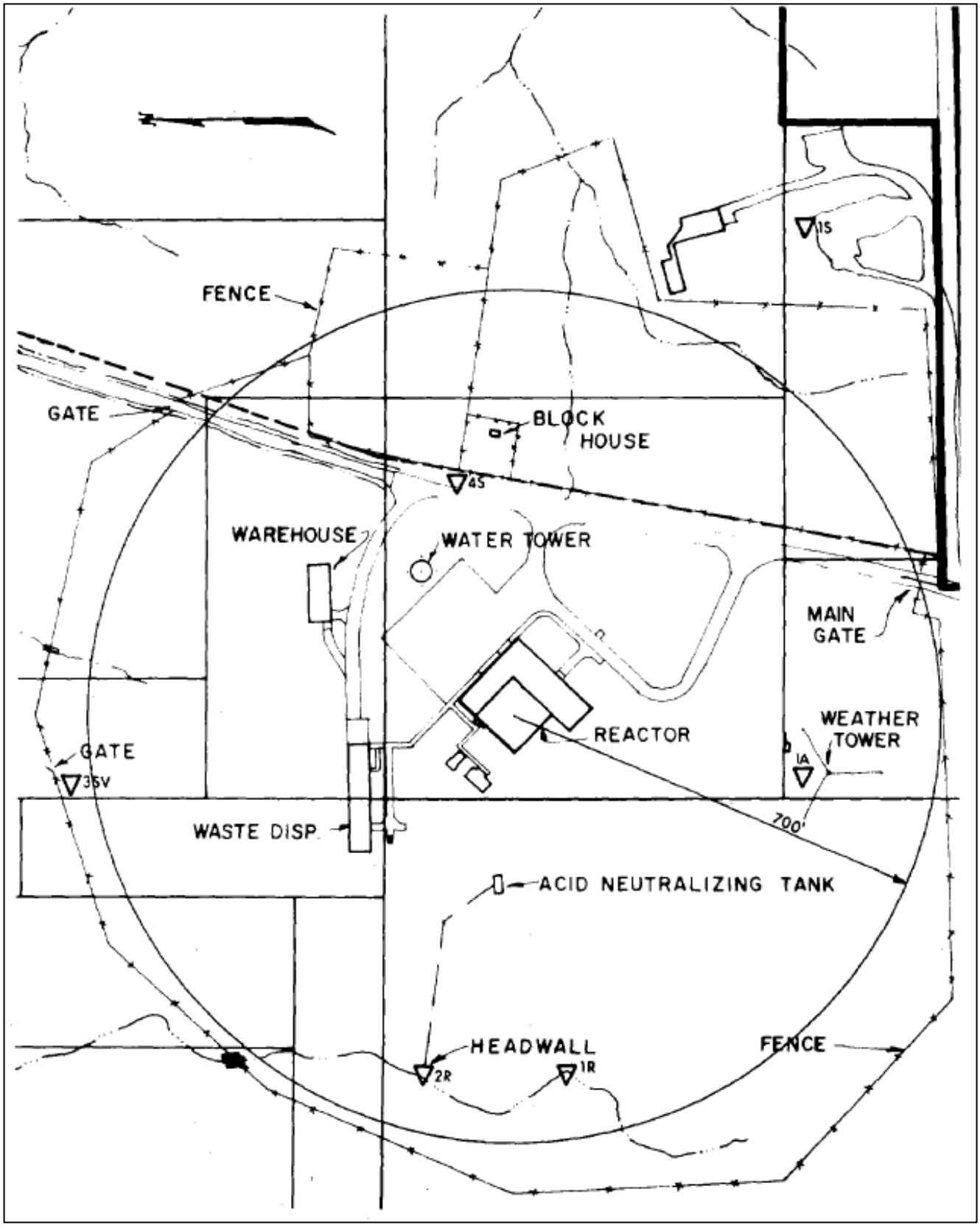

Figure 4-2. ALRR site [Voss 1979b, p. 38].

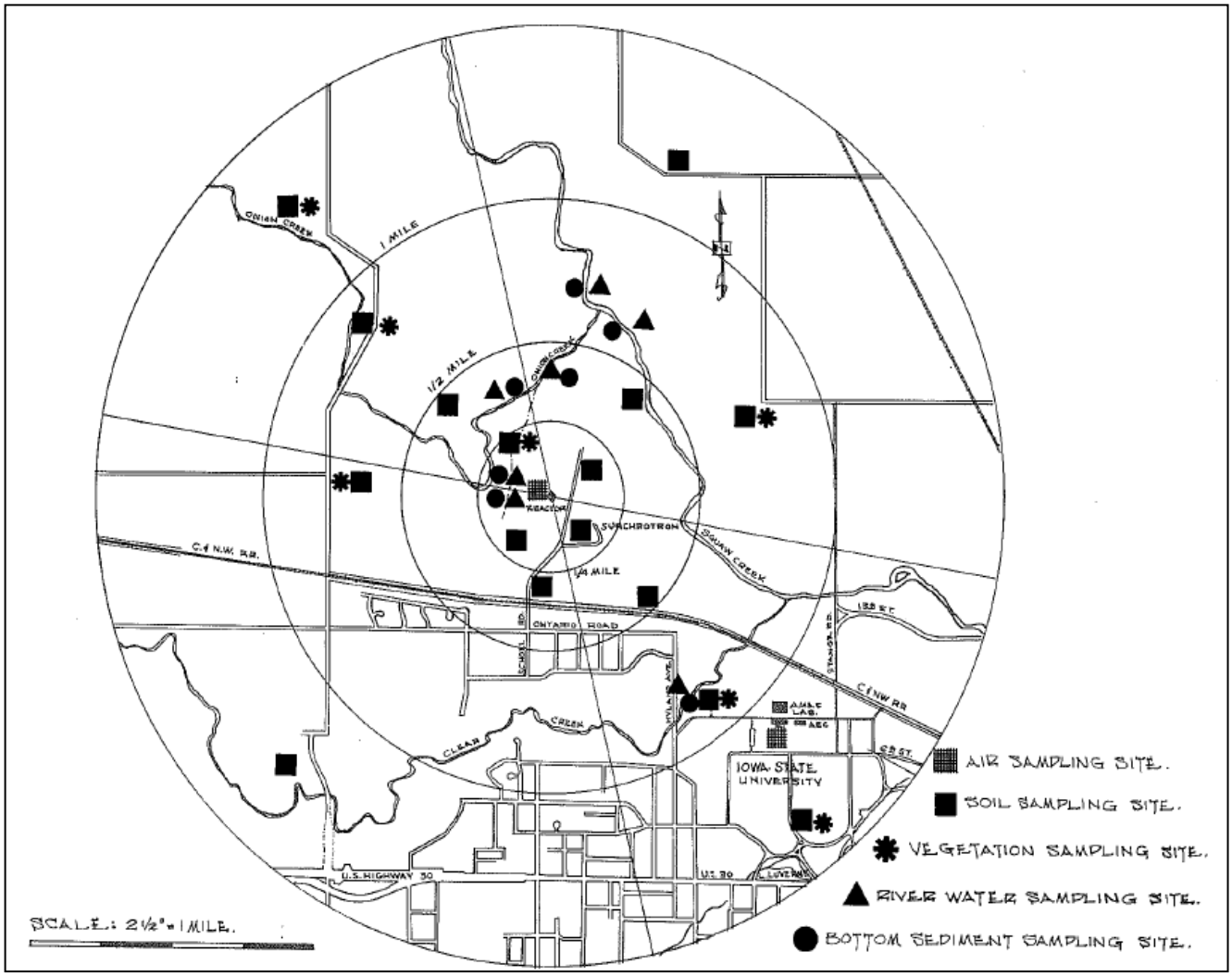

Figure 4-3. Environmental monitoring near the ALRR [Voss 1975].

At the fence line location with the highest concentration of tritium effluents, the average annual intake of tritium to a person for the entire year (8,760 hours) was estimated to be about 2.9 µCi/yr during the years of reactor operation. A worker at this location full time would not have been exposed for more than 2,080 hr/yr, which would result in an intake of tritium of about 0.7 µCi/yr or 2,700 pCi/d. This tritium intake would result in annual internal doses less than 0.001 rem and is considered negligible.

4.4 SIGNIFICANT ENVIRONMENTAL EVENT

The only significant environmental event in the history of the Ames Laboratory was the release to the environment from operations that occurred from July 1951 to August 1952 [Hayes 1956]. Metallic thorium was being produced from thorium nitrate tetrahydrate. During an early stage of the process, a filtrate with traces of thorium in the form of thorium nitrate and oxalate was released to the sewer that connected to the City of Ames sewer system. At the time disposal to the sewer was chosen, it was believed that this waste had a very low level of radioactivity. However, due to a change in feed material supplied to the laboratory, considerable quantities of mesothorium (^{228}Ra) were being discharged in the filtrate. Mesothorium is one of the progeny of thorium decay; it decays by emitting gamma rays and beta and alpha particles. All sewage was processed in a complete-treatment sewage plant, which resulted in liquid effluent and dry sludge that was used for fertilizer. The liquid effluent contained negligible quantities of mesothorium. The dry product was spread on lawns at the sewer plant, airport, municipal parkway, and a cemetery. A thorough study of the incident disclosed

that there was little hazard to the public or the workers at the sewer plant [Hayes 1956]. Table 4-2 is a summary of environmental dose measurements at the four facilities in Ames, Iowa.

An aerial survey showed doses to be lower than those measured on the ground. Occupancy factors would reduce the doses in Table 4-2 by a large fraction, making them below the current public dose limit of 100 mrem/yr as given in 10 *Code of Federal Regulations* (C.F.R.) Part 20. 10 C.F.R. 20, 2021.

Table 4-2. Environmental dose measurements at the four facilities surveyed for thorium release effects (mrem/yr).[a]

Lawn site	Maximum[b]	Average
Sewer plant	780	400
Cemetery	440	350
Airport	530	350
Parkway	530	350

a. Source: Voss [1979a].
b. Background in City of Ames and Rural Story County, Iowa were measured at approximately 75 mrem/yr. Source: Voss [1979a, p. 36].

All the locations in Table 4-2 are outside the ISU campus and accessible by the public except portions of the sewer plant. Most Ames Laboratory workers were not exposed to the radioactive materials released during this event and were not involved in responding to the event. Offsite exposures are not included as occupational environmental doses, therefore, no additional dose due to this event is recommended for occupational environmental dose for any worker.

However, the Ames Laboratory health physics staff responded to the release event and were exposed while making radiation measurements and collecting environmental samples for analysis. Any radiation exposures to the health physics staff being monitored during the incident response might have been included in their recorded occupational doses.

4.5 ENVIRONMENTAL CONTAMINATION, 1953 TO PRESENT

4.5.1 Residual Radioactivity Period Uranium Exposure

After 1953, the internal exposure potential to uranium was reduced and continued to be reduced throughout site operation. The median (50th percentile) intake rates derived in Section 5.1.3 were used to estimate surface contamination levels based on a 30-day suspension as discussed in Section 3.4.2 of Battelle-TBD-6000, *Site Profiles for Atomic Weapons Employers that Worked Uranium Metals* [NIOSH 2011b]. The contamination levels were multiplied by a resuspension factor of 1×10^{-5} m^{-1} and a breathing rate of 9.6 m^3/d to determine the following inhalation intake rates:

- Type F: 1.681 pCi/d
- Type M: 6.891 pCi/d
- Type S: 134.8 pCi/d

These intake rates are applicable for 1954. For subsequent years, a gradual reduction of the contaminants is presumed in accordance with depletion factors provided in ORAUT-OTIB-0070, *Dose Reconstruction During Residual Radioactivity Periods at Atomic Weapons Employer Facilities* [ORAUT 2012]. A depletion rate of 0.00067 per day was used to determine annual depletion factors, per guidance in ORAUT-OTIB-0070.

Table 4-3 presents the inhalation intake rates from residual radioactivity. A comparison should be made of the absorption types (F, M, S) and the intake resulting in the highest dose assigned.

Table 4-3. Uranium inhalation intake rates from residual contamination (pCi/d).[a]

Year	Type F	Type M	Type S
1954	1.68	6.89	134.8
1955	1.32	5.40	105.5
1956	1.03	4.22	82.61
1957	0.81	3.31	64.68
1958	0.63	2.59	50.67
1959	0.49	2.03	39.62
1960	0.39	1.59	31.13
1961	0.30	1.25	24.39
1962	0.24	0.97	19.00
1963	0.19	0.76	14.96
1964	0.15	0.60	11.68
1965	0.11	0.47	9.15
1966	0.089	0.37	7.17
1967	0.070	0.29	5.61
1968	0.055	0.22	4.39
1969	0.043	0.18	3.44
1970	0.034	0.14	2.70
1971	0.026	0.11	2.10
1972	0.021	0.085	1.66
1973	0.016	0.066	1.29
1974	0.013	0.052	1.01
1975	0.010	0.041	0.79
1976	0.0077	0.032	0.62
1977	0.0061	0.025	0.49
1978	0.0048	0.020	0.38
1979	0.0037	0.015	0.30
1980	0.0029	0.012	0.23
1981	0.0023	0.0094	0.18
1982	0.0018	0.0073	0.14
1983-end	0.0014	0.0057	0.11

a. Intake rates are normalized to calendar days and assigned as a lognormal distribution with a GSD of 3.

Ingestion intakes during the residual period are estimated from the derived surface contamination levels using the methods specified in OCAS-TIB-009 [NIOSH 2004]. The annual ingestion rates were then determined by multiplying the initial intake rate by the annual depletion factors per guidance in ORAUT-OTIB-0070. Ingestion intakes are provided in Table 4-4. These intakes should be assigned along with their associated inhalation values from Table 4-3.

Table 4-4. Uranium associated ingestion intake rates from residual contamination (pCi/d).[a]

Year	Type F (f1=0.02)	Type M (f1=0.02)	Type S (f1=0.002)
1954	3.5E−02	1.4E−01	2.8E+00
1955	2.7E−02	1.1E−01	2.2E+00
1956	2.1E−02	8.8E−02	1.7E+00
1957	1.7E−02	6.9E−02	1.3E+00
1958	1.3E−02	5.4E−02	1.1E+00
1959	1.0E−02	4.2E−02	8.3E−01
1960	8.1E−03	3.3E−02	6.5E−01
1961	6.3E−03	2.6E−02	5.1E−01
1962	4.9E−03	2.0E−02	4.0E−01
1963	3.9E−03	1.6E−02	3.1E−01
1964	3.0E−03	1.2E−02	2.4E−01
1965	2.4E−03	9.7E−03	1.9E−01
1966	1.9E−03	7.6E−03	1.5E−01
1967	1.5E−03	6.0E−03	1.2E−01
1968	1.1E−03	4.7E−03	9.2E−02
1969	8.9E−04	3.7E−03	7.2E−02
1970	7.0E−04	2.9E−03	5.6E−02
1971	5.5E−04	2.2E−03	4.4E−02
1972	4.3E-04	1.8E-03	3.5E-02
1973	3.4E−04	1.4E−03	2.7E−02
1974	2.6E−04	1.1E−03	2.1E−02
1975	2.1E−04	8.4E−04	1.7E−02
1976	1.6E−04	6.6E−04	1.3E−02
1977	1.3E−04	5.2E−04	1.0E−02
1978	9.9E−05	4.1E−04	7.9E−03
1979	7.7E−05	3.2E−04	6.2E−03
1980	6.1E−05	2.5E−04	4.9E−03
1981	4.8E−05	2.0E−04	3.8E−03
1982	3.7E−05	1.5E−04	3.0E−03
1983-end	2.9E−05	1.2E−04	2.3E−03

a. Intake rates are normalized to calendar days and assigned as a lognormal distribution with a GSD of 3.

4.5.2 Other Nuclides

Gamma spectral analysis of samples of environmental media did not begin until November 1974 [Ames 1974]. By that time, uranium and thorium production and scrap recovery had ceased and Annex 1 had been demolished in 1953 [Karsjen 2003]. Annex 2 operations ceased in 1953, and the building was razed in 1972 [Struss and Hawkins 1986]. Synchrotron operations ceased in 1971, and the building was decommissioned in 1990. ALRR operations ceased in 1977, and D&D was completed in 1981 [Voigt 1981]. Only R&D activities continued after 1981.

Soil samples collected at five locations around the campus in 1974 showed only ^{137}Cs in very low concentrations as listed in Table 4-5.

Table 4-5. Gamma analysis of soil samples.[a]

Site	Sample weight (g)	Cs-137 (pCi/g)[b]
1S	336	0.839
2S	332	1.100
4S	500	1.100
6S	341	0.991
7S	426	0.286
Background	336	0.294

a. Source: Voss [1975].
b. Gamma detection limit for Cs-137 in soil samples was 0.01 pCi/g.

A summary of soil samples from 24 locations around the ISU campus in 1974 for alpha and beta particle activity is given in Table 4-6.

Table 4-6. Summary of 24 soil samples for beta and alpha activity (pCi/g).[a]

Activity	Beta[b]	Alpha[c]
Average	10.56	0.61
High	13.01	0.96
Low	7.66	0.38
Background	11.9	0.76

a. Source: Voss [1975].
b. Beta detection limit was 0.25 pCi/g.
c. Alpha detection limit was 0.10 pCi/g.

These analytical results are consistent with the low doses that Ames Laboratory has reported over the years and with the policy of not monitoring workers in the environs of laboratory facilities. They are the bases for demonstrating that environmental intakes from contamination other than uranium and thorium discussed above were negligible.

4.6 SUMMARY OF ENVIRONMENTAL EXTERNAL DOSES AND INTAKES

Tables 4-7 and 4-8 summarize the conclusions of the preceding sections on environmental external doses and intakes.

Table 4-7. Environmental external doses (mrem/yr).

Location	Period	Dose[a]
Skyshine from Synchrotron Building	1949–06/1971	25
Ar-41 from ALRR	1965–1977	1

a. The energy range for all environmental external dose is assumed to be 100% 30 to 250 keV [NIOSH 2007b]. Distribution is constant. To be applied only to unmonitored workers.

Table 4-8. Summary of environmental intakes (pCi/d).[a]

Period	Radionuclide/absorption	Intake rate
08/1942–1953	U (assume U-234); type F, M or S	See Table 5-4
1954–present	U (assume U-234); type F, M, or S	See Tables 4-3 and 4-4
06/1943–04/1953	Th-232, Th-228; type M or S, Ra-228; type M	0.07[b]
05/1953–present[c]	Th-232, Th-228; type M or S, Ra-228; type M	0.0007[b,d]

a. Apply the environmental intakes in this table if no occupational intakes are applied for the same radionuclide and the same period in accordance with the Tables 5-2 and 5-3, or use the instructions in Table 5-6.
b. Distribution is constant.
c. This period was expanded to include the period after the end of thorium operations.
d. Environmental intakes during research activities and afterward were considered to be 0.01 of the intakes for the production period.

5.0 OCCUPATIONAL INTERNAL DOSE

The radionuclides of interest for internal dose at Ames Laboratory are uranium, thorium, tritium, and fission products. NIOSH has determined that internal doses from radionuclides other than uranium cannot be reconstructed for the period before 1990. Uranium can only be assessed for the period before 1971. Research using small quantities (micrograms) of plutonium in the 1940s involved methods of extraction of plutonium from up to 5 Ci of fission products in irradiated fuel, which would not have contained much plutonium [Fulmer 1947]. There is no indication of research that involved sufficient plutonium such that exposure to residual plutonium after 1989 would have been significant.

Similarly, internal exposures from mixed fission or activation products from the ALRR would not have been significant after operations ceased and the facilities were decommissioned. Tritium exposure from the ALRR operations is addressed in this section and can be assessed when bioassay results are provided for a worker.

Residual thorium contamination is addressed to assess the residual exposures beginning in 1990.

5.1 URANIUM EXPOSURE

Few data on uranium exposure were found; uranium bioassay data from 1944 and 1945 were collected for a study on the urinary excretion of uranium at some Manhattan Project sites [Ferretti et al., no date]. The evaluation report for SEC-00038 [NIOSH 2006] considered the bioassay data to be useful for estimating intakes. If uranium bioassay data are available for an individual worker, they should be used for dose reconstruction. For all other workers in all uranium facilities at Ames (Chemistry Building, Physical Chemistry Annex 1, and Physical Chemistry Annex 2) the data from Tables 7.1 to 7.4 in Ferretti et al. [no date] were used to estimate intakes from uranium production operations.

5.1.1 Analysis of Uranium Bioassay Data

The data in Ferretti et al. [no date] reported 67 sample results from 48 workers who were ranked by their supervisor into four exposure categories according to potential for exposure to uranium. The bioassay data are presented in Table 5-1.

Table 5-1. Ames uranium worker bioassay data (µg/L).[a]

Group	Sample	Case	Concentration
1	1	1	40
1	2	1	96

Group	Sample	Case	Concentration
1	3	2	52
1	4	3	86
1	5	3	50
1	6	4	100
1	7	4	44
1	8	4	70
1	9	4	200
1	10	5	126
1	11	5	96
1	12	5	74
1	13	6	84
1	14	6	200
1	15	6	73
1	16	7	48
1	17	7	40
1	18	8	29
1	19	9	25
1	20	10	12
1	21	11	31
2	1	12	15
2	2	13	17
2	3	14	13
2	4	15	38
2	5	16	21
2	6	17	40
2	7	18	21
2	8	19	33
2	9	19	58
2	10	20	33
2	11	21	54
2	12	22	64
2	13	23	10
2	14	23	16
2	15	24	11
2	16	24	11
2	17	25	87
2	18	25	64
2	19	25	80
2	20	26	130
2	21	27	80
2	22	28	108
2	23	29	64
2	24	29	64
2	25	30	28
2	26	31	43
3	1	32	24
3	2	33	27
3	3	34	7
3	4	35	9
3	5	36	19
3	6	37	22
3	7	38	22
3	8	38	18
3	9	38	3
3	10	38	3

Group	Sample	Case	Concentration
3	11	39	5
3	12	40	18
3	13	41	15
3	14	42	33
4	1	43	<3
4	2	44	<3
4	3	45	7
4	4	46	<3
4	5	47	<3
4	6	48	9

a. Source: Ferretti et al. [no date].

Group 1 was expected to be the highest (greatest amount of uranium exposure); Group 2 (next highest amount of uranium exposure); Group 3 (very little, but continuous exposure); and Group 4, the lowest exposure (occasional incidental exposure). The workers were given strict instructions to avoid sample contamination. Samples were submitted between September 1944 and July 1945 [Ferretti et al., no date].

Bioassay sample dates were not provided; however, the data reflect that some individuals were sampled more than once at intervals of a few weeks or months. For this analysis, all unique combinations of individual (Case) and group (Group) are considered unique individuals. If an individual has more than one result, a mean was calculated, thereby having one result for each individual. A one person–one statistic (OPOS) approach was performed as described in ORAUT-RPRT-0053, *Analysis of Stratified Coworker Datasets* [ORAUT 2014]. A regression on order statistics fit to the OPOS data was performed and provided a geometric mean (GM) of 24.69 µg/L and a GSD of 2.788. From these parameters:

The 50th-percentile bioassay result is estimated by:

$$50\text{th percentile} = GM \times 1.4 \text{ L/d} \quad (5\text{-}1)$$

giving

$$24.69 \text{ µg/L} \times 1.4 \text{ L/d} = 34.57 \text{ µg/d} \quad (5\text{-}2)$$

These data were evaluated with the Integrated Modules for Bioassay Analysis (IMBA) to obtain uranium intake rates for calculation of internal doses to workers. The following parameters were used:

- Start of chronic intake is September 1, 1942 (substantial production of uranium metal began in September 1942 at Ames).
- Date of the urine sample is January 31, 1945, which is midway between September 1, 1944, and July 1, 1945 (date range in Ferretti et al., no date] for bioassay samples).
- The chronic intake continues to the effective sample date of January 31, 1945.
- The specific activity of natural uranium (0.68296 pCi/µg) was used to convert the mass intake rates to activity intake rates.
- Based on process information, it is presumed that workers could have been exposed to absorption types F, M, or S materials.

The 50th-percentile intake rates are:

- Type F. 86.46 pCi/d
- Type M. 354.5 pCi/d
- Type S. 6,932 pCi/d

5.1.2 Worker Exposure Categories

In accordance with ORAUT-OTIB-0060, *Internal Dose Reconstruction* [ORAUT 2018]: "Coworker dose is applied as a best estimate for individuals with a potential for intakes of radioactive material but who lack bioassay data or have unmonitored intervals. Data can be lacking because it was not available from the site or because monitoring was not performed. Typically, workers with a significant potential for intake should be assigned doses at the 95th percentile with a constant distribution, while those with less potential should be assigned the 50th percentile with a lognormal distribution." ORAUT-OTIB-0014, *Assignment of Environmental Internal Doses for Employees Not Exposed to Airborne Radionuclides in the Workplace*, provides guidance on job categories and potential for exposure [ORAUT 2004].

Dose reconstructors should use the information from these references and the category information below to assign intakes to Ames workers:

- High (assign 95th-percentile intakes). Individuals who operated process equipment or routinely handled radiological materials. This category includes operators, maintenance workers, laboratory workers, health physics monitors, etc. Doses should be applied as a constant.
- Medium (assign 50th-percentile intakes). Individuals who routinely worked in production areas and may have been periodically present when processing occurred. This includes supervisory staff, engineers, and individuals not normally in contact with the radiological materials. Doses should be applied as a lognormal distribution.
- Low. Individuals exposed to ambient air in the environment outside of uranium production areas as well as incidentally exposed to uranium work areas. This includes office workers or nonuranium workers documented to have been in a different location from the uranium work. These intakes allow for incidental exposures and should be applied as a constant. The rationale for this value is provided below.

As discussed above, uranium bioassay data are available for 48 workers involved in uranium production in 1944 and 1945. The supervisor listed six of these as Group 4 workers thought to have only incidental occasional exposure to uranium. The distribution of the bioassay results for the four groups are consistent with those rankings, with some overlapping of the range of results. Of the six workers in the Group 4 category, four had a bioassay result of <3 µg/L, one had a result of 7 µg/L, and one had a result of 9 µg/L.

The Group 4 workers presumably would have been exposed to both ambient air outside the production facilities and occasional incidental exposure to uranium work areas. Therefore, the highest result from that group of workers should provide a bounding estimate for workers in other (nonuranium) facilities or locations. Dose reconstructors should use an intake rate derived from this value for the Low intake category and apply it as a constant.

5.1.3 Intake Calculations

Intakes are provided for the High, Medium, and Low exposure categories.

High Exposure Category
This category is the 95th percentile of the intake distribution and is applied as a constant value in the Interactive RadioEpidemiological Program (IREP). Using ORAUT-OTIB-0060, the GSD was rounded up to 3.0. The 95th-percentile intakes are derived from the 50th-percentile (GM) intakes given above with the GSD rounded up to 3.0, according to the equation:

$$95th\ percentile = GM \times GSD^{1.645} \quad (5\text{-}3)$$

where

$GSD = 3.0$

The 95th-percentile intake rates are then:

- Type F. 526.9 pCi/d
- Type M. 2160 pCi/d
- Type S. 42,240 pCi/d

Medium Exposure Category
This category consists of the 50th-percentile intake values in Section 5.1.1 applied as a lognormal distribution with the GSD rounded up to 3.0. The intake rates are:

- Type F. 86.46 pCi/d
- Type M. 354.5 pCi/d
- Type S. 6932 pCi/d

Low Exposure Category
This category is based on an excretion rate of 9 µg/L with the parameters discussed in Section 5.1.1. Those values were input into IMBA to determine the following intake rates:

- Type F. 31.52 pCi/d
- Type M. 129.2 pCi/d
- Type S. 2525 pCi/d

5.1.4 Assignment of Internal Exposures

The intakes were derived from bioassay during the uranium production period. Uranium production activities in Annex 1 and Annex 2 ended in 1945. Production work in the Chemistry Building ended in 1943. There were continuing activities in all three buildings after 1945.

Records of decontamination activities for the Chemistry Building are currently unavailable, but records for later years indicate the building was remodeled.

Thorium production continued at Annex 1 for a few years after 1945. No decontamination information is available. The facility was demolished in 1953; no radiological monitoring data are available from the demolition work.

The use of Annex 2 after 1945 is not clear and it is not known if or when the facility was decontaminated. However, the AEC sold Annex 2 to ISU in 1953; it was used as a plumbing shop until it was razed in 1972.

To allow for potential intakes of uranium after 1945, the production era intake rates should be applied through 1953 for the Chemistry Building, Annex 1, and Annex 2.

Workers at the uranium production facilities could have been exposed to uranium with absorption types of F, M, and S. Dose reconstructors should select the material type that provides the highest dose. These calculated intake rates presume that the period of the bioassay results included normal uranium production operations, including blowout and fire events.

Tables 5-2, 5-3, and 5-4 show the inhalation intake rates for the three absorption types. All intakes are per calendar day.

Table 5-2. High exposure potential inhalation intake rates for ^{234}U (pCi/d).[a]

Nuclide	Absorption type	Intake type	Intake rate	Distribution
U-234	F	Inhalation	526.9	Constant
U-234	M	Inhalation	2,160	Constant
U-234	S	Inhalation	42,240	Constant

a. These are based on the 95th percentile and should be assigned as a constant distribution from August 1, 1942, to December 31, 1953.

Table 5-3. Medium exposure potential inhalation intake rates for ^{234}U (pCi/d).[a]

Nuclide	Absorption type	Intake type	Intake rate	Distribution	GSD
U-234	F	Inhalation	86.46	Lognormal	3.0
U-234	M	Inhalation	354.5	Lognormal	3.0
U-234	S	Inhalation	6,932	Lognormal	3.0

a. Based on the 50th percentile and should be assigned as a lognormal distribution with GSD of 3.0 from August 1, 1942, to December 31, 1953.

Table 5-4. Low exposure potential inhalation intake rates for ^{234}U (pCi/d).[a,b]

Nuclide	Absorption type	Intake type	Intake rate[a]	Distribution
U-234	F	Inhalation	31.52	Constant
U-234	M	Inhalation	129.2	Constant
U-234	S	Inhalation	2,525	Constant

a. This is environmental exposure; see Section 4.1.
b. Based on the maximum Group 4 category bioassay result and should be assigned as a constant distribution from August 1, 1942, to December 31, 1953 (see Section 4.5.1 for explanation).

5.2 THORIUM EXPOSURE FROM RESIDUAL CONTAMINATION

According to the feasibility table in Section 1.3, dose reconstruction is not feasible for nuclides other than uranium before December 31, 1989. This section provides a method for estimating internal exposures to thorium and thoron after 1989.

The Metallurgy Building (Wilhelm Hall), the location of the main activities with thorium, is still in use. Therefore, a method to estimate internal exposures from thorium is provided for workers in this building after 1989.

In March 1952, a study was performed in Wilhelm Hall to identify health and safety issues that were occurring during refining and thorium metal production. The results of the study are in *Ames Research Laboratory Occupational Exposure to Thorium and Beryllium* [Klevin 1952]. Starting in 1984 and continuing to the early 1990s, surveys were conducted in Wilhelm Hall to determine locations of contamination left from the early production years [Hokel et al. 1998]. The following discussion using data from Hokel et al. and Klevin provides an estimate for intakes from 1990 to 2010. A summary of the air concentrations and daily inhalation and ingestion intakes is provided in Table 5-5.

All the data in Hokel et al. [1998] were reviewed and considered. Much of the data was related to locations that were hard to access and considered not to be an inhalation issue. The accessible areas of the building, including rooms, air ducts, hallways, stairwells, transformer rooms, etc., were surveyed starting in 1984. One data set had floor surveys made in 1988, but the locations all had fixed activity, which would not pose an airborne hazard (see Appendix 6 of Hokel et al. 1998). The data in Hokel et al. present an overview of the survey results. In 1996, some measurements were made using an alpha continuous air monitor in the subbasement pipe tunnels and in large vertical void spaces in the stairwells. All results were less than background for thorium, thoron, or radon [Hokel et al. 1998]. Therefore, the results used for this estimation are from a pipe tunnel survey that showed removable contamination on smears ranging from background (3 dpm) to 1,224 dpm. These numbers are considered high for generally accessible areas. Although other survey numbers in the report with removable contamination are higher, they are in inaccessible locations (in a drain line), hard to reach (inside a drawer), or small (edge of a sink), or the contamination was fixed.

Hokel et al. [1998] stated that the thorium in Wilhelm Hall is in equilibrium. For estimating dose to individuals working in Wilhelm Hall from 1990 to 2010, an intake estimate favorable to claimants would be as follows.

A removable surface concentration of 2,000 dpm/100 cm^2 of thorium in equilibrium with its progeny was assumed [4]. This means the ^{232}Th activity was approximately 200 dpm/100 cm^2. Applying a resuspension factor of 10^{-4} [5]:

$$A = \left(200\,\text{dpm}/100\,\text{cm}^2\right)\left(10^{-4}/\text{m}\right)\left(100 \times 100\,\text{cm}^2/\text{m}^2\right) = 2\ \text{dpm}/\text{m}^3 \qquad (5\text{-}4)$$

where

A = ^{232}Th air concentration

The value of 2 dpm/m^3 on November 15, 1995, when the survey of the pipe tunnel occurred, represents an upper bound.

To estimate residual air concentrations for other years, a single exponential decay of “available” activity over time in a facility was used. This applies to a facility in which the contamination is mostly undisturbed but undergoes some weathering or occasional cleaning such as minor moving of equipment or workbenches followed by cleaning.

Table 5-5. Daily intakes of ^{232}Th at Wilhelm Hall, 1990 to 2010 (pCi/d).[a,b,c]

Year	Inhalation intake rate	Ingestion intake rate
1990	12.2	11.4
1991	10.7	9.97
1992	9.34	8.72
1993	8.17	7.62
1994	7.14	6.67
1995	6.25	5.83
1996	5.47	5.10
1997	4.78	4.46
1998	4.18	3.90
1999	3.66	3.41
2000	3.20	2.99
2001	2.80	2.61
2002	2.45	2.28
2003	2.14	2.00
2004	1.87	1.75
2005	1.64	1.53
2006	1.43	1.34
2007	1.25	1.17
2008	1.10	1.02
2009	0.96	0.894
2010	0.84	0.782

a. Source: ORAUT [2023]. Distribution is constant.
b. Per the feasibility table in Section 1.3, exposures to nuclides other than uranium are not included before 12/31/1989. Therefore, thorium intakes are presented beginning in 1990.
c. Dose reconstructors should assign the 2010 value for employment years after 2010.

Klevin [1952] did a thorough survey during operations, including breathing-zone task-specific air concentrations, time-weighted air concentrations for various workers, and general room air concentrations. Because survey information in the building just after cessation of the thorium operations was not available, the Klevin data were used to represent air concentrations in 1955 with the caveats provided below:

- The Klevin air concentrations for specific tasks during production and the time-weighted averages are not relevant for Wilhelm Hall after 1954. The general room concentrations would probably be a bit high but reasonably representative when applied to long-term chronic intakes for people not actually performing tasks with thorium. These can be assumed to represent air concentrations in 1955.

- The general air concentrations included one room that was 10 times higher than all the others and the lunchroom. The highest room was clearly related to operations so that datum was excluded, as was the lunchroom, which was assumed not to be contaminated (the result was zero). With these results removed, the geometric mean of the distribution was 7.9 dpm/m^3 and the 95th percentile was 479 dpm/m^3.

Because the 2 dpm/m^3 from Hokel et al. [1998] represented an upper bound, this value is compared with the 479 dpm/m^3 value. With 479 as A_0 and 2 as $A(t)$ and assuming t is from January 1, 1955, to November 15, 1995, for a total of 14,928 days:

$$A(t) = A_0 \exp(-\lambda t) \quad (5\text{-}5)$$

where

λ = 3.67×10^{-4}/d or 0.134/yr
t = exposure time (d)

$A(t)$ was solved for the midpoint of each year from 1995 to 2010. The air concentration was converted to intake using:

$$I\left(\text{pCi/d}\right) = A\left(\text{dpm/m}^3\right)\left(1\ \text{pCi/2.22 dpm}\right)\left(1.2\ \text{m}^3\text{/hr}\right)\left(\frac{2{,}000\ \text{hr/yr}}{365\ \text{d/yr}}\right) \quad (5\text{-}6)$$

where

I = the daily intake rate
A = the air concentration

The estimates in Table 5-5 for ^{232}Th assume an occupancy factor of 1 (100% for a working year). This is an upper bound (constant) estimate for thorium intakes for individuals who worked in accessible areas in Wilhelm Hall from January 1990 to 2010.

The dose reconstructor should include equal intakes of ^{228}Ra and ^{228}Th to account for the progeny radionuclides [6].

The associated ingestion intake for the start of the residual period would be:

$$I_{Ing} = \left(S \div F\right) \times R \times O \quad (5\text{-}7)$$

where

S = ^{232}Th surface contamination level on November 15, 1995, i.e. 200 dpm/100 cm^2
F = fraction of the source term on November 15, 1995, i.e. Equation 5-5 above, with (t) = 14,928 d
R = ingestion rate [Biwer 2002], 1.12E-04 m^2/hour
O = occupancy, 2,000 hr/yr

This resulted in an initial ingestion rate at the start of the residual period, i.e. 01/01/1955, of 1,324 pCi/calendar day. Since thorium exposures cannot be applied before December 31, 1989, Equation 5-5 was used to calculate the residual ingestion intake rates, starting in 1990 (i.e. 35 years after 1955), and beyond. The daily ingestion intakes are listed in Table 5-5.

Workers occasionally entered areas with higher concentrations under radiation work permits to perform maintenance or remodeling. However, the spotty contamination in these areas was about 10 to 100 times greater than the value used in the calculation above [7]. Based on the rarity of exposure and the radiation protection measures used (including respiratory protection), the impacts from these possible acute intakes would have been adequately accounted for by the chronic intake scenario represented in Table 5-5 [8].

5.3 TRITIUM EXPOSURE

According to the feasibility table in Section 1.3, dose reconstruction is not feasible for nuclides other than uranium before December 31, 1989. This section provides a method to use, however, to estimate internal exposures due to tritium after 1989. Additionally, as stated in Section 1.3, monitoring

data can be used for individual claims to assess exposure. Therefore, this section provides a method to assess internal exposures due to tritium for monitored workers. The ALRR, a 5-MW, heavy water moderated research reactor, operated from February 1965 to December 1977. Decommissioning was completed in 1981. See Section 2.1.10 for more information on reactor operations. Because of the operation of the reactor, tritium is the primary radionuclide that must be considered for internal dose. No other radionuclides were considered internal dose hazards from the operation of the reactor. A routine bioassay program was established in 1965; bioassay data for workers were collected and recorded through at least 1981 while the reactor was being decontaminated and decommissioned [Voss 1971].

5.3.1 Tritium Exposure for Monitored Workers, 1965 to 1981

Several reports addressed tritium dose assessment. Highlights of those reports are given here and referenced for further study by the dose reconstructor.

Program for Monitoring Personnel for Tritium, Sources of Tritium at the Ames Laboratory describes potential sources of tritium exposure to laboratory personnel [Voss 1971].

In addition to the reactor, Ames Laboratory had a Texas Nuclear Model 9900 neutron generator, which was a potential source of exposure to tritium. The neutron generator used tritium targets with activities ranging from 5 to 10 Ci. The tritium, which was slowly released from the target, was documented as a potential airborne contaminant. Other possible sources of tritium were spent targets from the neutron generator, tritium gas in cylinders, and tritiated compounds that would have been present occasionally [Voss 1971].

Voss [1971] is summarized here to help understand dose records that might be in a worker's files. It stated that workers and other personnel who were part of the tritium monitoring program included:

1. Reactor operators (monthly samples),

2. Reactor operators involved in specific operations that were likely to cause tritium exposures (sampled during and after the operation),

3. Other reactor personnel and other personnel assigned to work at the reactor (provide samples semiannually for routine checks on tritium uptake),

4. Personnel described in Item 3 who were involved in operations in which tritium exposure conditions existed (sampled during and after the operation),

5. Other personnel under conditions of potential tritium exposure (monitored based on their work with sources of tritium),

6. All personnel who showed tritium concentration greater than 1,500 dpm/mL of urine were resampled weekly until the detected activity level was below 1,500 dpm/mL,

7. Samples were taken at the termination of workers assigned to areas where monitoring for tritium was required, and

8. As a check and control, termination samples were taken from other workers (it is not clear if it was all personnel or just some personnel).

Voss [1971] stated that liquid scintillation counting was used for tritium bioassay analysis.

Assumptions described in Voss [1971] for radiation dose determination were:

1. The concentration of tritium was the same in all body water. Urine samples were used as representative of all body water in terms of tritium activity levels. The radiation dose was for the whole body.

2. The radiation dose was due to tritium as tritiated water; other compounds of tritium and other organ configurations are not included. Except in unusual circumstances, tritiated water was the expected source of exposure. Therefore, body water was the critical organ.

3. For calculation and derivation consistency, the mass of body water was taken as 43 kg (standard man value).

4. The effective half-life for dose determination could vary. The actual half-life from the data points was used up to a half-life of 15 days. If the half-life could not be determined from the data, a value of 12 days was used. Data points that showed a half-life greater than 15 days were treated as additional separate exposures.

5. The quality factor was 1, the effective absorbed energy per disintegration was 0.006 MeV, and the half-life of tritium was 12.26 years (4.48×10^3 days).

Other considerations for dose assignment that were discussed in Voss [1971] are:

1. The dose assignment system had two separate conditions of radiation dose delivery to the body: (1) the dose delivered by the uptake of tritium from time $t = 0$ until complete decay-removal ($t = \infty$) (additional uptakes might occur during the decay removal of the preceding uptakes) and (2) the dose that would be delivered by maintenance of a fixed level of tritium in the body.

2. For anyone with a bioassay sample greater than 1,500 dpm/mL in urine, sampling continued until the urine sample level was less than 1,500 dpm/mL.

3. For any person on the routine and incident monitoring program, a basic dose assignment was made. This basic dose was associated with the maintenance of a level of 750 dpm/mL of urine, which was equal to 38 mrem/yr whole body based on the methodology used at the time.

4. For single or multiple exposures, the dose assessment was made based on the effective half-life applicable to the individual's data. The dose contribution from the incident exposure that would appear in the basic dose assignment was subtracted from the basic dose assignment.

5. The final reported dose was that due from an incident exposure plus the residual dose from the basic dose assignment. In summary, a person on the tritium monitoring program was assigned a basic radiation dose of 38 mrem/yr (prorated for a fraction of a year) to which was added the adjusted radiation dose contribution from all other exposures received during the year.

Several other documents discussed tritium dose assessment, but they are similar to the information provided above. *Personnel Monitoring Program* provides the tritium dose calculation procedures used at the time [Ames 1974].

Personnel in the tritium monitoring program should have bioassay and dose records. Tritium bioassay records were found for 1965 to 1981, although those for 1965 to 1968 appear to be incomplete.

Figures 5-1 and 5-2 show examples of what a bioassay record in a worker's file might look like. The data in this record include:

1. The year being reported.

2. The badge number of the individual. (Note: It appears that an individual would retain the same badge number during employment but, once they terminated, that badge number would be reassigned to a new worker.)

3. The name of the individual.

4. Dates during the reporting period for which monitoring for incidents was performed; the result was in "DPM." It is assumed that incidents occurred during planned operations and that sampling was based on potential for intake.

5. Date that individual was employed.

6. The individual's dose before January 1 of the year for the record.

7. If the person has terminated, the termination date.

8. The four quarters for the year. The example in Figure 5-1 is for the third quarter and shows the dose for quarter 3. The example in Figure 5-2 is for the second quarter and shows the dose for quarter 2. The dose would be added and the total for the year calculated. It can be assumed that "0.00" means the worker was not monitored, and not necessarily that there was no dose.

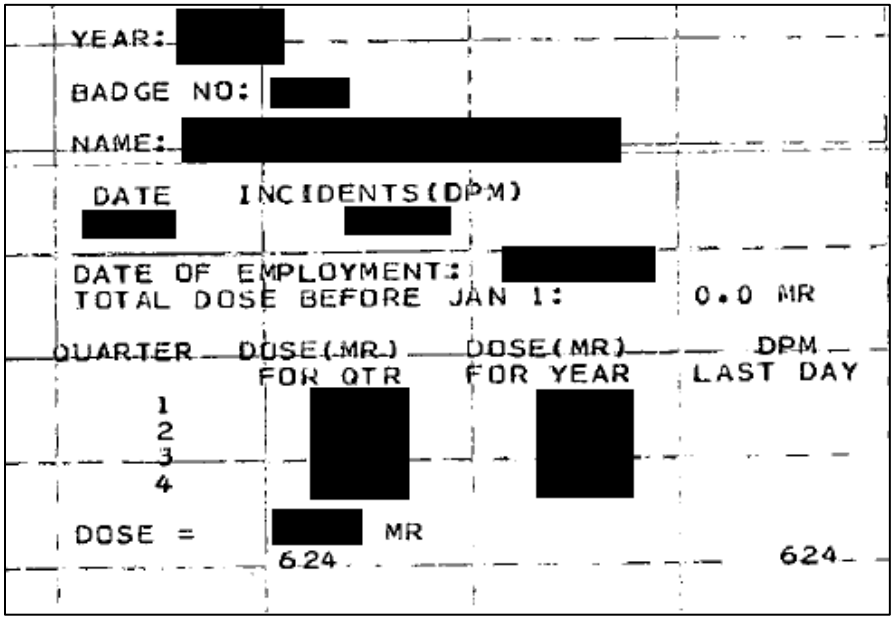

Figure 5-1. Bioassay record example 1 [Ames 1977, p. 74].

Documents from the early 1970s indicate that a person in the tritium monitoring program would have been assigned a default radiation dose of 38 mrem/yr (or prorated for the time monitored during the year); however, a review of the available dose records indicated that the policy to assign a 38-mrem/yr dose to everyone on the tritium program was not always followed [Voss 1971; Ames 1974].

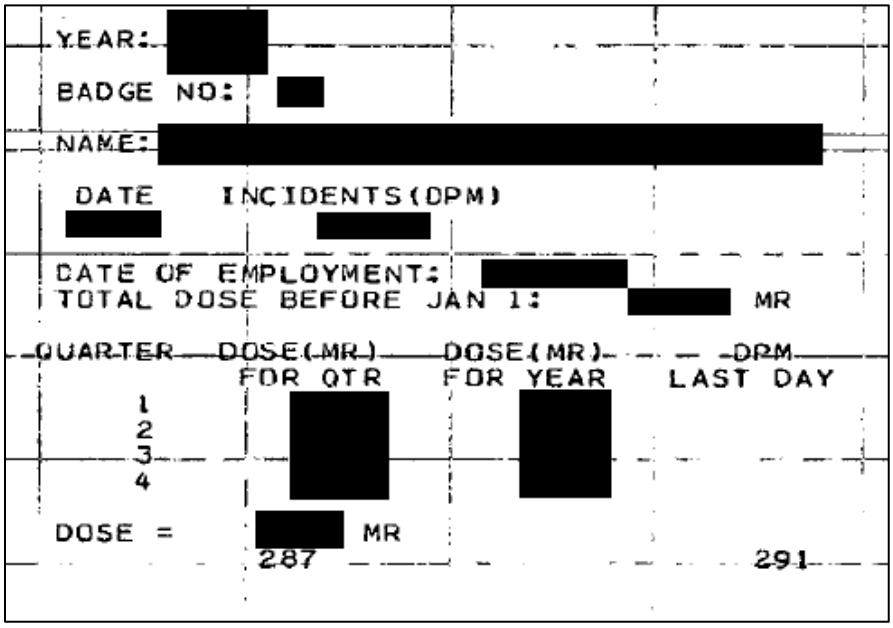

Figure 5-2. Bioassay record example 2 [Ames 1977, p. 36].

No information was found that indicated the analysis method or the minimum detectable amount (MDA); therefore, it is recommended that 0.1 µCi/L (220 dpm/mL) be used as the MDA. This is a reasonable assumption in comparison with MDAs at other sites during this period and is consistent with the way the data were recorded [9].

5.3.2 Tritium Dose to Workers, 1990 to Present

An interoffice memorandum dated May 8, 1987, addresses radiation dose at the Applied Science Center (inhalation exposure from tritium as tritiated water vapor in air resulting from deposition during reactor operations) [Voss 1987]. The memorandum addresses the methodology for estimation of dose to an individual in the reactor room assuming 100% occupancy without forced ventilation based on the standard man inhalation rates in Bureau of Radiological Health (BRH) [1970]. There is also an estimate for a maximum dose of 5.8 mrem/yr to an individual in the pump room. In a letter dated May 27, 1987, R.G. Struss, Associate Director for Operations, Ames Laboratory, discussed another estimate for airborne tritium concentrations that indicated an exposure potential of 8.6 mrem/yr in the reactor pump room for a 40-hr workweek [Struss 1987].

The dose reconstructor should assign a dose of 8.6 mrem/yr for personnel working in the Applied Science Center if no bioassay data are available. According to the feasibility table in Section 1.3, dose reconstruction is not feasible for nuclides other than uranium before December 31, 1989. Therefore, tritium exposures are assigned beginning in 1990.

5.4 FISSION PRODUCT INTAKES

5.4.1 Fission Product Intakes from Early Fuel Research

As described in Section 2.1.2, a hot laboratory was operated in the Chemistry Building; it was replaced in 1951 by a hot canyon/hot cell in the Research Building. In the 1940s, the hot laboratory was used to study extraction of plutonium from irradiated uranium by ion exchange columns [Fulmer 1947].

According to the feasibility table in Section 1.3, dose reconstruction is not feasible for nuclides other than uranium before December 31, 1989. Therefore, fission product intakes cannot be estimated from these operations.

5.4.2 Fission Product Intakes from Research Reactor Operations and Decontamination and Decommissioning

No evidence was found during review of any of the Ames Laboratory documents that bioassay was performed or considered necessary for radionuclides other than tritium for the ALRR. Review of *Decommissioning of the Ames Laboratory Research Reactor* indicated that there was a negligible amount of fission products in the building after shutdown [Voigt 1981]. This indicates that there was probably a negligible amount of fission products released during reactor operations. Therefore, accounting for internal dose from reactor operations is not necessary.

During D&D operations, radiation protection appeared to be acceptable for the time and external exposure and internal exposure for tritium were tracked [Voigt 1981]. No evidence exists that bioassay for other radionuclides was performed. However, during D&D of the reactor, which included dismantlement, cutting, grinding, etc., some intakes from activation products probably occurred.

According to the feasibility table in Section 1.3, dose reconstruction is not feasible for nuclides other than uranium before December 31, 1989. Therefore, fission product intakes cannot be estimated from these activities.

5.5 SUMMARY OF INTERNAL DOSE RECOMMENDATIONS

Default occupational intakes for workers without the applicable bioassay data are summarized in Table 5-6.

Table 5-6. Dose calculation and IREP input parameters for default intakes (if no bioassay results are available).

Job category or task/building	Period	Material	Mode	Absorption type or f_1	Intake rate (pCi/d)	IREP Parameter 1
All workers in Chemistry Building, Annex 1, Annex 2	08/1942–12/1953	Natural uranium	Chronic inhalation	F, M, or S	See Tables 5-2 and 5-3	Dose
Anyone routinely in Wilhelm Hall (Metallurgy Building)	1990–present	Th-232	Chronic inhalation	M or S	See Table 5-5	Dose
Anyone routinely in Wilhelm Hall	1990–present	Th-232	Chronic ingestion	5E-4 with M; 2E-4 with S	See Table 5-5	Dose
Anyone routinely in Wilhelm Hall	1990–present	Ra-228	Chronic inhalation	M	See Table 5-5	Dose
Anyone routinely in Wilhelm Hall	1990–present	Ra-228	Chronic ingestion	0.2	See Table 5-5	Dose
Anyone routinely in Wilhelm Hall	1990–present	Th-228	Chronic inhalation	M or S	See Table 5-5	Dose
Anyone routinely in Wilhelm Hall	1990–present	Th-228	Chronic ingestion	5E–4 with M; 2E–4 with S	See Table 5-5	Dose
Anyone routinely in Applied Science Center	1990–present	Tritium	Total of all modes	Not applicable	Not applicable	8.6 mrem/yr [a]

a. IREP distribution is constant.

6.0 OCCUPATIONAL EXTERNAL DOSE

Workers at Ames Laboratory received external radiation doses between 1942 and 1952 that were largely unmonitored [10]. Pocket chambers were available that might have been used to monitor external doses, but very few records could be found [11]. External exposures since 1953 have been monitored with film badges and thermoluminescent dosimeters (TLDs), and the records are essentially complete. However, there were extensive periods (1965 to 1981) when individual names were not recorded with dosimeter numbers, and many records cannot be clearly associated with individual workers [12]. For cases in which the individual's name is clearly associated with dosimetry records and the records are essentially complete, these individuals are considered monitored workers. For all other cases in which the records are unidentified or partially complete, the individuals are considered unmonitored workers for the missing or incomplete periods. External doses received since 1982 have been reliably recorded for each individual. Details of the external dosimetry program are addressed in this section.

6.1 INTRODUCTION

Ames Laboratory responses to DOL requests for claimant records were limited to raw data from dosimetry files. Not all these files had been summarized for annual total doses for individuals and the files for some individuals were incomplete as noted above. To assist dose reconstructors in determining annual doses for claimants, the raw data were entered into spreadsheets and summarized to give annual totals for identified individuals; the spreadsheet data were analyzed to give 50th- and 95th-percentile values that could be applied to unidentified (unmonitored) individuals [ORAUT 2006c].

Dose reconstructors should have access to dosimetry records from Ames Laboratory for each claimant, but the records might be incomplete and difficult to use. The spreadsheets assembled by ORAUT [2006c] should be used if there is any doubt about completeness.

According to the feasibility table in Section 1.3, external dose can be adequately estimated for unmonitored workers beginning January 1, 1955.

6.2 EXTERNAL RADIATION DOSIMETERS AND RECORDS

An AEC survey conducted at Ames Laboratory from March 18 to 21, 1952, found the personnel monitoring program inadequate. Several recommendations were made in the survey report to promote improvements in radiation protection including film badge service and regular radiation monitoring [Hokel et al. 1998]. Before this time, only pocket chambers (pencil dosimeters) were used to monitor radiation exposure and records were incomplete [Voss 1949].

Regular film badge service began in February 1953; beta/gamma film badges were exchanged on a biweekly frequency with the results tabulated monthly and summarized annually [Ames 1952–1954, 1953–1954a,b]. Dosimetry services evolved and improved over the following 50 years; the characteristics of the dosimeters are summarized in Table 6-1.

Table 6-1. Dosimeter type, period of use, exchange frequency, minimum recordable dose (MRD), and minimum detection level (MDL).[a]

Dosimeter type, provider	Period	Exchange frequency[b]	MRD skin (mrem)[c]	MRD β/γ deep (mrem)[c]	MRD neutron (mrem)[c]	MDL skin (mrem)[d]	MDL deep (mrem)[d]	MDL neutron (mrem)[d]
Pocket chambers, Ames Laboratory	1942–1952	Daily	N/A	5	N/A	N/A	5	N/A
β/γ film, Ames Laboratory in-house system	02/1953–05/1953	Biweekly	N/A	10	N/A	40	40	N/A
	06/1953–12/1953		N/A	25	N/A	40	40	N/A
	01/1954–02/1957		25	25	N/A	40	40	N/A
	03/1957–12/1961		10	10	N/A	40	40	N/A
β/γ/NTA film, BNL	04/1954–06/1957	Biweekly	15	15	10	40	40	50
β/γ/NTA film, NCA	07/1957–06/1963	Biweekly	10	10	10	40	40	50
β/γ/NTA film, Atomic Film Badge Corporation	07/1963–03/1965	Monthly	10	10	10	40	40	50
Pocket chambers, Ames Laboratory	04/1965–06/1965	Daily	N/A	5	N/A	N/A	5	N/A
β/γ/NTA film, HPS	04/1965–06/1979	Monthly	10	5	28	40	40	50
β/γ film, HPS	11/1979–09/1981	Monthly	10	5	N/A	40	40	N/A
β/γ TLDs, Landauer	06/1980–12/1981	Monthly and quarterly	40	10	N/A	30	30	N/A
β/γ TLDs, Landauer	01/1982–12/1994	Quarterly	40	10	N/A	30	30	N/A
β/γ TLDs, Siemens	01/1995–06/1996	Quarterly	10	10	N/A	30	30	N/A
β/γ TLDs, ICN Dosimetry Service	01/1996–09/1998	Quarterly	10	10	N/A	30	30	N/A
β/γ TLDs, Landauer	10/1998–12/2004	Quarterly	40	10	N/A	30	30	N/A
β/γ TLDs, Global Dosimetry	01/2005–present	Quarterly	10	10	N/A	30	30	N/A

a. BNL = Brookhaven National Laboratory; HPS = Health Physics Services; NCA = Nucleonic Corporation of America; NTA = nuclear track emulsion, type A; N/A = not applicable.
b. The exchange frequency was established from dosimetry reports.
c. Based on minimum doses recorded on dosimetry reports.
d. Estimated MDL typical of film dosimeter capabilities [Wilson 1960, 1987; Lalos 1989; Cardarelli et al. 1993; Wilson et al. 1990].

6.2.1 Historical Administrative Practices

Some of the early administrative practices at Ames Laboratory related to dosimetry recordkeeping were unusual and inconsistent with current practice. The recordkeeping practices that correspond to each step in the evolution of dosimetry services (Table 6-1) are addressed in this section.

Pocket chambers (pencil dosimeters) were used at Ames Laboratory at various times, possibly as early as 1942, until 1952 when film badge service began. However, the records of pocket chamber results that were found apply only to a brief period in February 1949 and only for a few individuals [Voss 1949].

An in-house film badge system was established at Ames in fall 1952 in response to recommendations from the AEC. Weekly film badges were provided to a few individuals who worked at the synchrotron from September 1952 to March 1953, but records are incomplete [Ames 1952–1954, 1953–1954a,b]. Regular film badge service began in February 1953 for all laboratory staff. Beta/gamma film badges were exchanged every 2 weeks and results were summarized monthly. However, between late September 1953 and early January 1954, there were three 4-week and one 3-week exchange periods [Ames 1952–1954, 1953–1954a,b]. The in-house film badge system had variable exchange periods during 1954, 1957, 1958, 1959, and 1961. There was a 4-week exchange period in January, a 3-week

period in February, and a 4-week period in December 1954; otherwise, the exchange periods were 2 weeks each [Ames 1954, 1954–1955a,b]. The exchange frequency during 1955 and 1956 was every 2 weeks with no exceptions [Ames 1954–1955a,b, 1955, 1955–1956, 1956]. There was a 4-week exchange period in May and June 1957; all other exchange periods in 1957 were 2 weeks [Ames 1957a,b,c]. There was a 3-week exchange period in December 1958 and January 1959; all other exchange periods in 1958 and 1959 were 2 weeks [Ames 1957–1959, 1958–1959, 1959–1960a,b]. The exchange frequency during 1960 was every 2 weeks without exception [Ames 1960b]. During 1961, there were 9 3-week exchange periods and 12 2-week periods [Ames 1961b].

Initially, the MRD was 10 mR, and no distinction was made between beta and gamma doses (recorded nonzero doses were assumed to be gamma doses). As of June 1953, the MRD was reported as 25 mR. In 1954, the MRD was specified as 25 mrep and 25 mR for beta and gamma, respectively. In March 1957, the MRD decreased to 10 mR for both beta and gamma doses; this MRD was unchanged through 1961 [Ames 1957a,b,c, 1957–1959, 1958–1959, 1959–1960a,b, 1960b, 1961b].

Between October 24 and November 21, 1953, unusually high beta dose readings (about 700 mR) were “caused by the film being left unprotected near X-ray radiation” [Ames 1952–1954, 1953–1954a,b]. Corrections that are favorable to claimants for this exposure that was not received by personnel are recommended in ORAUT [2006c].

In the fourth quarter of 1953 and continuing through 1961, beta and gamma doses were reported separately and were added to give a total dose [Ames 1952–1954, 1953–1954a,b]. Between 1954 and 1961, neutron doses were added to the beta and gamma doses to give a total dose [Ames 1952–1954, 1953–1954a,b, 1954, 1954–1955a,b, 1955, 1955–1956, 1956, 1957a,b,c, 1957–1959, 1958–1959, 1959–1960a,b, 1960b, 1961b].

In the annual summaries for 1953 to 1956 (and for January and February 1957), an assumed dose of 25-mR gamma was assigned for each month in which the dosimeter reading was zero or less than the MRD [Ames 1952–1954, 1953–1954a,b, 1954–1955a,b, 1955, 1955–1956, 1956]. From March 1957 to 1961, when the dosimeter readings were zero or less than the MRD, an assumed dose of 10-mR gamma was assigned for each dosimeter exchange period [Ames 1957a,b,c, 1957–1959, 1958–1959, 1959–1960a,b, 1960b, 1961b]. This practice of assigning doses equal to the MRD is roughly equivalent to the standard method for correction of missed dose for monitored workers [NIOSH 2007b]. Therefore, no additional correction to the gamma dose is required for monitored workers for the period from 1953 to 1961.

Beginning in April 1954 and continuing through June 1957, a beta/gamma/neutron film badge service was provided by Brookhaven National Laboratory (BNL) for the synchrotron staff [Ames 1954, 1954–1955a,b]. The film badges were exchanged every 2 weeks and results were included in the annual dose summaries. The MRD was 15 mrep and 15 mR for beta and gamma, respectively. Neutron exposure was reported as the number of recoil proton tracks in the open window, and the number of tracks was multiplied by 10 to give the neutron dose in millirem [Ames 1954, 1954–1955a,b, 1961b].

Between July 1957 and June 1963, beta/gamma/neutron film badge service was provided by the Nucleonic Corporation of America (NCA) for the synchrotron staff [Ames 1957a,b,c]. The film badges were exchanged every 2 weeks and results were included in the annual dose summaries. The MRDs were 10 mrad and 10 mrem for beta and gamma, respectively. Neutron exposure was reported as the number of recoil proton tracks in the open window, and the number of tracks was multiplied by 10 to give the neutron dose in millirem [Ames 1957a,b,c].

The data discussed above for 1953 to 1961 were compiled on a spreadsheet, and the inconsistencies were corrected or minimized [ORAUT 2006c]. For example, if beta, gamma, and neutron doses were

reported separately but added together for a total dose, the separated beta, gamma, and neutron doses were entered in the spreadsheet to facilitate analysis. For cases in which data were questionable, assumptions were made that are favorable to claimants [13].

Dosimetry recordkeeping from January 1962 to June 1963 was less than adequate. The only records found for 1962 were some calibration data from April and the annual summary data [Ames 1962b, 1962–1964]. It was assumed that the in-house film badge system continued through December 1962 with badges exchanged on a biweekly frequency, but no records could be found to confirm this assumption. Monthly film badge service was provided for Ames Laboratory personnel with the potential for radiation exposure by the Atomic Film Badge Corporation from July 1963 to March 1965. No records were found for the first half of 1963. The annual summary for 1963 reflects results from July to December 1963 only. Therefore, all Ames Laboratory workers are assumed to have been unmonitored for the first half of 1963 [Ames 1963]. The annual summary for 1964 accurately reflected the sum of the monthly dosimeter readings during 1964 [Ames 1964].

Dosimetry records for January to March 1965 appeared to be reliable; however, the Atomic Film Badge Corporation defaulted on its contract and went out of business in April 1965 [Mattmueller 1965]. Ames Laboratory staff were monitored with pocket chambers on a daily basis and records were compiled in house from April to June 1965 [Ames 1965]. Film badge service was provided by Health Physics Services (HPS) from July 1965 to September 1981. The monthly service included beta, gamma, and neutron film badges for reactor and synchrotron staff and beta/gamma film badges for the remaining laboratory personnel [Ames 1965]. The MRDs were 10 mrad for beta, 5 mR for gamma, and 28 mrem for neutrons [Ames 1965].

TLD services for beta and gamma dosimetry were provided by Landauer from June 1980 to June 1995. Similar services have been provided in subsequent years by Siemens, ICN Dosimetry Service (ICN), and Landauer. The MRD for TLD services was 10 mrem for beta and gamma, except Landauer specified an MRD of 40 mrem for hard beta (greater than 1.5 MeV) [Landauer 1982–1983; Siemens 1995; ICN 1996]. Dosimetry records compiled since 1981 are considered complete and reliable. Records for monitored workers include an identification number, name, Social Security Number, and recorded doses for the current period, calendar quarter, and calendar year. The TLD services used by Ames Laboratory have been accredited by the National Voluntary Laboratory Accreditation Program (NVLAP) since 1985 [Landauer 1985–1986].

6.2.2 Dosimetry Technology

Ames Laboratory used film badge dosimeters from 1952 to 1981; TLDs have been used since 1980. The initial beta/gamma film badge system was operated in house from 1952 to 1962. The film was Kodak type K and the developer was Kodak D-19. However, no records could be found that described the film holder, although it seems likely that one of several commercially available holders would have been procured and that such a holder would have had standard design features as described in AEC [1955].

The initial neutron dosimetry service at Ames Laboratory, which began in 1954 and included beta and gamma dosimetry, was provided by BNL. The film badge holder was the basic Oak Ridge National Laboratory multielement dosimeter; the neutron film was nuclear track emulsion, type A (NTA) [ORAUT 2006d]. Similar film badge holders and film were provided by NCA, Atomic Film Badge Corporation, and HPS for the periods listed in Table 6-1.

With the termination of operations at the synchrotron in 1971 and the removal of fuel from the ALRR in October 1979, neutron dosimetry services were no longer needed after 1979. From 1980 to the present, beta/gamma TLD service has been provided by Siemens, ICN, and Landauer for the periods

listed in Table 6-1. These services have been accredited by NVLAP since 1985 [Landauer 1985–1986].

6.2.2.1 Beta/Photon Dosimeters

Figure 6-1 shows the response of a film badge to photon radiation of different energies; it also shows the *Hp(10)* response. The figure shows two responses for film badges: one for a sensitive DuPont 502 emulsion in a two-element badge [Pardue et al. 1944] and one for a sensitive DuPont 555 emulsion in the multielement badge [Thornton et al. 1961]. The response of the sensitive Eastman Type 2 film in a multielement film badge is similar to that of the sensitive DuPont 555 emulsion. The film badges show an overresponse at photon energies around 100 keV, due primarily to relatively (compared with tissue) high atomic numbers (silver [47] and bromine [35]) in the film emulsions. The two-element film badges under respond to lower energy photons; the multielement film badge typically over responds to photons between 50 and 150 keV.

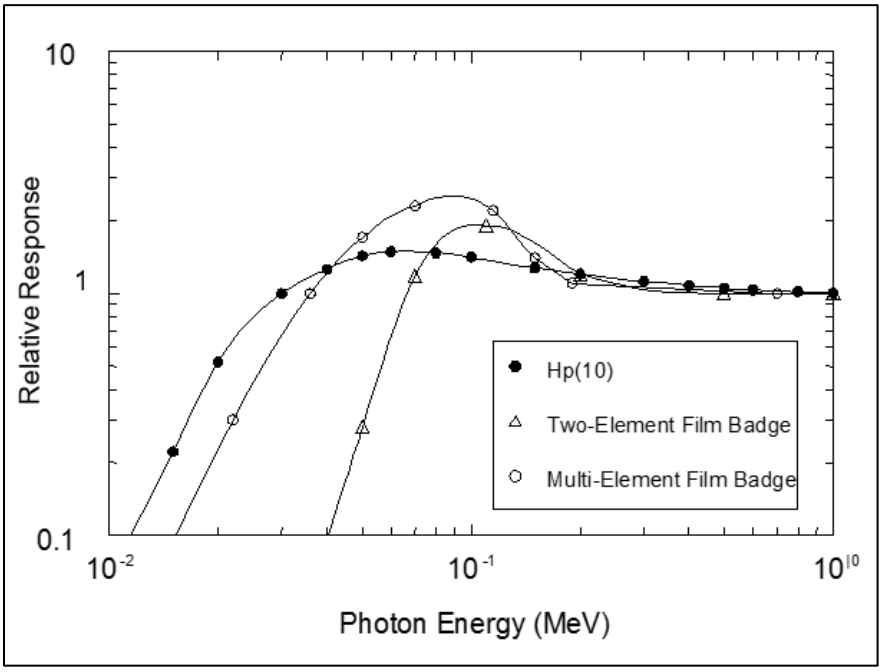

Figure 6-1. Comparison of *Hp(10)* for photons with energy responses for sensitive DuPont 502 emulsion in two-element film badge [Pardue et al. 1944] and sensitive DuPont 555 emulsion in multielement film badge [Thornton et al. 1961].

6.2.2.2 Neutron Dosimeters

NTA film was used by the dosimetry services provided to Ames Laboratory from 1954 to 1979. In general, the response of the NTA film decreases with decreasing neutron energies greater than a minimum threshold energy estimated to be between 500 and 800 keV [Griffith et al. 1990; ORAUT 2006d]. An unknown fraction of the total neutron dose was received from neutrons with energies less than about 800 keV.

6.2.3 Dosimeter Calibration Procedures

Calibration procedures for beta/photon dosimeters were followed consistently from 1953 to 1981 with the exception of 1962 and the first half of 1963 [14]. The suppliers of neutron dosimeters were generally relied on for neutron calibrations.

6.2.3.1 Beta/Photon Dosimeters

A set of calibration control film badges was exposed and processed with each biweekly set of films used in the Ames Laboratory in-house film badge system from 1953 to 1961 [Ames 1974]. The beta calibration was accomplished by exposing films for varying times to a milled uranium plate to produce beta doses between 10 and 1,000 mR. The gamma calibration was done by exposing films to doses of gamma radiation from a 10-mg ^{226}Ra source between 10 and 1,000 mR [Ames 1954, 1954–1955a,b]. The interpretation of film density into exposure units was made from curves drawn for the calibration films [Ames 1974].

Between January 1962 and June 1963, there was evidence of calibrations done only during April 1962 [Ames 1962–1964]. From June 1963 to March 1965, when the Atomic Film Badge Corporation provided film badge services, monthly gamma calibrations were done by exposing films to doses of gamma radiation from a 10-mg ^{226}Ra source from 100 to 10,000 mR [Ames 1963, 1965]. There was no evidence of beta or neutron calibrations during this period.

From July 1965 to September 1981, when film badge services were provided by HPS, a set of calibration control film badges were exposed to beta and gamma sources with each biweekly set of personnel film badges [Ames 1965; Voss 1971, 1975, 1979a,b, 1982]. The calibration procedures were the same as those used from 1953 to 1961.

Between 1980 and 1984, when TLD services were provided by Landauer, there is no evidence of any dosimeter calibrations by Ames Laboratory. After 1985, NVLAP accreditation was relied on for dosimeter calibrations.

6.2.3.2 Neutron Dosimeters

From April 1954 to June 1957, when film badge services were provided by BNL, a set of four calibration badges was included in each monthly set of films [Ames 1954, 1954–1955a,b, 1955, 1955–1956, 1956]. The calibration badges were exposed to known doses of beta, gamma, and neutron radiation. The beta exposures were to a milled uranium plate, and the gamma exposures were to a 10-mg ^{226}Ra source, but records of the source of neutron exposures were not found [Ames 1954, 1954–1955a,b, 1955, 1955–1956, 1956].

From July 1957 to June 1963, when NCA provided film badge services, a set of area monitor film badges was included with each month's set of personnel dosimeters [Ames 1957a,b,c, 1957–1959, 1958–1959, 1959–1960a,b, 1960b, 1961b, 1962–1964, 1963]. The monthly readings on area monitor film badges were used to check on the validity of personnel dosimeter readings, but actual calibrations were not performed by Ames Laboratory. NCA calibrated its NTA film badges by exposing films for 40 hours to a fast neutron flux of 18 n/cm^2/s (2.6×10^6 n/cm^2/40 hr), which produced approximately 10 recoil proton tracks in 25 fields or an exposure equivalent to 100 mrem [Ames 1960b]. From June 1963 to March 1965, when the Atomic Film Badge Corporation provided film badge services, there was no evidence of neutron calibrations.

Between July 1965 and September 1981, when HPS provided film badge services, a set of calibration control film badges were exposed to beta and gamma sources with each biweekly set of films [Ames 1974]. However, no evidence could be found that neutron exposures were included in this calibration procedure.

6.2.4 Workplace Radiation Fields

Workplace radiation fields at Ames Laboratory arose from the production of uranium and thorium metal, the operation of the synchrotron and ALRR, and research activities in laboratories. With few

exceptions, the following sections show that, for external dose reconstruction, all beta radiation fields were greater than 15 keV, all photon radiation fields were between 30 and 250 keV, and all neutron fields were between 0.1 and 2 MeV [ORAUT 2021]. Assuming that 100% of the radiation fields were within these ranges is a simplifying conservative assumption that is favorable to the claimant.

6.2.4.1 Beta Radiation

The major sources of beta radiation at Ames Laboratory between 1942 and 1954 were the large quantities of uranium and thorium metal produced. The uranium handled is assumed to have been in equilibrium with its ^{234}Th (24.1-day half-life) and ^{234m}Pa decay products [DOE 2001, p. 2–17]. From an external dose standpoint, the most significant beta radiation emitted from uranium metal is that from ^{234m}Pa, with a maximum energy of 2.29 MeV [Shleien et al. 1998]. The beta dose rate (with 7 mg/cm^2 filtration) is 233 and 179 mrad/hr at the surface of a uranium slab and UF_4, respectively [BRH 1970]. Thorium, if recently separated from its ^{228}Ra and subsequent decay products, would have very little beta emission. However, if ThF_4 was stored for several years before being processed to thorium metal, beta radiation from ^{228}Ra and ^{228}Ac would be measurable [Shleien et al. 1998].

A large number of beta-emitting radionuclides were handled in research work at Ames Laboratory throughout its history [15]. However, the activities of these sources were relatively small; the sources had a much smaller potential for beta radiation exposure to workers in comparison with the beta dose from uranium metal. With the exception of tritium, the energy of all beta sources was assumed to be greater than 15 keV; beta doses would have been readily measured in the open-window portion of the film badges used at the Laboratory. Tritium exposures at the ALRR were monitored by urine bioassay, which is addressed in Section 5.0 of this site profile.

6.2.4.2 Photon Radiation

Bremsstrahlung radiation doses from uranium metal ingots were calculated by Anderson and Hertel [2005]. Contact photon dose rates of a few milliroentgens per hour were calculated for typical plates, billets, and cylindrical ingots of the type produced at Ames Laboratory. Another source of photon radiation in the early years was stored thorium in the form of ThF_4. A gamma dose rate of 22 mR/hr in a thorium storage area was reported by Klevin [1952]. Exposures to photon radiation were possible in the experimental areas at the synchrotron and ALRR, and near the many gamma-emitting radionuclides that were handled in research work. A hot laboratory was located in the Chemistry Building, and a hot canyon/hot cell was located in the Research Building for work with more intense gamma sources. Photon sources had energies in the 30-to-250-keV and greater-than-250-keV ranges. X-ray diffraction machines could have operated at energies less than 30 kV, and measured exposures probably would have been reported as beta dose. Limited data do not permit an accurate estimate of the fraction of photon exposures expected in these energy ranges. Assuming that 100% of the photons were in the 30-to-250-keV range is a simplifying conservative assumption that is favorable to claimants [ORAUT 2021]. Photon radiation in the workplace could have been readily measured at Ames Laboratory with available dosimeter technology since 1953.

6.2.4.3 Neutron Radiation

The work involving plutonium and the research associated with thorium and uranium in the laboratories had the highest potential for exposure to neutrons.

The primary sources of neutrons at Ames Laboratory were the synchrotron, which operated from 1949 to 1971, and the ALRR, which operated from 1965 to 1977. In both facilities, fast, intermediate, and thermal neutrons would have been present in the workplace [ORAUT 2021]. Unfortunately, no records could be found that characterized the neutron spectrum in either facility, and there were no records of neutron surveys around experimental areas or penetrations in the shielding. The only documented

evidence of neutrons in the workplace is the many nonzero fast neutron doses measured with NTA film worn by personnel at each facility [ORAUT 2006c]. Assuming that 100% of the neutrons were in the 0.1-to-2-MeV energy range is a simplifying conservative assumption that is favorable to claimants.

6.2.5 Dosimeter Response to Radiation Fields

The personnel dosimeters used at Ames Laboratory were properly selected for the radiation fields encountered in the workplace. The response of each of the dosimeters used is described in the following sections.

6.2.5.1 Beta/Photon Film Dosimeter Response

Ames Laboratory used film badges for beta/photon dosimetry from 1952 to 1981. An in-house film badge system was used from 1952 to 1962; film badges were provided by four commercial services from 1954 to 1981 [16]. The dosimeters provided an open window with little filtration, a lower energy window that allowed beta particles and lower energy photons to enter a film area with a plastic filter, and a film area with a metal (usually aluminum) filter. The open window enabled measurement of beta particles and lower energy photons. The plastic filter enabled measurement of intermediate energy photons, and the metal filter enabled measurement of higher energy photons (1-cm depth).

The beta/photon dosimeters were calibrated regularly by methods consistent with accepted practice, but there was no evidence of any formal dosimeter response testing by an independent entity. The recorded beta and gamma doses appear to be consistent with those expected from the source terms and personnel monitoring described in Section 2.3.

6.2.5.2 Beta/Photon Thermoluminescent Dosimeter Response

Ames Laboratory has used TLDs for beta and photon dosimetry since 1980. The TLDs, their analyses, and recordkeeping have been provided by reliable commercial services. The dosimetry services have been accredited by NVLAP since 1985 [Landauer 1985–1986].

6.2.5.3 Neutron Dosimeter Response

The neutron doses received by synchrotron staff measured by NTA film appeared to be consistent with similar accelerator operations at other sites. The neutron doses received by ALRR personnel were generally higher than those experienced at other sites (e.g., the High Flux Beam Reactor at BNL) [ORAUT 2013]. Fast, intermediate, and thermal neutrons were present in both Ames Laboratory facilities, but no records were found that characterized the neutron energy spectrum at either facility. Thus, there is an unknown fraction of the total neutron dose (due to neutrons with energies below about 800 keV) that was not measured by NTA film.

To correct the measured neutron doses for the unmeasured fraction of neutrons with energies below 800 keV, data from similar facilities were examined. The 200-MeV electron synchrotron at SLAC was determined to be similar to the 80-MeV synchrotron at Ames Laboratory in relation to neutron exposures [ORAUT 2007]. The Materials Test Reactor (MTR) at the Idaho National Laboratory was determined to be similar to the ALRR with respect to neutron exposures [ORAUT 2010]. Neutron dosimeters with NTA film were used at both facilities and neutron spectral data are available to estimate the correction factor for missed neutron dose.

Accelerator operations at SLAC started in 1966; a multielement dosimeter was used until 1971 for beta/gamma and neutron (NTA film) dosimetry. ORAUT [2007] concluded that all SLAC neutron doses measured with NTA film should be multiplied by 1.53 ± 0.14 to account for the unmeasured neutrons with energies below 800 keV. The SLAC and Ames Laboratory synchrotrons were similar,

but their neutron spectra were not identical [17]. To allow for differences in the neutron spectra and other variables, a neutron dose correction factor of 2 is recommended for Ames synchrotron workers [18].

The MTR at Idaho National Laboratory, which operated from 1952 to 1970, was similar to the ALRR in that it was fueled with enriched uranium and had a power level of 30 MW [ORAUT 2010]. The MTR was water-cooled and light-water moderated, whereas the ALRR was heavy-water moderated. Both reactors had ports where fast neutron beams could be extracted from the core and directed to accessible experimental areas. Both were used to study reactor fuels and structural materials. Neutron doses at both reactors were monitored with multielement dosimeters including NTA film. The neutron spectrum in experimental areas at the MTR was measured with Bonner spheres in 1961 [Hankins 1961]. The data from these measurements were reanalyzed in ORAUT [2013]. Measurements made at 22 locations at the MTR were analyzed in relation to the response of NTA film. It was determined, on average for the 22 locations, that 52% of the total neutron dose would have been detected by NTA film and 48% would have been below the 800-keV threshold and undetected [ORAUT 2007]. Because the MTR and the ALRR had very similar neutron spectra, a neutron dose correction factor of 2 is recommended for ALRR workers.

6.2.5.4 Neutron Dose Weighting Factor

At Ames Laboratory, neutron dosimeter measurements were based on fluence-to-dose conversion factors and quality factors similar to those from International Commission on Radiological Protection (ICRP) Publication 21 [ICRP 1973] and NCRP Report 38 [NCRP 1971]. It is necessary to adjust the neutron dose to account for the change in neutron quality factors between historical and current scientific guidance. ICRP Publication 60 corrections factors [ICRP 1991] should be applied to the neutron doses in accordance with ORAUT-OTIB-0055, *Technical Basis for Conversion from NCRP Report 38 Neutron Quality Factors to ICRP Publication 60 Radiation Weighting Factors for Respective IREP Input Neutron Energy Ranges* [ORAUT 2006e]. Table 6-2 shows the correction factor to use.

Table 6-2. Neutron dose energies, percentages, and associated ICRP [1991] correction factors.

Process description	Neutron energy (MeV)	Default dose fraction[a] (%)	ICRP [1991]/NCRP [1971] correction factor
Neutron exposures associated with synchrotron and research reactor activities	0.1–2	100	1.91

a. The assumption that all neutron energies are between 0.1 and 2 MeV is favorable to the claimant.

6.3 RECOMMENDATIONS FOR WORKER EXTERNAL DOSE RECONSTRUCTION

Dose reconstruction for Ames Laboratory workers is based on the above information, which requires that assessment of additional dose be added to the measured photon dose from three primary causes:

- Adjustments to measured photon dose for dosimeter uncertainty,
- Adjustments to measured neutron dose using a correction factor to account for neutrons with energies less than 800 keV that were not measured by NTA film, and
- Multiplication of the adjusted neutron dose by an ICRP [1991] neutron weighting factor adjustment of 1.91 for neutron energies between 0.1 and 2 MeV.

6.3.1 Unmonitored External Dose

At Ames Laboratory, “unmonitored workers” includes workers who were monitored but for whom records have not been found [19]. According to the feasibility table in Section 1.3, NIOSH is not able to calculate unmonitored doses before 1955. Co-exposure dose, based on a review of Ames Laboratory dosimetry data, was used to estimate doses beginning in 1955.

6.3.1.1 Co-Exposure Doses, 1955 to Present

Extensive dosimetry records have been found for Ames Laboratory workers; however, many of the records for 1965 to 1981 do not identify the person receiving the radiation dose. If a worker was monitored but cannot be identified in the dosimetry records, that individual must be considered unmonitored and assigned a dose in each year for which no clearly identified records exist.

A co-exposure data study was used for this site profile to permit dose reconstructors to complete certain cases for which external monitoring data were unavailable or incomplete. Co-exposure data are data from workers at a site (potentially grouped by work location, job description, or other appropriate category) whose measured doses are considered representative of those received by one or more workers with no individual monitoring data [ORAUT 2011].

The general approach to applying co-exposure data for cases with little or no individual external monitoring data is to assign the 50th- or 95th-percentile dose with the intent that the assigned doses represent, but do not underestimate, the doses that would have been assigned if the worker had been monitored (50th percentile) or if the monitored worker was clearly identified in the dosimetry records (95th percentile). Dose reconstructors should assign the GM (50th percentile) or the 95th-percentile values as constants [ORAUT 2011].

Some workers might have never been monitored during their employment at Ames Laboratory. Workers with job titles such as security patrolman, craftsman, janitor, secretary, or clerk who did not work routinely in radiological areas were probably not monitored. External environmental doses should be assigned to those workers who were unlikely to be exposed to radiation. The 50th-percentile dose can be used to estimate doses for those workers when professional judgment indicates the worker was likely to have been exposed to intermittent low levels of external radiation [ORAUT 2011].

Some workers with job titles such as scientist, chemist, metallurgist, engineer, technician, or machinist were probably monitored, but some or all of their dosimetry records might be missing because of the lack of clearly identified dosimetry records between 1965 and 1981. If any part of a worker’s dosimetry record is missing (unidentified), co-exposure dose should be assigned for the years for which records are missing [ORAUT 2011]. The 95th-percentile dose should be assigned to those workers who could have been regularly exposed.

Other options are available through the guidance in ORAUT-OTIB-0020, *Use of Coworker Dosimetry Data for External Dose Assignment* [ORAUT 2011] and DCAS-IG-006, *Criteria for the Evaluation and Use of Coworker Datasets* [NIOSH 2020]. For instance, for cases in which routine monitoring data exist and co-exposure dose is used to supplement missing quarters or years, assign the percentile dose that is consistent with the recorded dose unless there is reason to believe that the worker’s job or location differs significantly from that held during the year in which the dose was recorded. Note that the period in which dosimetry records might be missing due to the lack of clearly identified dosimetry records (between 1965 and 1981) is also the period of the most varying co-exposure doses. Use judgment and other information in the claim files to determine whether 50th- or 95th-percentile doses are more appropriate [NIOSH 2020].

The co-exposure study for Ames Laboratory included all available dosimetry records from 1952 to 1981 [ORAUT 2006c]. All dose results were analyzed, including zeros and blank values, to determine the 50th- and 95th-percentile doses for each year for beta, gamma, and neutron exposures [McCartney 2006]. According to the feasibility table in Section 1.3, the co-exposure doses are assigned beginning in 1955. The results of the analysis are summarized in Table 6-3. The missed dose recommended for monitored workers in Table 6-4 was added to the 50th- and 95th-percentile values in Table 6-3. Specifically, half of the maximum annual missed doses were added to the reported annual doses except the reported positive doses, in which case the maximum missed dose was reduced by the dose corresponding to one badge exchange (because it is not possible that all individual badge results were zero if a positive annual dose was reported) [ORAUT 2011]. For beta doses, the maximum missed dose was not added to ensure missed dose is not assigned twice when evaluating dose to shallow dose organs [ORAUT 2005].

Table 6-3. Assigned dose for unmonitored workers (mrem/yr).[a]

Year	Beta 50th percentile[b]	Beta 95th percentile[b]	Gamma 50th percentile	Gamma 95th percentile	Neutron 50th percentile[c]	Neutron 95th percentile[c]
1955	0	0	520	520[d]	650	650
1956	0	0	520	520[d]	650	650
1957	0	0	520	520[d]	650	650
1958	0[b]	0[b]	520	520[d]	650	650
1959	0[b]	0[b]	520	520[d]	650	650
1960	0	0	520	520[d]	650	650
1961	0[b]	0[b]	520	520[d]	650	650
1962	0	0	520	520[e]	650	650[e]
1963	0	0	240	265[f]	650	650
1964	0	0	240	313[f]	650	650
1965	0	0	240	408[f]	650	820[f]
1966	0	86[f]	240	565[f]	806[g]	988[f]
1967	0	246[f]	240	745[f]	932[g]	1,128[f]
1968	0	87[f]	240	769[f]	876[g]	1,086[f]
1969	0	175[f]	240	1,182[f]	1,030[g]	1,296[f]
1970	0	0	240	671[f]	680[g]	932[f]
1971	0	0	240	809[f]	722[g]	950[f]
1972	0	0	240	512[f]	652[g]	988[f]
1973	0	0	240	701[f]	650	932[f]
1974	0	0	240	721[f]	650	876[f]
1975	0	0	240	1,298[f]	650	870[f]
1976	0	0	240	497[f]	650	958[f]
1977	0	0	240	752[f]	650	904[f]
1978	0	0	240	722[f]	650	652[f]
1979	0	0	240	819[f]	650	650
1980	0	0	240	1,595[f]	Not applicable	Not applicable
1981	0[b]	0[b]	240	240	Not applicable	Not applicable
1982	0[b]	0[b]	85	555	Not applicable	Not applicable
1983	325	510	105	134	Not applicable	Not applicable
1984	0	0	60	85	Not applicable	Not applicable
1985	0	0	60	125	Not applicable	Not applicable
1986	0	0	60	60	Not applicable	Not applicable
1987	0	0	60	114	Not applicable	Not applicable
1988	0	310	72	149	Not applicable	Not applicable
1989	0	0	60	81	Not applicable	Not applicable
1990	0	9	60	91	Not applicable	Not applicable
1991	0	51	60	85	Not applicable	Not applicable
1992	0	30	60	71	Not applicable	Not applicable
1993	0	22	60	118	Not applicable	Not applicable

Year	Beta 50th percentile[b]	Beta 95th percentile[b]	Gamma 50th percentile	Gamma 95th percentile	Neutron 50th percentile[c]	Neutron 95th percentile[c]
1994	0	20	62	138	Not applicable	Not applicable
1995	0	70	60	68	Not applicable	Not applicable
1996	0	0	60	65	Not applicable	Not applicable
1997	0	0	60	60	Not applicable	Not applicable
1998	0	0	205	245	Not applicable	Not applicable
1999	0	115	60	160	Not applicable	Not applicable
2000	0	150	60	110	Not applicable	Not applicable
2001	0[b]	0[b]	60	76	Not applicable	Not applicable
2002	0	49	60	68	Not applicable	Not applicable
2003	0	150	201	394	Not applicable	Not applicable
2004	0[b]	0[b]	63	118	Not applicable	Not applicable
2005	0	204	60	123	Not applicable	Not applicable

a. Sources: Values from McCartney [2006]; data from Ames [1952–1954, 1953–1954a,b to 1957–1959, 1958–1959, 1959–1960a,b, 1960b, 1961b, 1962–1964 to 1965], HPS [1966 to 1972], Ames [1973], HPS [1974], Ames/HPS [1975, 1976, 1976–1977, 1978–1981, 1979–1981], Ames/Landauer [1980], HPS [1981], Landauer [1982–1983 to 1994], Siemens [1995], ICN [1996], Hokel [1998], Landauer [1999a to 2000], Simpson [2001, p. 2], Beckel [2001a to 2002], Landauer [2003, 2004], Beckel [2004a to 2005], Global Dosimetry Solutions [2006].
b. No beta doses were measured or reported in 1952, 1958, 1959, 1961, 1981, 1982, 2001, or 2004.
c. Neutron dosimeters were not assigned after 1979.
d. As discussed in Section 6.2.1, the practice of assigning doses equal to the MRD is roughly equivalent to the standard method for correction for missed dose for monitored workers [NIOSH 2007b]. Therefore, no additional correction to gamma doses is required for monitored workers for the period from 1955 to 1961. However, this method resulted in adjusted doses that were less than the missed dose assigned to unmonitored workers (50th-percentile value), so the higher missed dose was assigned.
e. The dosimeter exchange frequency in 1962 is uncertain; therefore, the missed dose for a biweekly frequency was assumed to be favorable to claimants.
f. The 95th-percentile value was assumed to be received all in 1 month; missed dose was added for the other 11 months.
g. The 50th-percentile value was assumed to be received all in 1 month; missed dose was added for the other 11 months.

Table 6-4. Potential missed dose for monitored workers (mrem).

Dosimeter	Period	Exchange frequency[a]	MDL skin	MDL deep	MDL neutron
Film badge β, γ, n	1952–1962	Biweekly	40[b]	40[b]	50[b]
Film badge β, γ, n	1963–1981	Monthly	40[b]	40[b]	50[b,c]
TLD β, γ	1981–present	Quarterly	30	30	Not applicable[c]

a. Exchange frequencies were established from dosimetry reports.
b. Estimated MDL typical of film dosimeter capabilities [Wilson 1960, 1987; Cardarelli et al. 1993; Lalos 1989; Wilson et al. 1990].
c. Neutron dosimeters were not assigned after 1979 due to the removal of fuel from the ALRR in October 1979.

6.3.2 Missed External Dose for Monitored Workers

If external dose data are found in a worker's file, dose reconstructors should assign a missed photon dose based on the MDL/2 method and the number of exchange periods [NIOSH 2007b] listed in Table 6-4 for the dosimetry systems. These missed doses are included in the values in Table 6-3.

A flow chart is provided in Figure 6-2 to guide dose reconstructors in applying the above tables and recommendations. The Monitored Worker side of the figure should be used if there are record files for the entire employment period. If data for any exposure period are missing, the Unmonitored Worker side of the figure should be used for the missing period only. If there are no dose record files for a worker, the Unmonitored Worker side of the figure should be used for the entire employment period.

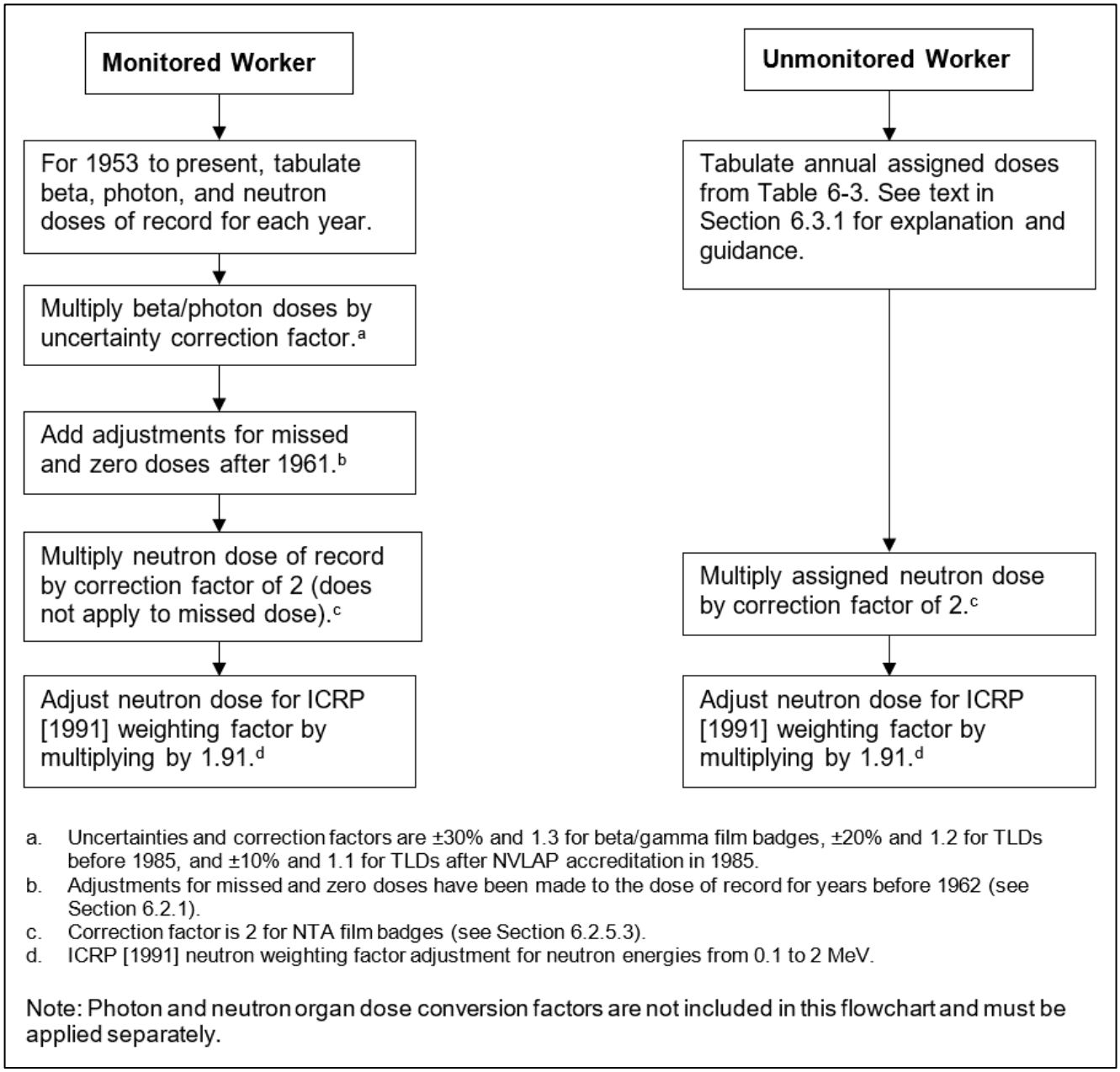

Figure 6-2. Flowchart for monitored and unmonitored workers. Attachment A contains an extended description of this image.

6.3.3 Uncertainty in Photon Doses

For the usual analysis of measured film badge doses, MDLs in the literature range from about 30 to 50 mrem for beta/photon irradiation [Wilson et al. 1990]. It is possible to read a photon dose of 100 mrem to within ±15 mrem if the exposure involved photons with energies between several keV and several MeV [Morgan 1961]. The estimated standard error in recorded film badge doses from photons of any energy is ±30% [ORAUT 2006f]. The estimated uncertainty in doses recorded by TLDs is ±20% from 1982 to 1984 and ±10% since 1985 with NVLAP accreditation [Landauer 1985–1986].

6.3.4 Skin Dose

Before 1981, the beta and skin dose records included beta doses only; that is, only nonpenetrating beta dose is recorded. In 1981 and subsequent years, the beta and skin dose has been calculated as the sum of the whole-body penetrating dose and the nonpenetrating dose [Landauer 1985–1986]. For cases in which no nonpenetrating dose was recorded, the skin dose is assumed to be equal to the whole-body penetrating dose. Guidance on determining skin dose can be obtained from ORAUT-OTIB-0017, *Interpretation of Dosimetry Data for Assignment of Shallow Dose* [ORAUT 2005].

6.3.5 Extremity Dose

Assignment to and use of extremity dosimeters by Ames Laboratory workers has been inconsistent. In some years, there are no reported extremity dose results; in many years, there are only a few results, which suggests a less-than-rigorous extremity dosimetry program given the types and quantities of radioactive materials handled. Results are so sparse that it must be concluded that extremity doses were essentially unmonitored.

6.3.6 Radiation Dose Fraction

Section 6.2.4 addresses the recommended energy ranges and fractions for Ames Laboratory dose according to facilities, processes, or activities as required by the IREP.

6.4 ORGAN DOSE

Organ doses are calculated using the external dose reconstruction implementation guidelines for irradiation geometry and dose conversion factors [NIOSH 2007b]. For photons measured with film badges and early TLD use (before 1985), use the conversion factor from exposure to organ dose. Beginning in 1985, when NVLAP accreditation was obtained, deep dose equivalent should be used. For neutron doses, use the conversion factors from deep dose equivalent to organ dose for anterior-posterior irradiation from NIOSH [2007b].

7.0 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in this document, bracketed callouts have been inserted to indicate information, conclusions, and recommendations provided to assist in the process of worker dose reconstruction. These callouts are listed here in the Attributions and Annotations section, with information to identify the source and justification for each associated item.

[1] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
Normally, the accelerator would have been operated at reduced beam currents and with targets that produced much lower radiation dose rates on and off site. This was verified by examining the dosimetry records of the synchrotron staff, which showed no unusually high exposures during the May 1961 survey or at any other time.

Background reading in this area (synchrotron) before beam being turned on was 0.5 to 1.0 mR/hr [Ames 1961a]. Apparently, the background reading was taken near the synchrotron where the radiation level was slightly elevated (due to activation products) above the normal natural background level. However, the exact location of the background reading cannot be determined. The fence line readings were taken some distance from the background reading location and should not have been influenced by the elevated background near the accelerator. In any event, the elevated background dose rates were not subtracted from the fence line dose rates reported in Table 4-1.

[2] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
It is assumed that generally about one-third of the total staff time is spent on nonoperational activities, such as experiment setup, equipment startup, maintenance, repairs, etc. Thus, about two-thirds of the total time is available for operations.

[3] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
The radiation conditions during the fence line radiation survey on May 16, 1961, produced dose rates greater than 1 mR/hr at occupiable locations inside the Synchrotron Building. Full-time occupancy in such a location would give an annual dose of greater than 2,000 mrem. A review of dosimetry records for synchrotron personnel indicated no one received such a dose during 1961 or at any other time. The average annual dose was less than 200 mrem. The average annual dose outside the Synchrotron Building would have been much lower.

[4] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
The air sample results were indistinguishable from background and were therefore not useful. Of the surface survey results in areas somewhat accessible to people, the highest result was 1,224 dpm; however, there was no record of the surface area smeared. Surface activity measurements are typically reported in units of activity per 100 cm^2. Because of that uncertainty, the 1,224-dpm value was raised to 2,000 dpm/100 cm^2 to represent an upper bound.

[5] Sharfi, Mutty M. ORAU Team. Principal Health Physicist. June 2022.
Indoor resuspension factors range from 10^{-6} to 10^{-3} [ORAUT 2012]. The factor 10^{-4} was chosen for this application to represent an upper bound for chronic intake from surfaces not immediately accessible and, therefore, not often disturbed.

[6] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
Hokel et al. [1998] indicated the thorium was assumed to be in equilibrium with its progeny. The intake dose conversion factors account for buildup/decay of ^{232}Th progeny in the body after the intake, but the activity of the progeny already in the air at intake has to be treated as separate intake radionuclides. Because of their short half-lives, ^{228}Ac is included in dose calculations for ^{228}Ra and all the progeny from ^{228}Th are included in the dose calculations for ^{228}Th, so only ^{228}Ra and ^{228}Th must be entered as intakes separate from ^{232}Th.

[7] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
Review of Hokel et al. [1998] suggested there were areas with higher contamination, such as crawlspaces and vertical void spaces in rooms that were rarely, if ever, occupied. The statement in Section 5.2 that contamination was 10 to 100 times greater generalizes the discussion in Hokel et al. on this subject.

[8] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
Hokel et al. [1998] contains statements that rarely accessed areas that are still contaminated are carefully controlled, and that workers wear protective equipment and are monitored by health physics technicians; therefore, the 6-pCi/d chronic intake is an upper bound.

[9] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
MDAs or recording levels varied at the major AEC sites in the 1960s and 1970s from 1 µCi/L at the Hanford Site, Savannah River Site, and Los Alamos, to 0.02 µCi/L at Oak Ridge, to 0.0002 µCi/L at Idaho National Laboratory. The Hanford and Savannah River values were

recording levels with actual laboratory MDAs generally being lower. Review of data recording methods at Ames Laboratory indicated that 0.1 µCi/L was the likely MDA or recording level.

[10] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
The uranium and thorium metal production processes at Ames Laboratory established that workers were exposed to external radiation doses between 1942 and 1952. The only records of radiation dosimetry measurements during this period are Tybout [1944] and Voss [1949], which are very incomplete. Either the radiation doses were not measured or essentially no records were kept. In either case, the workers during this period were unmonitored.

[11] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
Voss [1949] recorded radiation exposures measured by pocket chambers for 15 individuals during a 2-week period in February 1949. These were the only pocket chamber dosimeter records found for the 1942-to-1952 period. The record suggests that pocket chambers were available during this period, but either they were not used or, if they were, records of the dosimeter readings were not kept.

[12] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
From 1965 to 1981, the film badge dosimetry records reflect badge numbers only. Rosters of names and badge numbers for bioassay records were found and it was possible to correlate some badge numbers and individual names. However, there were many badge numbers for which a name could not be assigned.

[13] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
As the spreadsheets were assembled, some addition and subtraction errors in the dosimetry records were noted. In all cases, the result that gave the highest dose was assumed and recorded in the spreadsheets.

[14] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
As stated in Section 6.2.1, recordkeeping from January 1962 to June 1963 was less than adequate. The only records found for 1962 were some calibration data from April 1962 and the annual summary data for 1962 [Ames 1962–1964]. It was assumed that the in-house film badge system continued through December 1962, with film badges exchanged on a biweekly frequency; however, no records could be found to confirm this assumption. Monthly film badge service was provided for all Ames Laboratory personnel with the potential for radiation exposure by the Atomic Film Badge Corporation from July 1963 to March 1965. No records were found for the first half of 1963.

[15] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
The early history of research at Ames Laboratory was described by Fulmer [1947]; later history was described in Struss and Hawkins [1986]. These documents discussed numerous research projects that involved many beta-emitting radionuclides. The quantities used in research were much smaller than the quantities involved in production operations.

[16] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
Commercial film badge service was supplied by BNL from April 1954 to June 1957, by NCA from July 1957 to June 1963, by Atomic Film Badge Corporation from July 1963 to March 1965, and by HPS from June 1965 to September 1981 (see Table 6-1).

[17] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
The maximum beam energy at the Ames Laboratory synchrotron was 80 MeV; the maximum beam energy at the SLAC synchrotron was 200 MeV. Both accelerators produced neutrons,

but the spectrum at SLAC included higher energy neutrons, so the neutron radiation fields were not identical.

[18] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
The SLAC site profile [ORAUT 2007] used a neutron dose correction factor of 1.53 ±0.14 to account for unmeasured neutrons with energies below 800 keV. Although the neutron spectra of the Ames Laboratory and SLAC synchrotrons were not identical, they were similar enough to justify the assumption of a neutron dose correction factor of 2 for the Ames synchrotron.

[19] Ellis, Jackson R. ORAU Team. Senior Health Physicist. July 2022.
From 1965 to 1981, the film badge dosimetry records reflect badge numbers only. Rosters of names and badge numbers for bioassay records were found and it was possible to correlate some badge numbers and individual names. However, there were many badge numbers for which a name could not be assigned. These records indicate that some workers were monitored, but they have to be considered unmonitored because the records for specific individuals cannot be retrieved.

REFERENCES

10 C.F.R. 20 [2021]. Standards for protection against radiation. [SRDB Ref ID: 192784]

AEC [1955]. Intercomparison of film badge interpretations. Isotopics *2*(5):8–23. [SRDB Ref ID: 3640]

Ames [no date]. The Iowa State College Institute for Atomic Research (including the Ames Laboratory of the Atomic Energy Commission). Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 18855]

Ames [1951]. The history of the Ames Laboratory. Ames Laboratory, Ames, IA: United States Atomic Energy Commission, Iowa State College. August. [SRDB Ref ID: 18861]

Ames [1952–1954]. External exposure results. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 18821]

Ames [1953–1954a]. Weekly exposure and film badge dosimetry data. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 18822]

Ames [1953–1954b]. Film badge dosimetry records. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 18833]

Ames [1954]. Hand film dosimetry. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 25816]

Ames [1954–1955a]. Film badge and pocket chamber dosimetry results. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 18834]

Ames [1954–1955b]. Neutron film badge records. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 18835]

Ames [1955]. Film badge, pocket chambers, dosimetry reports. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 18841]

Ames [1955–1956]. Film badge reports. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 25169]

Ames [1956]. Dosimetry data. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 25171]

Ames [1957a]. Neutron film badge data from Nucleonics Corp. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 25214]

Ames [1957b]. Film badge exposure summary. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 25215]

Ames [1957c]. Change in film badge MDA and summary. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 25216]

Ames [1957–1959]. External dosimetry data. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25460]

Ames [1958–1959]. External neutron dosimetry results. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25459]

Ames [1959–1960a]. External dosimetry data. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25461]

Ames [1959–1960b]. Neutron film badge data from Nucleonic Corporation. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25898]

Ames [1960a]. News media report - Metals Process Development Building Ames Lab. Ames Laboratory, Ames, IA: Iowa State University. January 25. [SRDB Ref ID: 18832]

Ames [1960b]. Film badge exposure reports for the year. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25907]

Ames [1961a]. Synchrotron Building radiation survey. Ames Laboratory, Ames, IA: Iowa State University. May 16. [SRDB Ref ID: 25766]

Ames [1961b]. Film badge exposure reports. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25913]

Ames [1962a]. Publicity brochure for Ames Laboratory - Institute for Atomic Research. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 18856]

Ames [1962b]. Film badge records. Ames Laboratory, Ames, IA: Iowa State University. April 2. [SRDB Ref ID: 25909]

Ames [1962–1964]. Individual film badge radiation report. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25837]

Ames [1963]. External dose records from Atomic Film Badge Corporation. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25914]

Ames [1964]. External dose records from Atomic Film Badge Corporation. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25916]

Ames [1965]. External dose records from Atomic Film Badge Corporation and Health Physics Services, Inc. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25919]

Ames [1967]. Ames Laboratory 25th year open house 1942-1967. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 18830]

Ames [1968]. Tour guide Iowa State University physics building addition open house. Ames Laboratory, Ames, IA: Iowa State University. April 29. [SRDB Ref ID: 167081]

Ames [1973]. External dose records 1973. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25839]

Ames [1974]. Personnel monitoring program. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 25767]

Ames [1977]. Tritium in urine third quarter 1977. Ames Laboratory, Ames, IA: Iowa State University. November 2. [SRDB Ref ID: 25463]

Ames/HPS [1975]. External dose records 1975. Ames Laboratory, Ames, IA: Iowa State University. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 25860]

Ames/HPS [1976]. External dose records 1976. Ames Laboratory, Ames, IA: Iowa State University. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 25861]

Ames/HPS [1976–1977]. External dose records 1977. Ames Laboratory, Ames, IA: Iowa State University. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 26613]

Ames/HPS [1978–1981]. External dose records 1978. Ames Laboratory, Ames, IA: Iowa State University. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 26615]

Ames/HPS [1979–1981]. External dose records 1979. Ames Laboratory, Ames, IA: Iowa State University. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 26619]

Ames/Landauer [1980]. External dose records 1980. Ames Laboratory, Ames, IA: Iowa State University. Glenwood, IL: R. S. Landauer, Jr. & Co. [SRDB Ref ID: 26622]

Anderson JL, Hertel NE [2005]. Bremsstrahlung doses from natural uranium ingots. Radiat Prot Dosimetry *115*(1–4):298-301. [SRDB Ref ID: 29254]

Azar AM II [2018]. U.S. Department of Health and Human designation of additional members of the Special Exposure Cohort under the Energy Employees Occupational Illness Compensation Program Act of 2000 designating a class of employees from Ames Laboratory Ames, Iowa. Washington, DC: U.S. Department of Health and Human Services, Office of the Secretary. February 1. [SRDB Ref ID: 195157]

Beckel J [2001a]. Ames Laboratory exposure data for 2nd quarter of 2001. Letter to M. Saar, U.S. Department of Energy, Chicago Operations Office. Ames Laboratory, Ames, IA: Iowa State University. July 26. [SRDB Ref ID: 192216]

Beckel J [2001b]. Ames Laboratory exposure data for 3rd quarter of 2001. Letter to M. Saar, U.S. Department of Energy, Chicago Operations Office. Ames Laboratory, Ames, IA: Iowa State University. November 19. [SRDB Ref ID: 192217]

Beckel J [2002]. Ames Laboratory exposure data for 4th quarter of 2001. Letter to M. Saar, U.S. Department of Energy, Chicago Operations Office. Ames Laboratory, Ames, IA: Iowa State University. February 11. [SRDB Ref ID: 192218]

Beckel J [2004a]. Ames Laboratory exposure data for 2nd quarter of 2004. Letter to R. Purucker, U.S. Department of Energy, Chicago Operations Office. Ames Laboratory, Ames, IA: Iowa State University. September 1. [SRDB Ref ID: 192219]

Beckel J [2004b]. Ames Laboratory exposure data for 3rd quarter of 2004. Letter to R. Purucker, U.S. Department of Energy, Chicago Operations Office. Ames Laboratory, Ames, IA: Iowa State University. December 2. [SRDB Ref ID: 192220]

Beckel J [2005]. Ames Laboratory exposure data for 4th quarter of 2004. Letter to R. Purucker, U.S. Department of Energy, Chicago Operations Office. Ames Laboratory, Ames, IA: Iowa State University. February 14. [SRDB Ref ID: 192221]

Biwer BM, Kamboj S, Arnish J, Yu C, Chen SY [2002]. Technical basis for calculating radiation doses for the building occupancy scenario using the probabilistic RESRAD-BUILD 3.0 code. Washington, DC: U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research. NUREG/CR-6755, February. [SRDB Ref ID: 91669]

BRH [1970]. Radiological health handbook. Revised ed. Rockville, MD: U.S. Department of Health, Education, and Welfare, Public Health Service. PHS-PUBL-2016, January. [SRDB Ref ID: 75017]

Cardarelli J II, Elliott L, Spitz H, eds. [1993]. Epidemiologic use of nondetectable values in radiation exposure measurements. Workshop held in Cincinnati, Ohio, September 9 and 10, 1993. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. [SRDB Ref ID: 13723]

DOE [2001]. Guide of good practices for occupational radiological protection in uranium facilities. Washington, DC: U.S. Department of Energy. DOE-STD-1136-2000 Change Notice No. 3, December. [SRDB Ref ID: 4617]

Ferretti RJ, Price GR, Schwartz S [no date]. Uranium excretion studies. In: Stone RS. Industrial medicine on the Plutonium Project Survey and collected papers. 1st ed. New York: McGraw-Hill Book Company. [SRDB Ref ID: 198494]

Friedell HL [1942]. Supplemental report to complete preliminary survey of plants engaged in production of materials. Washington, DC: U.S. Department of War, U.S. Army Corps of Engineers. December 23. [SRDB Ref ID: 8967]

Fulmer EI, ed. [1947]. History of the Ames Project under the Manhattan District to December 31, 1946. Ames Laboratory, Ames, IA: Iowa State College. ISC-10, December 9. [SRDB Ref ID: 18823]

Global Dosimetry Solutions [2006]. Occupational radiation exposure report. Irvine, CA. February 13. [SRDB Ref ID: 26811]

Griffith RV, Palfalvi J, Madhvanath U [1990]. Compendium of neutron spectra and detector responses for radiation protection purposes. Vienna, Austria: International Atomic Energy Agency. IAEA Technical Reports Series 318, June. [SRDB Ref ID: 168569]

Hankins DE [1961]. A method of determining the intermediate energy neutron dose. Idaho Falls, ID: U.S. Atomic Energy Commission, Idaho Operations Office. IDO-16655, March 10. [SRDB Ref ID: 8084]

Hayes DF [1956]. A summary of accidents and incidents involving radiation in atomic energy activities June 1945 to December 1955. Washington, DC: U.S. Atomic Energy Commission, Division of Organization and Personnel. August. [SRDB Ref ID: 30143]

Hokel BW [1998]. CY1997 radiation exposure reports, Ames Laboratory, contract no. W-7405-ENG-82. Letter to Y. McCormick, SAIC. Ames Laboratory, Ames, IA: Iowa State University. May 6. [SRDB Ref ID: 26683]

Hokel BW, Withers JH, Waters WP, Ewing KJ [1998]. An assessment of the causes, mitigation efforts, and current status of Th-232, U-238, and beryllium contamination in Wilhelm Hall at Ames Laboratory. Ames Laboratory, Ames, IA: Iowa State University. April. [SRDB Ref ID: 18848]

HPS [1966]. External dose records from Health Physics Services, Inc. 1966. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 25922]

HPS [1967]. External dose records from Health Physics Services, Inc. 1967. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 25923]

HPS [1968]. External dose records from Health Physics Services, Inc. 1968. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 25808]

HPS [1969]. External dose records from Health Physics Services, Inc. 1969. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 25809]

HPS [1970]. External dose records from Health Physics Services, Inc. 1970. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 25810]

HPS [1971]. External dose records from Health Physics Services, Inc. 1971. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 25811]

HPS [1972]. External dose records from Health Physics Services, Inc. 1972. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 25834]

HPS [1974]. External dose records from Health Physics Services, Inc. 1974. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 25859]

HPS [1981]. Health Physics Services personnel exposure reports 1981. Baltimore, MD: Health Physics Services. [SRDB Ref ID: 26626]

ICN [1996]. ICN Dosimetry Service radiation exposure report October - December 1996. Fountain Valley, CA: ICN Dosimetry Service. December 9. [SRDB Ref ID: 26681]

ICRP [1973]. ICRP 21 - Data for protection against ionizing radiation from external sources: supplement to ICRP Publication 15. ICRP Publication 21. Oxford, England: Pergamon Press. [SRDB Ref ID: 165854]

ICRP [1991]. ICRP 60 - 1990 recommendations of the International Commission on Radiological Protection. ICRP Publication 60. ICRP Ann ICRP *21*(1-3). [SRDB Ref ID: 11517]

ISU [2006]. Iowa State University campus maps. Ames Laboratory, Ames, IA: Iowa State University. [SRDB Ref ID: 29252]

Karsjen SR [2003]. The Ames Project: History of the Ames Laboratory's contributions to the historic Manhattan Project, 1942-1946. Ames Laboratory, Ames, IA: Iowa State University. IS-T 2564. [SRDB Ref ID: 18859]

Klevin PB [1952]. Occupational exposure to thorium and beryllium. New York: U.S. Atomic Energy Commission, New York Operations Office. AMES-1, July 14. [SRDB Ref ID: 18942]

Lalos G, ed. [1989]. Film badge dosimetry in atmospheric nuclear tests. Washington, DC: National Research Council, National Academy Press. [SRDB Ref ID: 1905]

Landauer [1982–1983]. Landauer personnel exposure report 1982. Glenwood, IL: R. S. Landauer, Jr. & Co. [SRDB Ref ID: 26628]

Landauer [1983–1984]. Landauer personnel exposure report 1983. Glenwood, IL: R. S. Landauer, Jr. & Co. [SRDB Ref ID: 26631]

Landauer [1984]. Landauer personnel exposure report 1984. Glenwood, IL: R. S. Landauer, Jr. & Co. [SRDB Ref ID: 26632]

Landauer [1985–1986]. Landauer personnel exposure report 1985. Glenwood, IL: R. S. Landauer, Jr. & Co. [SRDB Ref ID: 26642]

Landauer [1985–1987]. Landauer personnel exposure report 1986. Glenwood, IL: R. S. Landauer, Jr. & Co. [SRDB Ref ID: 26645]

Landauer [1986–1988]. Landauer personnel exposure report 1987. Glenwood, IL: R. S. Landauer, Jr. & Co. [SRDB Ref ID: 26647]

Landauer [1988]. Landauer exposure reports 1988. Glenwood, IL. [SRDB Ref ID: 26653]

Landauer [1989–1990]. Landauer exposure reports 1989. Glenwood, IL. [SRDB Ref ID: 26657]

Landauer [1990]. Landauer exposure reports 1990. Glenwood, IL. [SRDB Ref ID: 26659]

Landauer [1991]. Landauer exposure reports 1991. Glenwood, IL. [SRDB Ref ID: 26664]

Landauer [1992]. Landauer exposure reports 1992. Glenwood, IL. [SRDB Ref ID: 26666]

Landauer [1992–1993]. Landauer exposure reports 1993. Glenwood, IL. [SRDB Ref ID: 26668]

Landauer [1994]. Landauer exposure reports 1994. Glenwood, IL. [SRDB Ref ID: 26672]

Landauer [1999a]. Landauer 1998 fourth quarter and YTD exposure reports. Glenwood, IL. February 11. [SRDB Ref ID: 26685]

Landauer [1999b]. Individual radiation exposure reports Landauer 1999. Glenwood, IL. February 16. [SRDB Ref ID: 26750]

Landauer [2000]. Landauer 2000 third quarter, YTD, and lifetime exposure report. Glenwood, IL. October 13. [SRDB Ref ID: 26799]

Landauer [2003]. Landauer 2002 fourth quarter and YTD exposure report. Glenwood, IL. February 7. [SRDB Ref ID: 26808]

Landauer [2004]. Landauer 2003 fourth quarter and YTD exposure report. Glenwood, IL. February 17. [SRDB Ref ID: 26809]

Leavitt MO [2006]. HHS designation of additional members of the Special Exposure Cohort under the Energy Employees Occupational Illness Compensation Program Act designating a class of employees from Ames Laboratory Ames, Iowa January 1, 1942 through December 31, 1954. Washington, DC: Department of Health and Human Services, Office of the Secretary. August 8. [SRDB Ref ID: 94027]

Leavitt MO [2007]. HHS designation of additional members of the Special Exposure Cohort under the Energy Employees Occupational Illness Compensation Program Act of 2000 designating a class of employees from Ames Laboratory Ames, Iowa January 1, 1955 through December 31, 1970. Washington, DC: Department of Health and Human Services, Office of the Secretary. September 12. [SRDB Ref ID: 94028]

Mattmueller FC [1965]. Failure of the Atomic Film Badge Corporation to provide results of personnel exposures for the period of April - June 1965. Letter to F.H. Spedding, Ames Laboratory. Argonne, IL: U.S. Atomic Energy Commission, Chicago Operations Office. August 25. [SRDB Ref ID: 25818]

McCartney KA [2006]. Statistical analysis of Ames Laboratory external dose records (1952-2005). Spreadsheet. Cincinnati, OH: Oak Ridge Associated Universities Team. [SRDB Ref ID: 30977]

Morgan KZ [1961]. Dosimetry requirements for protection from ionizing radiation. In: Selected topics in radiation dosimetry proceedings of the symposium on selected topics in radiation dosimetry sponsored by the International Atomic Energy Agency and held in Vienna, 7–11 June 1960, pp. 3–23. [SRDB Ref ID: 8345]

Napier BA [2006]. GENII Version 2 users' guide. Richland, WA: Pacific Northwest National Laboratory. PNNL-14583 Rev. 1, August. [SRDB Ref ID: 30771]

Napier BA [2007]. Occupational environmental doses for Ames Laboratory, U and Th operations. Memorandum to Dose Calculation File. Pacific Northwest National Laboratory, Richland, WA: Battelle Memorial Institute. March 15. [SRDB Ref ID: 30770]

Napier BA, Strenge DL, Ramsdell JV Jr., Eslinger PW, Fosmire C [2004]. GENII version 2 software design document. Pacific Northwest National Laboratory, Richland, WA: Battelle Memorial Institute. PNNL-14584, November. [SRDB Ref ID: 24168]

NCRP [1971]. NCRP 38 - Protection against neutron radiation. Bethesda, MD: National Council on Radiation Protection and Measurements. NCRP Report 38, January 4. [SRDB Ref ID: 11520]

NCRP [2003]. NCRP 144 - Radiation protection for particle accelerator facilities. Bethesda, MD: National Council on Radiation Protection and Measurements. NCRP Report 144, December 31. [SRDB Ref ID: 115764]

NIOSH [2004]. Estimation of ingestion intakes. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. OCAS-TIB-009 Rev. 0, April 13. [SRDB Ref ID: 22397]

NIOSH [2006]. Special Exposure Cohort petition evaluation report Petition SEC-00038 Rev. 0 Ames Laboratory qualified September 23, 2005. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Rev. 0, April 9. [SRDB Ref ID: 54550]

NIOSH [2007a]. Special Exposure Cohort petition evaluation report Petition SEC-00075 Rev. 0 Ames Laboratory qualified January 30, 2007. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Rev. 0, May 9. [SRDB Ref ID: 54551]

NIOSH [2007b]. External dose reconstruction implementation guideline. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. OCAS-IG-001 Rev. 3, November 21. [SRDB Ref ID: 38864]

NIOSH [2010a]. Radiation exposures covered for dose reconstructions under Part B of the Energy Employees Occupational Illness Compensation Program Act. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. DCAS-IG-003 Rev. 1, October 5. [SRDB Ref ID: 88929]

NIOSH [2010b]. Special Exposure Cohort petition evaluation report Petition SEC-00166 Rev. 0 Ames Laboratory qualified March 26, 2010. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Rev. 0, July 26. [SRDB Ref ID: 94025]

NIOSH [2011a]. Special Exposure Cohort petition evaluation report Petition SEC-00185 Rev. 0 Ames Laboratory qualified April 13, 2011. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Rev. 0, June 7. [SRDB Ref ID: 99020]

NIOSH [2011b]. Site profiles for atomic weapons employers that worked uranium metals. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Battelle-TBD-6000 Rev. 1, June 17. [SRDB Ref ID: 101251]

NIOSH [2017]. Special Exposure Cohort petition evaluation report Petition SEC-00245 Rev. 0 Ames Laboratory qualified December 6, 2017. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Rev. 0, November 30. [SRDB Ref ID: 172430]

NIOSH [2020]. Criteria for the evaluation and use of co-exposure datasets. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. DCAS-IG-006 Rev. 00, March 6. [SRDB Ref ID: 179686]

ORAUT [2004]. Technical information bulletin - assignment of environmental internal doses for employees not exposed to airborne radionuclides in the workplace. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-OTIB-0014 Rev. 00, June 22. [SRDB Ref ID: 19432]

ORAUT [2005]. Interpretation of dosimetry data for assignment of shallow dose. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-OTIB-0017 Rev. 01, October 11. [SRDB Ref ID: 19434]

ORAUT [2006a]. ALRR workers badged? E-mail to Oak Ridge Associated Universities Team. Oak Ridge, TN: Oak Ridge Associated Universities Team. November 1. [SRDB Ref ID: 29257]

ORAUT [2006b]. Unbadged workers at the Synchrotron. E-mail to Oak Ridge Associated Universities Team. Oak Ridge, TN: Oak Ridge Associated Universities Team. November 1. [SRDB Ref ID: 29256]

ORAUT [2006c]. Ames Laboratory, external dose records 1952 - 2005, ORAU Team project spreadsheet. Oak Ridge, TN: Oak Ridge Associated Universities Team. [SRDB Ref ID: 29229]

ORAUT [2006d]. Effect of threshold energy and angular response of NTA film on missed neutron dose at the Oak Ridge Y-12 facility. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-OTIB-0051 Rev. 00, May 15. [SRDB Ref ID: 29977]

ORAUT [2006e]. Technical basis for conversion from NCRP Report 38 neutron quality factors to ICRP Publication 60 radiation weighting factors for respective IREP input neutron energy ranges. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-OTIB-0055 Rev. 00, June 5. [SRDB Ref ID: 29980]

ORAUT [2006f]. A standard complex-wide methodology for overestimating external doses measured with film badge dosimeters. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-OTIB-0010 Rev. 01, June 5. [SRDB Ref ID: 29953]

ORAUT [2007]. Site profile for the Stanford Linear Accelerator Center. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-TKBS-0051 Rev. 01, August 17. [SRDB Ref ID: 34370]

ORAUT [2010]. Idaho National Laboratory and Argonne National Laboratory-West – site description. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-TKBS-0007-2 Rev. 04, August 2. [SRDB Ref ID: 84106]

ORAUT [2011]. Use of coworker dosimetry data for external dose assignment. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-OTIB-0020 Rev. 03, November 14. [SRDB Ref ID: 104029]

ORAUT [2012]. Dose reconstruction during residual radioactivity periods at atomic weapons employer facilities. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-OTIB-0070 Rev. 01, March 5. [SRDB Ref ID: 108851]

ORAUT [2013]. Site profile for the Brookhaven National Laboratory. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-TKBS-0048 Rev. 02, February 7. [SRDB Ref ID: 122464]

ORAUT [2014]. Analysis of stratified coworker datasets. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-RPRT-0053 Rev. 02, October 08. [SRDB Ref ID: 136245]

ORAUT [2017]. Guidance on assigning occupational X-ray dose under EEOICPA for X-rays administered off site. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-OTIB-0079 Rev. 02, June 15. [SRDB Ref ID: 166967]

ORAUT [2018]. Internal dose reconstruction. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-OTIB-0060 Rev 02, April 20. [SRDB Ref ID: 171554]

ORAUT [2021]. External dose reconstruction. Oak Ridge, TN: Oak Ridge Associated Universities Team. ORAUT-OTIB-0088 Rev. 02, June 11. [SRDB Ref ID: 187044]

ORAUT [2023]. ORAUT-TKBS-0055 rev. 04 support files zip file. Oak Ridge, TN: Oak Ridge Associated Universities Team. February 2. [SRDB Ref ID: 195852]

Pardue LA, Goldstein N, Wollan EO [1944]. Photographic film as a pocket radiation dosimeter. Chicago, IL: University of Chicago, Metallurgical Laboratory. CH-1553 (A-2223), April 8. [SRDB Ref ID: 8599]

Payne CS [1992]. The Ames Project: Administering classified research as a part of the Manhattan Project at Iowa State College, 1942-45. Dissertation. Ames, IA: Iowa State University. [SRDB Ref ID: 18851]

Rutherford LB [2022a]. Ames infeasibility question. E-mail to Oak Ridge Associated Universities Team. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. May 6. [SRDB Ref ID: 193212]

Rutherford LB [2022b]. Ames TBD guidance. E-mail to Oak Ridge Associated Universities Team. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. May 24. [SRDB Ref ID: 193213]

Sebelius K [2010]. HHS designation of additional members of the Special Exposure Cohort under the Energy Employees Occupational Illness Compensation Program Act of 2000 designating a class of employees from Ames Laboratory Ames, Iowa January 1, 1955 through December 31, 1960. Washington, DC: U.S. Department of Health and Human Services, Office of the Secretary. October 6. [SRDB Ref ID: 94029]

Sebelius K [2011]. HHS designation of additional members of the Special Exposure Cohort under the Energy Employees Occupational Illness Compensation Program Act of 2000 designating a class of employees from Ames Laboratory at Iowa State University Ames, Iowa August 13, 1942 through December 31, 1970. Washington, DC: U.S. Department of Health and Human Services, Office of the Secretary. October 18. [SRDB Ref ID: 141455]

Shleien B, Slaback LA Jr., Birky BK, eds. [1998]. Handbook of health physics and radiological health. 3rd ed. Baltimore, MD: Williams & Wilkins. [SRDB Ref ID: 22737]

Siemens [1995]. Siemens radiation exposure report November 1995. Hoffman Estates, IL: Siemens Medical Systems. November 15. [SRDB Ref ID: 26679]

Simpson SA [2001]. Ames Laboratory exposure data for 1st quarter of 2001. Letter to M. Saar, U.S. Department of Energy, Chicago Operations Office. Ames Laboratory, Ames, IA: Iowa State University. May 10. [SRDB Ref ID: 192222]

Struss RG [1987]. Tritium levels remaining in the former reactor facility. Letter to P. Neeson, U.S. Department of Energy, Chicago Operations Office. Ames Laboratory, Ames, IA: Iowa State University. May 27. [SRDB Ref ID: 18818]

Struss R, Hawkins L [1986]. The building of the Ames Laboratory. Ames Laboratory, Ames, IA: Iowa State University. October. [SRDB Ref ID: 18860]

Thornton WT, Davis DM, Gupton ED [1961]. The ORNL badge dosimeter and its personnel monitoring applications. Oak Ridge National Laboratory, Oak Ridge, TN: Union Carbide Corporation. ORNL-3126, December 5. [SRDB Ref ID: 8573]

Tybout RA [1944]. Urine results. Letter to F.H. Spedding, Iowa State College. Washington, DC: U.S. Department of War, U.S. Army Corps of Engineers. November 21. [SRDB Ref ID: 8959]

Voigt AF [1981]. Final report decommissioning of the Ames Laboratory research reactor. Ames Laboratory, Ames, IA: Iowa State University. IS-4789, December. [SRDB Ref ID: 25824]

Voss MD [1949]. Pocket chamber readings. Ames Laboratory, Ames, IA: Iowa State College. [SRDB Ref ID: 25819]

Voss MD [1957]. Medical X-ray exposure. Letter to P. Van Bemmel and J. Bacon, McFarland Clinic. Ames Laboratory, Ames, IA: Iowa State University. February 8. [SRDB Ref ID: 25846]

Voss MD [1963]. Survey of environmental radioactivity report 1. Ames Laboratory, Ames, IA: Iowa State University. December 31. [SRDB Ref ID: 25165]

Voss MD [1971]. Health physics memorandum bioassay program for monitoring personnel for tritium, sources of tritium at the Ames Laboratory. Ames Laboratory, Ames, IA: Iowa State University. September 1. [SRDB Ref ID: 25796]

Voss MD [1975]. Environmental monitoring at Ames Laboratory CY1974. Ames Laboratory, Ames, IA: Iowa State University. IS-3613, May. [SRDB Ref ID: 25446]

Voss MD [1976]. Environmental monitoring at Ames Laboratory CY1975. Ames Laboratory, Ames, IA: Iowa State University. IS-3856, April. [SRDB Ref ID: 25445]

Voss MD [1977]. Environmental monitoring at Ames Laboratory CY1976. Ames Laboratory, Ames, IA: Iowa State University. IS-4139, April. [SRDB Ref ID: 25444]

Voss MD [1979a]. History and current radiological condition of the Ames Laboratory. Letter to W.E. Mott, U.S. Department of Energy and A. Wollen, Aerospace Corporation. Ames Laboratory, Ames, IA: Iowa State University. December 3. [SRDB Ref ID: 18840]

Voss MD [1979b]. Environmental monitoring at Ames Laboratory CY1978. Ames Laboratory, Ames, IA: Iowa State University. IS-4679, April. [SRDB Ref ID: 18839]

Voss MD [1982]. Environmental summary for Ames Laboratory CY1981. Ames Laboratory, Ames, IA: Iowa State University. IS-4798, April. [SRDB Ref ID: 25429]

Voss MD [1987]. Tritium exposures/doses - committed dose - Applied Science Center. Memorandum to R. Struss and L. Mathison. Ames Laboratory, Ames, IA: Iowa State University. May 8. [SRDB Ref ID: 18817]

Wilson RH [1960]. Detection level of the film badge system. Hanford Works, Richland, WA: General Electric Company. HW-67697, November 28. [SRDB Ref ID: 15403]

Wilson RH [1987]. Historical review of personnel dosimetry development and its use in radiation protection programs at Hanford 1944-1980s. Pacific Northwest Laboratory, Richland, WA: Battelle Memorial Institute. PNL-6125, February. [SRDB Ref ID: 262]

Wilson RH, Fix JJ, Baumgartner WV, Nichols LL [1990]. Description and evaluation of the Hanford personnel dosimeter program from 1944 through 1989. Pacific Northwest Laboratory, Richland, WA: Battelle Memorial Institute. PNL-7447, September. [SRDB Ref ID: 4793]

GLOSSARY

absorption type
Categories for materials according to their rates 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 absorption into blood from the respiratory tract (moderate rate of solubilization), and S: deposited materials that are relatively insoluble in the respiratory tract (slow solubilization).

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.

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.

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.

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

curie (Ci)
Traditional unit of radioactivity equal to 37 billion (3.7×10^{10}) becquerels, which is approximately equal to the activity of 1 gram of pure ^{226}Ra.

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.

dose equivalent (DE, *H*)
In units of rem or sievert, product of absorbed dose in tissue multiplied by a weighting factor and sometimes by other modifying factors to account for the potential for a biological effect from the absorbed dose. See *dose*.

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 *film dosimeter* and *thermoluminescent dosimeter*.

dosimetry
Measurement and calculation of internal and external radiation doses.

dosimetry system
System for assessment of received radiation dose. This includes the fabrication, assignment, and processing of external dosimeters, and/or the collection and analysis of bioassay samples, and the interpretation and documentation of the results.

enriched uranium
Uranium in which processing has increased the proportion of ^{235}U to ^{238}U to above the natural level of 0.7% by mass. Reactor-grade uranium is usually about 3.5% ^{235}U; weapons-grade uranium contains greater than 90% ^{235}U.

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

film
(1) In the context of external dosimetry, radiation-sensitive photographic film in a light-tight wrapping. See *film dosimeter*. (2) X-ray film.

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.

fission product
(1) Radionuclides produced by fission or by the subsequent radioactive decay of radionuclides. (2) Fragments other than neutrons that result from the splitting of an atomic nucleus.

gamma radiation
Electromagnetic radiation (photons) 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; the difference is that X-rays do not originate in the nucleus.

hot cell
Shielded laboratory for handling of radioactive materials with the aid of remotely operated manipulators. The walls and windows are made of materials that protect workers from radiation.

intake
Radioactive material taken into the body by inhalation, absorption through the skin, injection, ingestion, or through wounds.

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.

ionizing radiation
Radiation of high enough energy to remove an electron from a struck atom and leave behind a positively charged ion. High enough doses of ionizing radiation can cause cellular damage. Ionizing particles include alpha particles, beta particles, gamma rays, X-rays, neutrons, high-speed electrons, high-speed protons, photoelectrons, Compton electrons,

positron/negatron pairs from photon radiation, and scattered nuclei from fast neutrons. See *beta radiation*, *gamma radiation*, *photon radiation*, and *X-ray radiation*.

minimum detectable amount (MDA)

Smallest amount (activity or mass) of an analyte in a sample that can be detected with a probability *β* of nondetection (Type II error) while accepting a probability *α* of erroneously deciding that a positive (nonzero) quantity of analyte is present in an appropriate blank sample (Type I error).

minimum detection level (MDL)

See *minimum detectable amount*.

missed dose

(1) In relation to external dose, dose to monitored workers that was not measured or recorded due to such factors as a missing or damaged dosimeter or a result below the detection limits of the dosimeter. Missed dose is especially important in the early years of radiation monitoring, when relatively high detection limits were combined with short exchange periods. (2) In relation to internal dose, potential dose that could have been received by a bioassay program participant but, because of limitations in the monitoring system, was undetected.

monitoring

Periodic or continuous determination of the presence or amount of ionizing radiation or radioactive contamination in air, surface water, groundwater, soil, sediment, equipment surfaces, or personnel (for example, bioassay or alpha scans). In relation to personnel, monitoring includes internal and external dosimetry including interpretation of the measurements.

natural uranium

Uranium as found in nature, approximately 99.27% ^{238}U, 0.72% ^{235}U, and 0.0054% ^{234}U by mass. The specific activity of this mixture is 2.6×10^7 becquerel per kilogram (0.7 microcuries per gram). See *uranium*.

neutron (n)

Basic nucleic particle that is electrically neutral with mass slightly greater than that of a proton. There are neutrons in the nuclei of every atom heavier than normal hydrogen.

nuclear track emulsion, type A (NTA)

Film made by the Eastman Kodak Company that is sensitive to fast neutrons. The developed image has tracks caused by neutrons that become visible under oil immersion with about 1,000-power magnification. The number of tracks in a given area is a measure of the dose from that radiation.

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 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.

personal dose equivalent [*Hp(d)*]

Dose equivalent in units of rem or sievert in soft tissue below a specified point on the body at an appropriate depth *d*. The depths selected for personal dosimetry are 0.07 millimeters (7 milligrams per square centimeter) and 10 millimeters (1,000 milligrams per square centimeter), respectively, for the skin (shallow) and whole body (deep) doses. These are noted as *Hp(0.07)* and *Hp(10)*, respectively. In 1993 the International Commission on Radiological Measurement and Units recommended *Hp(d)* as the dose quantity for radiological protection.

photon

Quantum of electromagnetic energy generally regarded as a discrete particle having zero rest mass, no electric charge, and an indefinitely long lifetime. The entire range of electromagnetic radiation that extends in frequency from 10^{23} cycles per second (hertz) to 0 hertz.

photon radiation

Electromagnetic radiation that consists of quanta of energy (photons) from radiofrequency waves to gamma rays.

progeny

Nuclides that result from decay of other nuclides. Also called decay products and formerly called daughter products.

radiation

Subatomic particles and electromagnetic rays (photons) with kinetic energy that interact with matter through various mechanisms that involve energy transfer. See *ionizing radiation*.

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.

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.

roentgen (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} coulomb per kilogram (or 1 electrostatic unit of electricity per cubic centimeter) of dry air at 0 degrees Celsius and standard atmospheric pressure. An exposure of 1 roentgen is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher energy photons (generally greater than 100 kiloelectron-volts).

routine monitoring

Monitoring carried out at regular intervals during normal operations.

synchrotron

Roughly circular particle accelerator in which the particles travel in synchronized bunches at a fixed radius.

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.

unmonitored dose
Potential unrecorded dose that could have resulted because a worker was not monitored. See *missed dose*.

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. See *enriched uranium* and *natural uranium*.

whole body dose
Dose to the entire body excluding the contents of the gastrointestinal tract, urinary bladder, and gall bladder and commonly defined as the absorbed dose at a tissue depth of 10 millimeters (1,000 milligrams per square centimeter). Also called penetrating dose. See *dose*.

X-ray radiation
Electromagnetic radiation (photons) produced by bombardment of atoms by accelerated particles. X-rays are produced by various mechanisms including bremsstrahlung and electron shell transitions within atoms (characteristic X-rays). Once formed, there is no difference between X-rays and gamma rays, but gamma photons originate inside the nucleus of an atom.

ATTACHMENT A
EXTENDED DESCRIPTION OF FIGURE 6-2 FLOWCHART

This attachment describes Figure 6-2 for accessibility by visually impaired readers. It is a flowchart to guide dose reconstructors in constructing doses for monitored or unmonitored workers. There are two pathways, one for monitored workers and one for unmonitored workers.

The monitored workers pathway is on the left with five boxes indicating sequential steps.

1. The first box instructs the reader to, for 1953 to present, tabulate beta, photon, and neutron doses of record for each year.

2. The second box instructs the reader to multiply beta/photon doses by uncertainty correction factor and contains a footnote (a) that gives the uncertainty correction factors as ±30% and 1.3 for beta/gamma film badges, ±20% and 1.2 for TLDs before 1985, and ±10% and 1.1 for TLDs after NVLAP accreditation in 1985.

3. The third box instructs the reader to add adjustments for missed and zero doses after 1961, with a footnote (b) that indicates that adjustments for missed and zero doses have been made to the dose of record for years before 1962 and informs the reader that more information is in Section 6.2.1.

4. The fourth box instructs the reader to multiply the neutron dose of record by correction factor of 2 and parenthetically states that this dose does not apply to missed dosed. A footnote (c) is included that states the correction factor is 2 for NTA film badges and instructs the reader to see Section 6.2.5.3.

5. The fifth box instructs the reader to adjust the neutron dose using the ICRP [1991] weighting factor by multiplying by 1.91 with a footnote (d) that states that the neutron weighting factor adjustment is for neutron energies from 0.1 to 2 MeV.

The unmonitored workers pathway is on the right with three drop boxes indicating sequential steps.

1. The first box instructs the reader to tabulate annual assigned doses from Table 6-3 and instructs the reader to see the text in Section 6.3.1 for explanation and guidance.

2. The second box instructs the reader to multiply the assigned neutron dose by a correction factor of 2. A footnote (c) is included that states the correction factor is 2 for NTA film badges and instructs the reader to see Section 6.2.5.3.

3. The third box instructs the reader to adjust the neutron dose using the ICRP [1991] weighting factor by multiplying by 1.91 with a footnote (d) that states that the ICRP [1991] neutron weighting factor adjustment is for neutron energies from 0.1 to 2 MeV.

A note under the footnotes states that the photon and neutron organ dose conversion factors are not included in this flowchart and must be applied separately.