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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
06/21/2004	00-A	New technical basis document for the ANL-W Site Facilities and Processes. Initiated by Norman D. Rohrig.
08/17/2004	00-B	Incorporates NIOSH review comments. Initiated by Norman D. Rohrig.
09/09/2004	00	First approved issue. Initiated by Norman D. Rohrig.
06/22/2007	01	Approved revision initiated for biennial review. Added Purpose, Scope, and Attributions and Annotations sections. Updated References and formatting. Incorporates formal internal review comments. No further changes occurred as a result of formal NIOSH review . Constitutes a total rewrite of document. This revision results in no change to the assigned dose and no PER is required. Training required: As determined by Task Manager. Initiated by Jo Ann M. Jenkins.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AFSR	Argonne Fast Source Reactor
ANL	Argonne National Laboratory
ANL-E	Argonne National Laboratory – East
ANL-W	Argonne National Laboratory – West
BORAX	Boiling-Water Reactor Experiment
BWR	boiling-water reactor
CAM	continuous air monitor
CFA	Central Facilities Area
Ci	curie
cm	centimeter
DOE	U.S. Department of Energy
DOE-ID	DOE Idaho Operations Office
DU	depleted uranium
EBR	Experimental Breeder Reactor
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
FASB	Fuel Assembly and Storage Building
FMF	Fuel Manufacturing Facility
ft	foot
g	gram
gal	gallon
HFEF	Hot Fuel Examination Facility
hr	hour
IDO	Idaho Operations Office
IMBA	Integrated Modules for Bioassay Analysis
in.	inch
INL	Idaho National Laboratory
IREP	Interactive RadioEpidemiological Program
IWP	Industrial Waste Pond
kg	kilogram
kW	kilowatt
m	meter
MAP	mixed activation product
MFP	mixed fission product
mi	mile
min	minute
mR	milliroentgen
mrem	millirem
MW	megawatt

n	neutron
NIOSH	National Institute for Occupational Safety and Health
NRAD	Neutron Radiography Facility
NRTS	National Reactor Testing Station
ORAU	Oak Ridge Associated Universities
POC	probability of causation
psi	pounds per square inch
psig	pounds per square inch gauge
RAM	radiation (or remote) area monitor
s	second
SRDB Ref ID	Site Research Database Reference Identification (number)
TBD	technical basis document
TLD	thermoluminescent dosimeter
TREAT	Transient Reactor Experiment and Test (facility)
U.S.C.	United States Code
yd	yard
ZPPR	Zero Power Plutonium (later Physics) Reactor
ZPR	Zero Power Reactor
µCi	microcurie
°C	degree Celsius
§	section or sections

2.1 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH staff in the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy [DOE] facility" as defined in the Energy Employees Occupational Illness Compensation Program Act [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility as "any building, structure, or premise, including the grounds upon which such building, structure, or premise is located … in which operations are, or have been, conducted by, or on behalf of, the Department of Energy (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program)" [42 U.S.C. § 7384l(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled "Exposure in the Performance of Duty." That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer "shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) … " [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation) define "performance of duty" for DOE employees with a covered cancer or restrict the "duty" to nuclear weapons work.

As noted above, the statute includes a definition of a DOE facility that excludes "buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program" [42 U.S.C. § 7384l(12)]. While this definition contains an exclusion with respect to the Naval Nuclear Propulsion Program, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled "Exposure in the Performance of Duty"] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external dosimetry monitoring results are considered valid for use in dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived:

- Radiation from naturally occurring radon present in conventional structures
- Radiation from diagnostic X-rays received in the treatment of work-related injuries

[1] The U.S. Department of Labor is ultimately responsible under the EEOICPA for determining the POC.

2.1.1 Purpose

The purpose of this TBD is to assist in the evaluation of worker dose from Argonne National Laboratory – West (ANL-W) processes using the methodology in *External Dose Reconstruction Implementation Guideline* (NIOSH 2006) and *Internal Dose Reconstruction implementation Guideline* (NIOSH 2002).

2.1.2 Scope

This TBD provides supporting technical data to evaluate, with assumptions that are favorable to claimants, the total ANL-W occupational dose that can be reasonably associated with worker radiation exposure as covered in the EEOICPA legislation. This TBD describes facilities, processes, and historical information in relation to worker internal and external exposures for use when actual monitoring data might be unavailable. The information in this TBD is primarily from the INL Site Description TBD (ORAUT 2005).

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 2.3.

2.2 SITE ACTIVITIES AND PROCESSES, FEBRUARY 1951 TO FEBRUARY 2005

Proving the Principle, *A History of the Idaho National Engineering and Environmental Laboratory, 1949-1999* (Stacy 2000) was a resource in the development of facility and process descriptions.

In 1949, the U.S. Atomic Energy Commission (AEC) established the National Reactor Testing Station (NRTS) in Idaho as a Federal reservation to build, test, and operate nuclear reactors. In 1974, the NRTS became the Idaho National Engineering Laboratory and, in 1997, the Idaho National Engineering and Environmental Laboratory. In 2005, the site became the Idaho National Laboratory (INL).

ANL-W operated on the INL site, an 890-mi^2 (572,000-acre) reservation with maximum dimensions of about 39 mi from north to south and 36 mi from east to west. It is 30 to 60 mi west of Idaho Falls, Idaho. The site is on the Snake River Plain of southeastern Idaho at an elevation of about 5,000 ft. INL played a major role in early reactor research and development; ANL-W performed much of this work. The INL site has operated 52 reactors, about 12 of them by ANL-W, plus fuel handling and reprocessing and radioactive waste storage and disposal facilities since it began operations in 1949 (Stacy 2000).

ANL-W was originally known as the Idaho Division of Argonne National Laboratory (ANL). It was an extension of what is now known as Argonne National Laboratory – East (ANL-E) near Chicago, Illinois. ANL is a research laboratory that has been operated by the University of Chicago throughout its history. The original ANL-W site is in the southwest portion of INL, approximately 18 mi via Highway 20/26 east of Arco, 40 mi via Highway 26 northwest of Blackfoot, or 50 mi west via Highway 20 from Idaho Falls. The original ANL-W location is now a National Historic Landmark and is the site of the decommissioned Experimental Breeder Reactor No. 1 (EBR-I), Boiling-Water Reactor Experiment (BORAX), Argonne Fast Source Reactor (AFSR), and Zero Power Reactor No. 3 (ZPR-III) facilities.

The more recent ANL-W site is in the southeast portion of INL, about 35 mi west of Idaho Falls. There are 52 major buildings at this site including reactor buildings, laboratories, warehouses, technical and administrative support buildings, and craft shops. In February 2005, ANL-W was absorbed into the

INL during a contract reconfiguration. Figure 2-1 shows the relative location of each facility or technical area discussed in this TBD, including the EBR-II, Transient Reactor and Experiment Test (TREAT) facility, and Zero Power Plutonium Reactor (ZPPR). ANL-W operated the EBR-I and BORAX areas before their shutdowns. Other INL facilities that are indicated on Figure 2-1 include the Auxiliary Reactor Area, Central Facilities Area (CFA), Idaho Chemical Processing Plant (now the Idaho Nuclear Technology and Engineering Complex), Radioactive Waste Management Complex, Special Power Excursion Reactor Test area, Grid III, Test Reactor Area, Experimental Field Station, and Naval Reactors Facility (Hoff, Chew, and Rope 1987, p. 46).

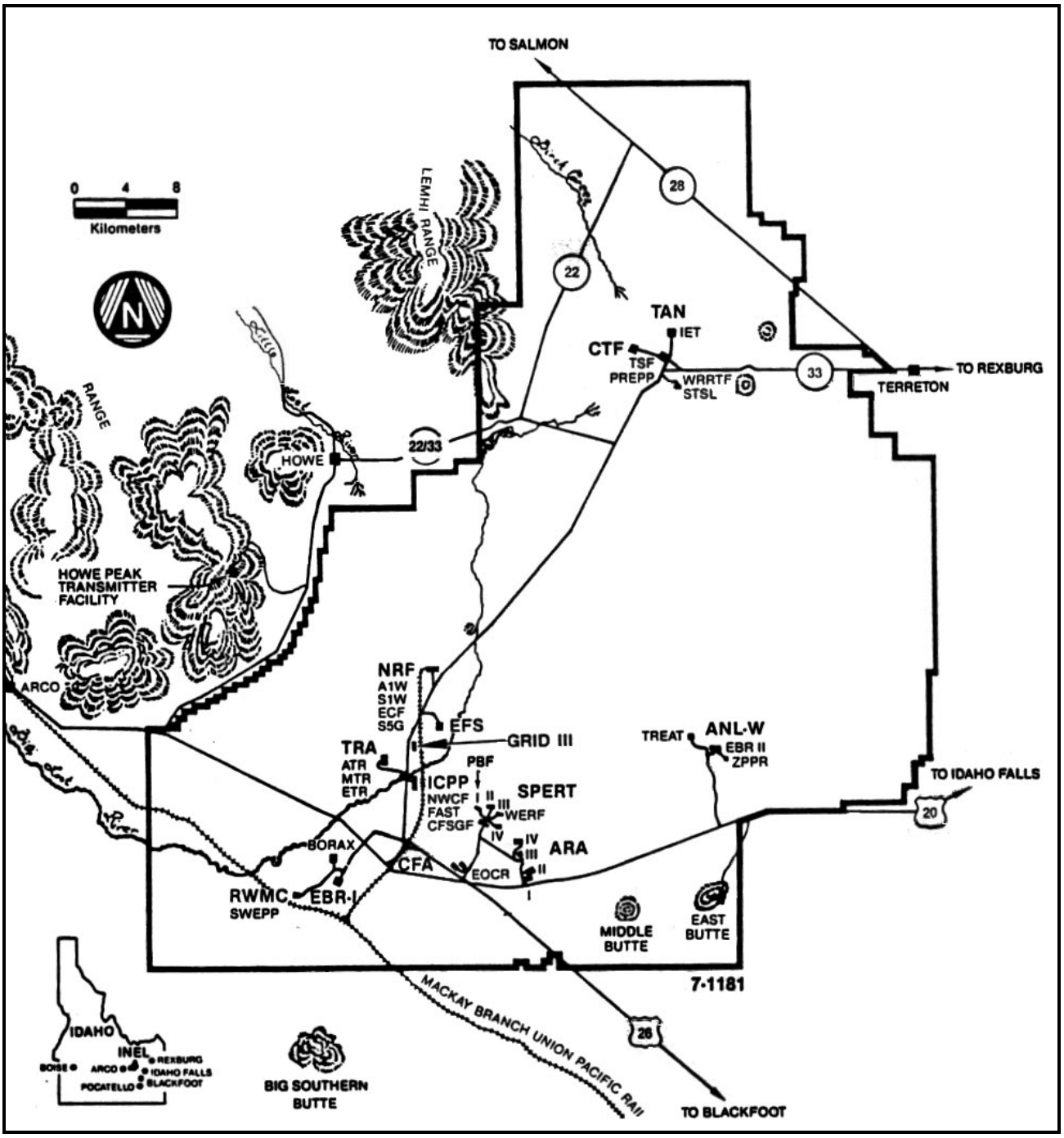

Figure 2-1. Idaho National Laboratory showing ANL-W facilities.

Dosimetry services at INL including ANL-W were unique among DOE facilities in that DOE Idaho Operations Office (IDO) personnel operated and provided internal and external dosimetry services. The IDO Dosimetry Branch provided and analyzed external dosimetry badges, counted workers in the whole-body counter, and analyzed bioassay samples. At first, IDO personnel at the Radiological Environmental Sciences Laboratory in Building CF-690 in the CFA maintained exposure histories of personnel based on dosimetry records, including bioassay data. With the advent of the DOE Laboratory Accreditation Program, dosimetry responsibility transferred to the prime contractor on January 2, 1989, to eliminate a conflict of interest on the part of IDO.

Personnel working at ANL-W in designated radiological areas were typically required to wear state-of-the-art dosimetry [film badges, thermoluminescent dosimeters (TLDs), personal ion chambers, etc.] as well as respiratory protection, anticontamination clothing, etc. [1]. Facilities and radiological areas were monitored by remote and portable radiation/remote area monitors (RAMs) and continuous air monitors (CAMs). Portable RAMs, CAMs, air samplers, etc., were used for work where fixed units were not available [2]. If airborne radioactivity might have been present or if internal exposure was possible, applicable respirators were provided to prevent or reduce internal exposure [3].

Engineered systems were incorporated as practicable to minimize the potential for radiological airborne radioactivity and direct radiation exposure. Bioassay programs were instituted to monitor and assess potential internal exposures. Environmental monitoring systems were placed around the site at multiple locations to measure direct radiation, fallout, and effluent discharges or releases to onsite personnel and members of the public. There have been film or TLD badges in specific building areas for each facility and around perimeter fences to measure direct environmental radiation accumulation as a check and balance on source terms within site locations [4].

The following sections describe the facilities and the associated operations for ANL-W. Table 2-1 lists common radionuclides for reactors.

Table 2-1. Radionuclides of concern for all reactors [5].

Am-241	Co-60	I-131	Ru-103
Ba-140	Cr-51	I-133	Ru-106
Ce-141	Cs-134	La-140	Sr-90/Y-90
Ce-143	Cs-137	Mn-54	Sr-91
Ce-144	Eu-152	Nb-95	Sr-92
Cm-242	Eu-154	Np-239	U-234
Cm-244	Fe-59	Pu-238	Zn-65
Co-58	H-3	Pu-239	Zr-95

2.2.1 Experimental Breeder Reactor No. 1, April 1951 to December 30, 1963

The date information is from Stacy (2000, p. 262). EBR-I, the first reactor built at INL, was a NaK-cooled, solid-fuel (enriched uranium), unmoderated heterogeneous fast reactor designed for full-power operation at a level of 1 MW. It was built to explore the possibilities of breeding nuclear fuel and for the use of liquid metal cooling. A blanket of ^{238}U around the core provided the fertile material in which nuclear material breeding took place.

Because the primary coolant was intensely radioactive during and shortly after operation, all primary components were enclosed in concrete-shielded cells. The secondary coolant, which was nonradioactive, required no shielding (Kittel, Novick, and Buchanan 1957). The facility was entirely inside a single building of brick, concrete, and steel. Construction of EBR-I began in May 1949 and was complete in April 1951. Reactor startup occurred on August 24, 1951.

On November 29, 1955, the reactor suffered a 40% to 50% core meltdown. Radiation detection instrumentation measured radioactivity in the building above normal background levels, and all personnel were evacuated (Zinn 1956; Stacy 2000, p, 135). After the partial meltdown, the core assembly was removed from the reactor through a temporary cave constructed on the reactor top and shipped to ANL-E (Kittel, Novick, and Buchanan 1957). The core was replaced, and the reactor remained operational until December 30, 1963 (Stacy 2000). On August 26, 1966, EBR-I was dedicated as a National Historic Landmark. The principal radiological activity associated with the coolant during operation and shortly after shutdown was ^{24}Na with a half-life of 15 hr. The saturation level at full-power operation was approximately 24 µCi/g. The second most significant activity was about 2 µCi/g ^{137}Cs, which apparently entered the system during and after the meltdown incident. No other long-lived activity was identified in the primary coolant. Short-lived activity in the form of ^{133}Xe and ^{135}Xe was observed in the cover gas (Haroldson et al. 1963).

Internal exposure potential existed from airborne radioactivity from mixed fission products (MFPs) and mixed activation products (MAPs) [6].

External exposure occurred from MFPs and MAPs during activities associated with reactor operation and maintenance [7].

2.2.2 Boiling-Water Reactor Experiment No. 1, Late 1953 to July 22, 1954

The date information is from Stacy (2000, p. 261). BORAX-I was an open-top, water-cooled, water-moderated, boiling-water reactor (BWR) used to conduct a series of nondestructive experiments in the latter part of 1953 and early summer of 1954 (Dietrich 1956). The reactor was built in an excavated area approximately 0.5 mi northwest of EBR-I and was housed in a 10-ft-diameter tank open to the atmosphere. The control room was approximately 0.5 mi away near EBR-I.

BORAX-I was intentionally destroyed in its final experiment on July 22, 1954. The explosion scattered fuel plate fragments and other debris over an area of approximately 200 by 350 ft south of the reactor area fence. Instrumentation at the control center showed an instantaneous radiation level higher than 500 mrem/hr, which decreased in about 30 s to 25 mrem/hr and within 5 min to less than 1 mrem/hr. Detailed discussions of this incident are available (Griffiths, Sill, and Wilhelmsen 1956; Brodsky and Beard 1960).

Internal exposure might have occurred from airborne radioactivity during operation and other associated activities, core destruction, coolant, and cleanup activities [8].

External exposure occurred from direct radiation associated with the reactor operation and maintenance activities from MFPs and MAPs [9].

2.2.3 Boiling-Water Reactor Experiment No. 2, October 19, 1954, to March 1955

The date information is from Stacy (2000, p. 261). BORAX-II replaced BORAX-I as a new reactor that would more closely approximate the characteristics of a practical power reactor operating on the boiling-water principle (Dietrich 1956). BORAX-II, a short distance northeast of the BORAX-I site, was built in 1954 and became operational on October 19, 1954. It was significantly larger than BORAX-I. The vessel was shielded by concrete and housed in a sheet-metal building. Tests of new core combinations used various enrichments of ^{235}U in metal fuel plates (AEC 1962). The boiling-water system operated at 300 psi, which essentially made BORAX-II a power experiment. The power level was about 6.4 MW-thermal but, because it had no turbine generator, it produced no electricity. The energy produced was released in the form of steam (Dietrich 1956).

Internal exposure was possible from MAPs associated with activities involving the reactor coolant [10].

External exposure occurred during routine operations and loading and unloading of fuel [11].

2.2.4 Boiling-Water Reactor Experiment No. 3, June 9, 1955, to December 1956

The date information is from Stacy (2000, p. 261). A program began in March 1955 to modify the BORAX-II reactor to produce electrical energy. The modified reactor became BORAX-III. The previous BORAX reactors were not designed to produce electricity, so a turbine generator was added to the facility to convert thermal energy to electricity. The modified facility was capable of generating 12 MW of thermal energy and 2,300 kW of electrical energy. For 2 hr on July 17, 1955, BORAX-III generated approximately 2,000 kW of electricity; 500 kW were used to power the BORAX-III facility, 1,000 kW were used to power the CFA at the NRTS, and 500 kW were used to light the entire town of Arco, Idaho. BORAX-III became the first nuclear power plant in the world to generate electricity for an entire city. It was operational from June 9, 1955, until sometime before December 3, 1956.

Internal exposure was possible from MAPs associated with activities involving the reactor coolant [12]. Fuel cladding failure occurred, and resulting radionuclides were identified in the reactor water (Zinn et al. 1956).

External exposure occurred from routine operation and loading and unloading of fuel [13]. High radiation levels (up to 430 mR/hr) were reported associated with the steam system. Decay curves were measured for the steam, condensate, and reactor water (~10^4 higher activity) (Zinn et al. 1956). Nitrogen-16 was identified as the principal radiation source in the coolant (Dietrich, Lichtenberger, and Zinn 1956).

2.2.5 Boiling-Water Reactor Experiment No. 4, December 3, 1956, to June 1958

The date information is from Stacy (2000, p. 261). BORAX-IV, the successor to BORAX-III, began operation in December 1956. This reactor, with a design power of 20 MW-thermal, was used principally to test high-thermal-capacity fuel elements made from ceramics of uranium and thorium (Handwerk, Hoenig, and Lied 1957). Like the previous BORAX reactors, BORAX-IV was a BWR operating at 300 psig. It was capable of producing 2.5 MW of electricity. It was brought to criticality on December 3, 1956, at atmospheric pressure. BORAX-IV operated with a core of uranium-thorium fuel elements until April 17, 1957. Beginning in May 1957, it operated with a 59-element core at 300 psig and 216°C and continued intermittent operations until December 5, 1957. After the core was revised to increase the maximum power, the reactor was restarted on February 19, 1958, to evaluate the effect of operating with a fuel element defect and to identify defective elements in the core (Robertson and Hall 1959). BORAX-IV released approximately 4,565 Ci of short-lived radionuclides to the atmosphere in March 1958 (Novick 1958). It operated until June 1958. The following measurements were made during reactor operations (Robertson and Hall 1959):

- Radiation levels of the steam plant equipment
- Quantitative determination of fission gases ^{138}Xe and ^{88}Kr, which were released to the atmosphere through the air ejector
- Analysis of reactor water, condensed steam before the turbine, and condensed steam after the turbine (hot-well condensate) for fission products
- Area contamination downwind from the reactor

Internal exposure might have occurred during work with the defective fuel elements or during planned releases of short-lived fission activity and from airborne MAPs and MFPs associated with the reactor coolant [14].

External exposure occurred during operation and loading and unloading of fuel [15].

2.2.6 Boiling-Water Reactor Experiment No. 5, February 9, 1962, to September 1964

The date information is from Stacy (2000, p. 261). BORAX-V was a flexible BWR with the same configuration as BORAX-IV and was used primarily for testing nuclear superheating concepts. The facility was operational from February 9, 1962, until September 1964.

Internal exposure might have occurred from coolant and airborne activity during routine BWR operation with fuel elements made from ceramics of uranium and thorium and from associated maintenance work [16].

External exposure occurred from routine activities associated with reactor operation and maintenance [17].

2.2.7 Zero Power Reactor No. 3, October 1955 to November 1970

The date information is from Stacy (2000, p. 268). ZPR-III was a low-power, split-table reactor that achieved criticality by bringing two halves of a fuel configuration together. It was used to determine the accuracy of predicted mass geometries and critical measurements for fast reactor core designs.

The building consisted of a reinforced concrete high-bay assembly room and a one-story section that contained the control room, workroom, vault, laboratory rooms, offices, etc. The assembly (reactor) room of reinforced concrete was approximately 45 by 42 by 29 ft high (Brittan et al. 1961).

The assembly machine was a platform on which two tables or carriages were mounted, one of which was moveable. Half of the reactor was built up on each carriage by inserting drawers containing the reactor material into a matrix structure. Each half of the assembly contained five safety control rods and a 15-Ci polonium-beryllium neutron source. Workers could swing a hinged platform into place between the halves on which they could stand while loading or unloading the machine.

The storage vault room was approximately 29 ft long by 26 ft wide with walls and roof of reinforced concrete 9 in. thick. The fuel slugs were stored either on racks or in special *birdcage* containers that limited the storage density to 2 kg $^{235}U/ft^3$.

Internal exposure potential existed from possible airborne radioactivity during maintenance operations from MFPs and MAPs [18].

External exposure occurred during maintenance activities and during loading and unloading of fuel [19].

2.2.8 Argonne Fast Source Reactor, October 29, 1959, to Late 1970s

The date information is from Stacy (2000, p. 261). AFSR was a small fast reactor facility designed to produce neutrons for the development of special equipment for the EBR-I, EBR-II, and ZPR-III fast reactor programs. AFSR, built in 1954 with a design power of 1 kW, was in a prefabricated Butler-type building with its own heating and air compressor plant near the EBR-I facility. No water was

plumbed into the building. Control and safety mechanisms were in a pit below the reactor. The reactor, designed to supply both fast and thermal neutron fluxes for laboratory experiments, was built around a cylindrical core of solid highly enriched uranium with a blanket of solid depleted uranium (DU; Brunson 1959). Reactor startup occurred on October 29, 1959; the reactor was operational until the late 1970s when it was moved to a new location adjacent to the ZPPR facility at the ANL-W site. The reactor is now shut down and defueled.

Internal exposure might have occurred during routine operations that could create airborne radioactivity [20].

External exposure occurred from maintenance activities and loading and unloading of fuel [21].

2.2.9 Transient Reactor Test and Experiment Facility, February 23, 1958, to April 1994

The following information is from Stacy (2000, p. 268). TREAT was an air-cooled thermal heterogeneous system designed to evaluate reactor fuels and other material under conditions that simulated various types of reactor excursions. Construction began in February 1958 and ended in November 1958, and criticality occurred on February 23, 1959. The TREAT complex consists of a reactor building and a control building approximately 1 mi northwest of the EBR-II containment building (Freund et al. 1960).

The reactor building features a high-bay section and an adjacent service wing. The high-bay section contains the reactor, fuel storage pit, instrument room, and the basement subreactor and equipment rooms. The control building is a single-story concrete block structure approximately 0.5 mi from the reactor that contains control panels and necessary instrumentation for remote control of the reactor.

Shielding permitted personnel access around and atop the reactor during steady-state operations at 100 kW. Access to the subreactor room was controlled during steady-state operation. Before transient operations, the building was evacuated of all personnel. General neutron and gamma radiation levels at a distance of 10 ft from the reactor during operations at 100 kW were (Freund et al. 1960):

- Fast neutrons Negligible
- Thermal neutrons 50 to 1,500 n/cm^2/s
- Gamma 5 to 8 mrem/hr

Internal exposure might have occurred during routine operations that could create airborne radioactivity; however, it was not expected to occur [22].

External exposure occurred from routine operations [23].

2.2.10 Experimental Breeder Reactor No. II, May 1961 to September 30, 1994

The date information is from Stacy (2000, p. 262). EBR-II at the ANL-W site is a liquid sodium-cooled, unmoderated, heterogeneous fast breeder reactor rated at 62.5 MW-thermal with an intermediate closed loop of secondary sodium and a steam plant capable of producing electric power through a conventional turbine generator. A fuel processing facility is attached to the reactor. EBR-II was designed to prove the breeding of fuels and the feasibility of a central power station and onsite fuel processing. It met these objectives in the late 1960s, and its role changed to test reactor. Construction of EBR-II ended in May 1961, and the reactor reached criticality on September 30, 1961. It operated until September 30, 1994, when it was taken to a subcritical configuration and shut down

to start a defueling operation. On January 19, 2001, ANL-W verified that the liquid-metal sodium coolant had been completely drained from the reactor vessel. At present, the reactor is defueled, the sodium systems are drained, and the power plant is depressurized.

The reactor was submerged in a primary tank that contained approximately 90,000 gal of liquid sodium. This tank was suspended in an airtight steel-shell containment building of 1-in.-thick steel plate, which would contain an accidental release of fission products, etc., from the primary system. The structure of the primary system was designed to contain the energy release associated with a reactor incident. The reactor building was designed to confine the effects of a maximum sodium-air interaction caused by a major sodium release. The reactor consisted of an enriched core surrounded on all sides by a fertile blanket of DU (McVean et al. 1962; Koch et al. 1957).

The Sodium Plant contains pumping, purification, and storage facilities for the secondary sodium system. It also contains a receiving station for the sodium. The building was not normally occupied. The primary and secondary coolant from EBR-II was converted in the Sodium Processing Facility from its elemental, chemically unstable form to a chemically stable composition suitable for landfill disposal.

The Fuel Manufacturing Facility (FMF) is a secure facility designed for the fabrication of EBR-II fuel. The FMF vault stored Special Nuclear Material in support of the EBR-II shutdown.

An additional building, the Laboratory and Office Building near the EBR-II plant, provided supporting analytical and personnel facilities.

2.2.11 Hot Fuel Examination Facility, 1964 to 2006

The Hot Fuel Examination Facility (HFEF) complex consists of two hot cell facilities, HFEF/South and HFEF/North. HFEF/South, originally known as the Fuel Cycle Facility and/or the Fuel Conditioning Facility, was used to demonstrate remote processing and refabrication of uranium-fission, metal-alloy, driver fuel elements in a closed cycle with EBR-II.

Some 35,000 fuel elements were remotely reprocessed and refabricated into EBR-II subassemblies between 1964 and 1968. HFEF/South contains two large heavily shielded hot cells, one with an inert gas (argon) atmosphere and the other with an air atmosphere. The shielding walls of both cells are of high-density concrete. The HFEF/South air cell was decontaminated and refurbished in 1969 and again in 1976 (Baca 1979).

HFEF/North is a large alpha-gamma hot cell facility that was activated in March 1975. This facility provided the capability for postirradiation and nondestructive or destructive examination of fuel and material experiments irradiated in EBR-II (Baca 1979). HFEF/North contains two hot cells, one with an argon gas atmosphere and the other with an air atmosphere. The air atmosphere cell is known as the decontamination cell. The shielding walls of both cells are of high-density concrete (Baca 1979). HFEF began operation as a fully automated facility for examining highly radioactive experimental reactor fuel elements and other components in 1975. The examinations conducted in HFEF provide data that are essential for the determination of the performance and condition of fuels and materials irradiated in DOE reactor facilities. HFEF continues in operation as a vital component of the DOE energy research program.

Remote characterization of material to be shipped to the Waste Isolation Pilot Plant in New Mexico for disposal takes place in the Waste Characterization Area of the HFEF high bay.

Internal exposure might have occurred during cell entries when suspended radioactive contamination materials could cause airborne radioactivity from MFPs and MAPs [24].

External exposure occurred when entries to the hot cell were made after experiment processes or during equipment maintenance and refurbishment [25].

2.2.12 Zero Power Plutonium (Physics) Reactor, April 18, 1969, to April 1992 (standby)

The date information is from Stacy (2000, p. 268). ZPPR is a split-table critical facility approximately 300 m from EBR-II in the ANL-W area and about 3 mi north of U.S. Highway 20. The facility is divided into two areas, the mound area and the support wing. The mound area consists of the reactor cell, fuel storage vault, workroom, and equipment rooms as well as access and escape tunnels. The reactor cell is a 50-ft-diameter circular room with floor and walls of reinforced concrete. The roof consists of layers of washed and dried sand and gravel supported by a catenary cable network.

The basic element of the ZPPR is a bed-and-table system that holds the matrix assembly. The two tables, one moveable and one stationary, are supported on a cast steel bed. The control and safety rod drives are mounted near the rear of each table. The main floor consists of the reactor control room, offices, an electronics shop, and a core coating room. The core coating room, adjacent to the control room and the entrance to the mound area, is used to clean core stimulants such as ^{235}U and stainless steel. The room contains two hoods for handling suspect materials and a core coating machine that is used primarily to dry and coat DU with a protective film [26].

Internal exposure potential was minimal due to the use of hoods and other protective equipment [27].

External exposure occurred from working with reactor processes, loading and unloading of fuel, etc. [28].

2.2.13 Neutron Radiography Facility, October 1, 1977 to 2006

The Neutron Radiography (NRAD) Facility is a 250-kW, steady-state Training, Research, Isotope, General Atomics reactor in the basement beneath the HFEF/North main cell. The reactor core consists of fuel elements surrounded by graphite assemblies. The core is submerged in a water-filled tank. NRAD began operation in March 1978, with two radiography stations (Richards and McClellan 1979). The East station services the hot cell complex where specimens can be radiographed without removal from the hot cell environment (Richards and McClellan 1979). The North station is outside the cell in a separate clean, shielded location for the radiography of irradiated or unirradiated items without introducing them into the contaminated cell (Richards and McClellan 1979). Cask handling and specimen shielding allow for full-size reactor assemblies. The radiography room is easily accessible for development work (Richards and McClellan 1979).

NRAD has limited irradiation capabilities in the core. It has a water-filled port at the center of the core and a dry port at the edge of the core. NRAD operates an MF Physics linear particle accelerator that is used for nondestructive assays of waste and expended nuclear fuel.

Internal exposure potential exists from possible airborne radioactivity, primarily from the hot cell environment from MFPs and MAPs [29].

External exposure occurred during sample handling and maintenance associated with radioactive samples. Remote handling techniques are used to minimize dose [30].

2.2.14 Fuel Assembly and Storage Building, 1970 to present

The Fuel Assembly and Storage Building (FASB) is a multipurpose facility about 100 yd northeast of EBR-II that supports development of low-enrichment uranium fuel for research reactors, storage of spent fuel, and examination of the condition of other experimental projects. The East (clean) room houses offices, restrooms, etc. The West room contains a vault for the storage of nuclear material. It also contains equipment for performing materials testing and preparing metallurgical samples and inert atmosphere gloveboxes and hoods. The facility ceased fuel assembly about 1990, but other radiological work is ongoing.

Internal exposure might have occurred from airborne radioactivity associated with the described processes from the uranium fuel and spent fuel examinations [31].

External exposure occurred from movement of radiological samples and reactor fuel [32].

2.2.15 Other ANL-W Support Facilities

At ANL-W, an Analytical Laboratory provides the capability for performing chemical and physical measurements of radioactive and nonradioactive samples. This facility includes six analytical hot cells (the Junior Cave area) and general and specialized chemistry laboratories. Personnel were subjected to radiation levels in the multiroentgen-per-hour range on occasion in the Junior Cave area [33].

The Radioactive Scrap and Waste Facility provides in-ground retrievable dry storage for nuclear fuels and other highly radioactive scrap and waste as well as interim storage for EBR-II spent fuel [34].

The Radioactive Liquid Waste Treatment Facility evaporates low-level radioactive liquid waste generated at ANL-W facilities into solidified residue packaged in shielded containers [35].

The Industrial Waste Pond (IWP) is an unlined evaporative seepage pond that is fed by a system of drainage ditches. It has been used since 1964 to receive wastewater from a number of sources. The largest sources of liquid industrial waste going to the IWP are blowdown effluents from the main and auxiliary cooling towers, auxiliary boiler blowdown; water from once-through air conditioning, and cooling water from other sources. There might be inadvertent low-level radioactive contamination in this pond [36].

The three Sanitary Sewage Treatment Ponds north of EBR-II cover an area of about 2 acres. These ponds are not suspected to be radiologically contaminated [37].

Internal exposure is possible from airborne radioactivity associated with the various types of samples worked in these facilities [38].

External exposure occurred from working with the variety of radioactive materials associated with these facilities (MFPs, MAPs, and transuranic elements) [39].

2.3 ATTRIBUTIONS AND ANNOTATIONS

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

section of this document that link data, quotations, and other information to documents available for review on the Oak Ridge Associated Universities (ORAU) Team servers.

Norman Rohrig served as the initial Document Owner for this document. Mr. Rohrig was previously employed at INL, which shared boundaries with ANL-W and used the same dosimetry systems. His work involved management, direction, or implementation of radiation protection and/or health physics program policies, procedures, or practices in relation to atomic weapons activities at the site. This revision has been overseen by a new Document Owner, who is fully responsible for the content of this document, including all findings and conclusions. In all cases where such information or previous studies or writings are included or relied upon by the Document Owner, those materials are fully attributed to the source.

Earl Graham served as one of the initial Subject Experts for this document. Mr. Graham was previously employed at ANL-W and his work involved management, direction or implementation of radiation protection and/or health physics program policies, procedures or practices related to atomic weapons activities at the site. This revision has been overseen by a new Document Owner who is fully responsible for the content, including all findings and conclusions. In all cases where such information or prior studies or writings are included or relied upon by Mr. Graham, those materials are fully attributed to the source.

[1] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This statement by Mr. Graham is based on information from a review of Cipperley (1968), Andersen, Perry, and Ruhter (1995), and INEEL (2001).

[2] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This statement by Mr. Graham is based on information from a review of Andersen, Perry, and Ruhter (1995) and INEEL (2001).

[3] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This statement by Mr. Graham is based on information from a review of Andersen, Perry, and Ruhter (1995) and INEEL (2001).

[4] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This statement is based on a review of Hoff et. al. (1987).

[5] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
The radionuclides listed in Table 2-1 are mixed fission products, mixed activation products and corrosion products that are common to reactors. This table is based on a review of Brodsky and Beard (1960).

[6] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Haroldson et. al. (1963).

[7] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Haroldson et. al. (1963).

[8] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Dietrich, Lichtenberger, and Zinn (1956) and Griffiths, Sill, and Wilhelmsen (1956).

[9] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Dietrich, Lichtenberger, and Zinn (1956) and Griffiths, Sill, and Wilhelmsen (1956).

[10] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Dietrich, Lichtenberger, and Zinn (1956) and Griffiths, Sill, and Wilhelmsen (1956).

[11] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Dietrich, Lichtenberger, and Zinn (1956) and Griffiths, Sill, and Wilhelmsen (1956).

[12] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Zinn et. al. (1956).

[13] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Zinn et. al. (1956).

[14] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Robertson and Hall 1959.

[15] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Robertson and Hall 1959.

[16] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at BORAX-V.

[17] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at BORAX-V.

[18] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Brittan et al. (1961).

[19] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Brittan et al. (1961).

[20] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at AFSR and a review of Brunson 1959.

[21] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at AFSR and a review of Brunson 1959.

[22] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Freund et al. (1960).

[23] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of Freund et al. (1960).

[24] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This statement by Mr. Graham is based on his understanding of the sources of exposure based on experience at HFEF. Because the hot cells were used to examine irradiated fuel, they would be contaminated with MFPs and MAPs. This contamination is a potential internal exposure hazard during hot cell entries.

[25] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This statement by Mr. Graham is based on his understanding of the sources of exposure based on experience at HFEF. Because the hot cells were used to examine irradiated fuel, they would be contaminated with MFPs and MAPs. This contamination is a potential external exposure hazard during hot cell entries.

[26] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at ZPPR and a review of Kunze and Chase (1970).

[27] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at ZPPR and a review of Kunze and Chase (1970).

[28] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at ZPPR and a review of Kunze and Chase (1970).

[29] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This statement by Mr. Graham is based on his understanding of the sources of exposure based on experience at NRAD. Because the hot cells were used to examine irradiated fuel, they would be contaminated with MFPs and MAPs. This contamination is a potential internal exposure hazard.

[30] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This statement by Mr. Graham is based on his understanding of the sources of exposure based on experience at NRAD and a review of Richards and McClellan (1979).

[31] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at FASB.

[32] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at FASB.

[33] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at the Junior Cave.

[34] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of ERDA (1977).

[35] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of ERDA (1977).

[36] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at ANL-W and on a review of ERDA (1977).

[37] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on a review of ERDA (1977).

[38] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at ANL-W.

[39] Graham, Earl. Intrepid Technology and Resources. Principal Health Physicist. June-August 2003.
This information is based on understanding of the sources of exposure based on experience at ANL-W.

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GLOSSARY

activation
Creation of a radioisotope by interaction of a stable (nonradioactive) element with neutrons, protons, or other types of radiation.

activation product
Radioisotope produced through activation, usually in a nuclear reactor but also as a byproduct of nuclear weapons discharge and other nucleic reactions.

background radiation
Radiation from cosmic sources, naturally occurring radioactive materials including naturally occurring radon, and global fallout from the testing of nuclear explosives. Background radiation does not include radiation from source, byproduct, or Special Nuclear Materials regulated by the U.S. Nuclear Regulatory Commission. The average individual exposure from background radiation is about 360 millirem per year.

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. Most of the direct fission products are (negative) beta emitters. Exposure to large amounts of beta radiation from external sources can cause skin burns (erythema), and beta emitters can be harmful inside the body. Thin sheets of metal or plastic can stop beta particles.

boiling-water reactor (BWR)
Nuclear reactor in which boiling water in the core serves as both coolant and moderator.

breeder reactor
Nuclear reactor in which the operation produces a net increase in fissionable reactor fuel.

containment building
Building typically engineered to be air tight and made of thick heavy material to prevent the release of radioactive gases or radiological contamination to the atmosphere or area outside the containment.

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

control rod
Neutron-absorbing device in a reactor used to slow or speed the reaction. Also called safety rod.

control room
Room in a nuclear reactor facility that houses the controls for operation and monitoring.

coolant
Gas or liquid in a nuclear reactor that removes the heat from the fission process.

core

Central region of a nuclear reactor where fission of the fuel takes place.

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.

decontamination

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

depleted uranium (DU)

Uranium with a percentage of ^{235}U lower than the 0.7% found in natural uranium. As examples, spent (used) fuel elements, byproduct tails, residues from uranium isotope separation, and some weapons materials contain DU. DU can be blended with highly enriched uranium to make reactor fuel or used as a raw material to produce plutonium.

dose

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

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 *thermoluminescent dosimeter*.

dosimetry

Measurement and calculation of internal and external radiation doses.

enriched uranium

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

excursion

Planned or accidental increase in the normal operating power level of a reactor.

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.

fast neutron

Neutron with energy equal to or greater than 10 kiloelectron-volts. This type of neutron causes fission in some isotopes (e.g., ^{238}U, ^{239}Pu).

film

Radiation-sensitive photographic film in a light-tight wrapping.

fission

Splitting of the nucleus of an atom (usually of a heavy element) into at least two other nuclei and the release of a relatively large amount of energy. This transformation usually releases two or three neutrons.

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.

flux

Rate of flow of mass, volume, or energy.

fuel assembly

Arrangement of nuclear fuel for use in a nuclear reactor. Fuel is most commonly in the form of pellets arranged in rods of various diameters but can also be formed into plates or other shapes.

gamma radiation

Electromagnetic radiation (photons) of short wavelength and high energy (10 kiloelectron-volts to 9 megaelectron-volts) that originates in atomic nuclei and accompanies many nuclear reactions (e.g., fission, radioactive decay, and neutron capture). Gamma rays are very penetrating, but dense materials such as lead or uranium or thick structures can stop them. Gamma photons are identical to X-ray photons of high energy; the difference is that X-rays do not originate in the nucleus.

half-life

Time in which half of a given quantity of a particular radionuclide disintegrates (decays) into another nuclear form. During one half-life, the number of atoms of a particular radionuclide decreases by one half. Each radionuclide has a unique half-life ranging from trillionths of a second to billions of years.

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.

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.

irradiate

To expose to ionizing radiation.

isotope

One of two or more atoms of a particular element that have the same number of protons (atomic number) but different numbers of neutrons in their nuclei (e.g., ^{234}U, ^{235}U, and ^{238}U).

Isotopes have very nearly the same chemical properties but often have different physical properties.

moderator

Material such as water, heavy water, or graphite that slow the neutrons in a reactor to cause more fission.

natural uranium

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

neutron

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 energy

Energy released by nuclear reaction, some of which can be ionizing radiation. Of particular importance is the energy released when a neutron initiates fission or when two nuclei join together under millions of degrees of heat (fusion).

nuclear power plant

Electrical generating facility that uses nuclear fuel.

nucleus

Central core of an atom, which consists of positively charged protons and, with the exception of ordinary hydrogen, electrically neutral neutrons. The number of protons (atomic number) uniquely defines a chemical element, and the number of protons and neutrons is the mass number of a nuclide. The plural is nuclei.

nuclide

Stable or unstable isotope of any element. Nuclide relates to the atomic mass, which is the sum of the number of protons and neutrons in the nucleus of an atom. A radionuclide is an unstable nuclide.

photon

Basic unit of electromagnetic radiation. Photons are massless “packages” of light energy that range from low-energy microwave photons to high-energy gamma rays. Photons have energies between 10 and 100 kiloelectron-volts.

proton

Basic nucleic particle with a positive electrical charge and mass slightly less than that of a neutron. There are protons in the nuclei of every atom, and the number of protons is the atomic number, which determines the chemical element.

quality factor

Historical value assigned to reflect the average effectiveness of a particular kind of radiation in producing biological effects in humans, now called radiation weighting factor. The quality factor multiplied by the absorbed dose yields the dose equivalent.

rad

Traditional unit for expressing absorbed radiation dose, which is the amount of energy from any type of ionizing radiation deposited in any medium. A dose of 1 rad is equivalent to the absorption of 100 ergs per gram (0.01 joules per kilogram) of absorbing tissue. The rad has been replaced by the gray in the International System of Units (100 rads = 1 gray). The word derives from radiation absorbed dose.

radiation

Subatomic particles and electromagnetic rays (photons) that travel from one point to another, some of which can pass through or partly through solid materials including the human body.

radioactive

Giving off ionizing radiation such as alpha particles or X-rays.

radioactivity

Disintegration of certain elements (e.g., radium, actinium, uranium, and thorium) accompanied by the emission of alpha, beta, gamma, and/or neutron radiation from unstable nuclei. See *radionuclide*.

radioactive waste

Radioactive solid, liquid, and gaseous materials for which there is no further use. Wastes are generally classified as high-level (with radioactivity as high as hundreds of thousands of curies per gallon or cubic foot), low-level (in the range of 1 microcurie per gallon or cubic foot), intermediate level (between these extremes), mixed (also contains hazardous waste), and transuranic.

radionuclide

Radioactive nuclide. See *radioactive* and *nuclide*.

reactor vessel

Structure enclosing the fuel elements, control elements, coolant piping, and other structures that support the reactor core.

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 average American receives 360 millirem a year from background radiation. 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.

reprocessing

Mechanical and chemical processing of spent nuclear fuel to separate useable fissionable products (i.e., uranium and plutonium) from waste material. Reprocessing was discontinued in the United States in 1992.

roentgen

Unit of photon (gamma or X-ray) exposure for which the resultant ionization liberates a positive and negative charge equal to 2.58×10^{-4} coulombs per kilogram (or 1 electrostatic unit of electricity per cubic centimeter) of dry air at 0° 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).

shielding

Material or obstruction that absorbs ionizing radiation and tends to protect personnel or materials from its effects.

sievert

International System unit for dose equivalent, which indicates the biological damage caused by radiation. The unit is the radiation value in gray (equal to 1 joule per kilogram) multiplied by a weighting factor for the type of radiation and a weighting factor for the tissue; 1 sievert equals 100 rem.

spent fuel

Fuel that has been in a reactor long enough to become ineffective because the proportion of fissile material has dropped below a certain level.

thermal neutron

Neutron in thermal equilibrium with its surroundings. The term usually refers to neutrons with energy less than 0.5 electron-volts. The average energy of thermal neutrons is 0.025 electron-volts.

thermoluminescent dosimeter (TLD)

A device 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.

U.S. Atomic Energy Commission (AEC)

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

X-ray radiation

Penetrating electromagnetic radiation (photons) of short wavelength (0.001 to 10 nanometers) and energy less than 250 kiloelectron-volts. X-rays usually come from excitation of the electron field around certain nuclei. Once formed, there is no difference between X-rays and gamma rays, but gamma photons originate inside the nucleus of an atom.

zero power

Reactor power level that maintains a chain reaction at an extremely low power level producing very little heat. Also called low power.