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08/30/2006	00	New Site Profile for the Brookhaven National Laboratory. First approved issue. Incorporates internal and NIOSH formal review comments. Training required: As determined by the Task Manager. Initiated by Melton H. Chew.
04/26/2010	01	Revision to incorporate SEC language, BNL comments, and clarifies that background radiation is not included in occupational exposure. References were consolidated at the end of the document. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Melton H. Chew.

TABLE OF CONTENTS

SECTION **TITLE** **PAGE**

Acronyms and Abbreviations 7

1.0 Introduction 10
1.1 Purpose 11
1.2 Scope 11
1.2.1 Site Description 11
1.2.2 Occupational Medical Dose 12
1.2.3 Occupational Environmental Dose 12
1.2.4 Occupational Internal Dose 12
1.2.5 Occupational External Dosimetry 12
1.2.6 Attributions and Annotations 12

2.0 Site Description 13
2.1 Introduction 13
2.2 Purpose 13
2.3 Scope 13
2.4 Site Description and General Information 13
2.4.1 Brookhaven Graphite Research Reactor, Building 701 15
2.4.2 High Flux Beam Reactor, Building 750 20
2.4.3 Medical Research Center, Building 490 21
2.4.4 Brookhaven Medical Research Reactor, Building 491 21
2.4.5 Positron Emission Tomography, Building 906 22
2.4.6 Cosmotron, Building 902 22
2.4.7 Alternating Gradient Synchrotron, 900 Series Buildings 22
2.4.8 Brookhaven LINAC Isotope Producer, Building 931 27
2.4.9 Tandem Van de Graaff, Building 901 27
2.4.10 National Synchrotron Light Source, Building 725 29
2.4.11 Relativistic Heavy Ion Collider Complex, Building 1000 Series 29
2.4.12 Hot Laboratory, Building 801 31
2.4.13 High Intensity Radiation Development Laboratory, Building 830 33
2.4.14 Chemistry Department, Building 555 33
2.4.15 Physics Department, Building 510 34
2.4.16 Other Miscellaneous Radiological Research Facilities 34
2.4.16.1 LMFR Support, Building 820 34
2.4.16.2 Hot Machine Shop, Building 530 34
2.4.16.3 Health Physics and Safety Instrumentation, Building 535 35
2.4.17 Waste Management Facility, Radwaste Reclamation Building, Building 865 35
2.4.18 Radiological Waste Decontamination Facility, Building 650 36
2.5 Isotopes of Concern 36
2.6 Magnitude of Site Activity 41
2.7 Major Incidents 46
2.8 Radiological Access Controls 47

3.0 Occupational Medical Dose 48
3.1 Purpose 48
3.2 Scope 48
3.3 Examination Frequency 48
3.4 Equipment and Techniques 49

3.5 Entrance Air Kerma in Air 50
3.6 Organ Dose Calculations 52
3.6.1 Organ Dose from Collimated Exposure 52
3.6.2 Organ Dose from Poorly Collimated Exposure 52
3.6.3 Skin Dose 53
3.7 Dose Reconstruction 54
3.8 Uncertainty 54

4.0 Occupational Environmental Dose 59
4.1 Introduction 59
4.2 Purpose 59
4.3 Scope 59
4.4 Ambient External Radiation 59
4.4.1 Use of Offsite Monitoring 59
4.4.2 Applicability for Dose Reconstruction 60
4.5 Inhalation of Onsite Airborne Radionuclides 60
4.5.1 Stack Monitoring 60
4.5.2 Estimates of Potential Inhalation Intake 61
4.6 Ingestion 61
4.7 Uncertainty 65

5.0 Occupational Internal Dose 66
5.1 Introduction 66
5.2 Purpose 66
5.3 Scope 66
5.4 Bioassay Records in the Individual Files 66
5.4.1 Bioassay Record (Form 1720) 66
5.4.2 Tritium Exposure Evaluation Form 67
5.4.3 Summary of Whole-Body Counting Results 67
5.4.4 Individual Whole-Body Counting Results 67
5.5 *In Vitro* Minimum Detectable Activities, Counting Methods, and Reporting Protocols 68
5.5.1 *In Vitro* Urine Analysis 68
5.5.2 History of *In Vitro* Urine Analysis 68
5.5.3 Fecal Sample Analysis 69
5.6 *In Vivo* Minimum Detectable Activities, Counting Methods, and Reporting Practices 70
5.6.1 Whole-Body Counting 70
5.6.2 Chest Counting 71
5.7 Uncertainty 71
5.8 Detection Limits 72
5.9 Excreta Sample Kit Codes 72
5.10 Solubility Type, Fraction Activity, and Particle Size by Facility 74
5.11 Facility-Specific Radionuclide Conversions 78
5.12 Workplace Monitoring Data 79
5.13 Source Term Data 79
5.14 Radon 79
5.15 Guidance for Dose Reconstructors 79

6.0 Occupational External Dosimetry 80
6.1 Introduction 80
6.2 Purpose 80

6.3 Scope 80
6.4 BNL Dosimetry Program 80
6.4.1 Neutron Dosimetry 80
6.4.2 Special Dosimetry 80
6.4.3 Lost or Destroyed Dosimeters 81
6.5 Missed Dose 81
6.5.1 Unmonitored Worker 81
6.6 Radiation Energies and Percentages at Selected BNL Facilities 82
6.7 Neutron Radiations and Percentages 83
6.8 Recorded Dose Practices 85
6.9 Interpretation of Reported Doses 85
6.10 Adjustments to Recorded Dose 86
6.11 Bias and Uncertainty 86

7.0 Attributions and Annotations 89

References 91

Glossary 105

LIST OF TABLES

TABLE	TITLE	PAGE
2-1	Site information of major nuclear research facilities at BNL	17
2-2	Area information and parameters	36
2-3	Magnitude of site activity	41
2-4	Major incidents	46
3-1	Default frequency of chest X-rays at BNL	49
3-2	Organ doses for PFG, PA, and LAT 14-in. × 17-in. chest radiography	54
3-3	Skin dose guidance for various chest projections and periods	55
3-4	Skin dose from various chest projections	57
4-1	External gamma radiation dose	60
4-2	Maximum annual environmental occupational radionuclide inhalation	62
5-1	Internal dose control program (*in vitro*)	69
5-2	Internal dose control program (*in vivo*)	71
5-3	Detection limits	72
5-4	Excreta sample kit codes	74
5-5	Solubility type, fraction activity, and particle size by facility	75
5-6	Facility-specific radionuclide conversions	78
6-1	Estimated annual missed photon, beta, and neutron dose	81
6-2	Selection of beta and photon energies and percentages	82
6-3	Beta and photon energies and percentages (support facilities)	82
6-4	Facilities, neutron energies, percentages, and correction factors	83
6-5	Recorded dose practices	85
6-6	Interpretation of reported data	86
6-7	Adjustments to recorded dose	86
6-8	Uncertainty factors	87
6-9	Landauer gamma film, NTA film, and CR-39 specifications	87

LIST OF FIGURES

FIGURE	TITLE	PAGE
2-1	Aerial view of Brookhaven National Laboratory	14
2-2	Nuclear and radioactivity sites at BNL	16
2-3	The AGS complex	23
2-4	The Relativistic Heavy Ion Collider complex	30
2-5	RHIC ring intersection points	31
6-1	Neutron Spectrum in the Thermal Column with the Converter Plate (left) and in the Instrument Tunnel (right)	84
6-2	Neutron Energy Spectrum at the Cosmotron	84

ACRONYMS AND ABBREVIATIONS

ADD	average depth dose
AEC	U.S. Atomic Energy Commission
AF	absorption factor
AGS	Alternating Gradient Synchrotron
AMAD	activity median aerodynamic diameter
amu	atomic mass unit
AP	anterior-posterior
BF	Backscatter factor
BGRR	Brookhaven Graphite Research Reactor
BLAF	Brookhaven Laboratory Animal Facility
BLIP	Brookhaven LINAC Isotope Producer
BMRR	Brookhaven Medical Research Reactor
BNL	Brookhaven National Laboratory
Bq	becquerel
cGy	centigray
Ci	curie
CLIF	Chemistry LINAC Irradiation Facility (also CLIP in some documents)
cm	centimeter
CNF	Cold Neutron Facility
CR-39	Columbia Resin Number 39
d	day
D&D	decontamination and decommissioning
DAS	Department of Applied Science
DAT	Department of Applied Technology
DCF	dose conversion factor
DTL	Drift-Tube-LINACS
DOE	U.S. Department of Energy
DOELAP	Department of Energy Laboratory Accreditation Program
dpm	disintegrations per minute
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
EML	Environmental Measurement Laboratory
ENSD	entrance skin dose
ENSDNPB	entrance skin dose near primary beam
ESE	entrance skin exposure
EXSD	exit skin dose
EXSDNPB	exit skin dose near primary beam
F	fast (solubility rate)
ft	foot
g	gram
GeV	gigaelectron-volt
GIF	Gamma Irradiation Facility
HEBT	High Energy Beam Transport
HEPA	high-efficiency particulate air (filter)
HFBR	High Flux Beam Reactor

HIRDL	High Intensity Radiation Development Laboratory
hr	hour
HVL	half-value layer
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt (1,000 electron-volts)
kV	kilovolt
kVp	kilovolts-peak
L	liter
LAT	lateral
lb	pound
LEAF	Low Energy Accelerator Facility
LINAC	linear accelerator
LMFR	Liquid Metal Fuel Reactor
M	moderate (solubility rate)
m	meter
mAs	milliampere-second
mCi	millicurie
MDA	minimum detectable activity or amount
MDL	minimum detectable level
MEL	Metallurgical Evaluation Laboratory
MeV	megaelectron-volt, 1 million electron-volts
MFP	mixed fission product
min	minute
mL	milliliter
mm	millimeter
mR	milliroentgen
mrad	millirad
MRC	Medical Research Center
mrem	millirem
MW	megawatt
NaI(Tl)	Sodium iodide doped with thallium
nCi	nanocurie
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
NSLS	National Synchrotron Light Source
NSRL	NASA Space Radiation Laboratory
NTA	nuclear track emulsion, type A
NVLAP	National Voluntary Laboratory Accreditation Program
NYOO	New York Operations Office
ORAU	Oak Ridge Associated Universities
OW	open window
PA	posterior-anterior
pCi	picocurie
PET	positron emission tomography

PFG	photofluorography
POC	probability of causation
QF	quality factor
R	roentgen
R&D	research and development
RARAF	Radiological Research Accelerator Facility
RBE	relative biological effectiveness
RF	radio frequency
RFQ	Radio-Frequency Quadrupole
RHIC	Relativistic Heavy Ion Collider
RSD	remote skin dose
RTF	Radiation Therapy Facility
S	slow (solubility rate)
s	second
S&EP	Safety and Environmental Protection (Division)
SEC	Special Exposure Cohort
ST	Severn-Trent
TBD	technical basis document
TPL	Target Processing Laboratory
U.S.C.	United States Code
VUV	Vacuum Ultraviolet
WB	whole-body
WBC	whole-body counter
WMF	Waste Management Facility
yr	year
µA	microampere
µCi	microcurie
µg	microgram
µm	micrometer
§	section or sections

1.0 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide 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, 42 C.F.R. Pt. 82) define "performance of duty" for DOE employees with a covered cancer or restrict the "duty" to nuclear weapons work (NIOSH 2007a).

The statute also 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 excludes Naval Nuclear Propulsion Facilities from being covered under the Act, 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 occupational radiation exposures are considered valid for inclusion in a 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 (NIOSH 2007a):

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

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

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

1.1 PURPOSE

The purpose of this document is to provide a site profile that contains technical basis information for the evaluation of the total occupational dose for EEOICPA claimants who were employed at the Brookhaven National Laboratory (BNL).

1.2 SCOPE

This site profile consists of the following sections: 1.0, Introduction; 2.0, Site Description; 3.0, Occupational Medical Dose; 4.0, Occupational Environmental Dose; 5.0 Occupational Internal Dose; 6.0, Occupational External Dosimetry; and 7.0, Attributions and Annotations.

A Special Exposure Cohort (SEC) class has been established for all employees who worked in any area of BNL from January 1, 1947, through December 31, 1979, for a number of workdays aggregating at least 250 workdays or in combination with workdays within the parameters established for one or more classes of employees in the SEC. This document also provides guidance for EEOICPA-covered employees who participated in BNL operations, specifically for non-SEC cancers and those presumptive cancer claims for workers who have fewer than 250 workdays under this employment or in combination with workdays within the parameters established for other classes of employees in the SEC. Based on the findings and recommendations of NIOSH and the Advisory Board on Radiation and Worker Health, the Secretary of Health and Human Services has concurred with the finding that NIOSH does not have access to sufficient personnel or area monitoring data, or sufficient source or source term information, associated with BNL operations to bound potential internal exposures for the period from January 1, 1947, through December 31, 1979 (other than tritium after December 31, 1964) (Sebelius 2009).

NIOSH has found that it does have access to sufficient personnel monitoring and workplace monitoring data to bound potential external exposures and occupational medical dose for workers at BNL during the period from January 1, 1947, through December 31, 2007.

NIOSH found that while it is not possible to completely reconstruct radiation doses for employees who worked at BNL from January 1, 1947, through December 31, 1979, NIOSH intends to use any reliable internal and external monitoring data that may be available for an individual claim (and that can be interpreted using existing NIOSH dose reconstruction processes or procedures) to support a partial dose reconstruction for nonpresumptive cancers and/or cases that have less than 250 work days of employment.

1.2.1 Site Description

Section 2.0 of this site profile describes the features and the history of BNL, including site areas or buildings, site processes, periods of operation, radionuclides of concern, and other information pertinent to dose reconstruction.

This section provides a description and general information for the facilities that operated or are operating at BNL. These include the Brookhaven Graphite Research Reactor (BGRR) and its replacement, the High Flux Beam Reactor (HFBR); the operations of the Medical Research Center (MRC), the positron emission tomography facility and the medical research reactor; the operation of the accelerators and the production of radiopharmaceuticals. The section also addresses some of the high-energy physics facilities such as the relativistic heavy ion collider complex where ion beams traveling in opposite directions in a circular orbit collide.

1.2.2 Occupational Medical Dose

Section 3.0 of this site profile provides information regarding the historical BNL occupational X-ray program. Beginning in 1947 and continuing through at least 1964, workers, including visiting scientists employed for more than three months, were given an entry and annual physical examination including a posterior-anterior (PA) chest X-ray. Later, the annual frequency may have actually been closer to about once every 2.5 years. The section presents organ doses for both PA and lateral (LAT) chest radiographs assuming both properly collimated and poorly collimated exposures. Skin doses inside and outside the primary beam are determined for PA and LAT chest projections.

1.2.3 Occupational Environmental Dose

Section 4.0 discusses the radiation doses received by workers at BNL but outside the facilities. From 1967 to 1984, ambient gamma radiation dose rates are available from four perimeter stations surrounding the site at northwest, southwest, southeast, and northeast coordinates. Beginning in 1985, the onsite monitoring program was expanded to approximately 20 onsite stations. The ambient external gamma radiation outside the radiological controlled areas is the result of background radiation or gamma emissions from stack effluent such as ^{41}Ar or skyshine due to air scatter from an otherwise well-shielded radiation source. The radionuclides emitted from the BNL stacks are identified and their annual inhalation (becquerels/year) listed. Neither potable groundwater nor soil ingestion has been found to be a pathway of exposure. No ingestion dose is indicated.

1.2.4 Occupational Internal Dose

Section 5.0 discusses the internal dosimetry systems and practices employed at BNL. The section provides supporting technical data to evaluate internal occupational doses that can reasonably be associated with worker radiation exposures covered by EEOICPA. It lists the types of routine monitoring that constitute the *in vitro* and the *in vivo* dose control programs as well as the minimum detectable activities, counting methods, and reporting practices. The section addresses the uncertainty for BNL exposure and dose records.

1.2.5 Occupational External Dosimetry

Section 6.0 discusses external dosimetry systems and practices at BNL. It presents historical and current practices in relation to the evaluation of external exposure data for monitored and unmonitored workers. It contains supporting documentation to assist in the evaluation of occupational external exposures from processes that occurred at BNL. In addition, it addresses the evaluation of worker exposure, missed dose, and the bias and uncertainty associated with the monitoring of external dose. The missed doses were basically those resulting from dosimeter minimum detectable levels (MDLs) and exchange periods, as well as the inability to determine true doses from high-energy particles generated by the accelerators. Neutron doses were measured with nuclear track emulsion, type A (NTA) film until 1995, after which Columbia Resin No. 39 (CR-39) has been used.

1.2.6 Attributions and Annotations

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.

2.0 SITE DESCRIPTION

2.1 INTRODUCTION

BNL was founded in 1947, and it has been in operation since then at Upton, Long Island, New York. The site was formerly Camp Upton and it was used by the Army during World Wars I and II.

BNL's early research focused on advanced physics, but expanded into its current suite of research in the fields of medicine, biology, chemistry, physics, materials science, nuclear engineering, and environmental research. BNL was established to provide facilities for scientific research and was organized into departments that provide research nuclear reactors, particle accelerators, and engineering facilities, and that support the Biology, Chemistry, Physics, Medicine, Applied Science, Accelerator, and Applied Mathematics Departments.

2.2 PURPOSE

The purpose of this section is to describe the BNL facilities, the time and period of the process operations, and major site incidents that resulted in a significant internal or external exposure to one or more persons.

2.3 SCOPE

This section describes the features and history of BNL, including the site areas or buildings, site processes, periods of operation, radionuclides of concern, and other information pertinent to dose reconstruction.

2.4 SITE DESCRIPTION AND GENERAL INFORMATION

Figure 2-1 shows an aerial view of BNL.

Research Reactors
The Laboratory's scientific history began in 1950 with the operation of the BGRR, a research reactor used for peaceful scientific exploration in the fields of medicine, biology, chemistry, physics, and nuclear engineering. The BGRR operated until 1968. In 1965, its capacity was replaced and surpassed by the HFBR, which provided neutrons to researchers of all disciplines, from solid state physics to art history. The HFBR ceased operations in December 1996.

Medical Research Center
Medical research at BNL began in 1950 with the opening of one of the first hospitals devoted to nuclear medicine. It was followed by the MRC in 1958 and the Brookhaven Medical Research Reactor (BMRR) in 1959. The BMRR is the first nuclear reactor built exclusively for medical and biological research and came on line on March 15, 1959, and operated until October 2000.

The Radiation Therapy Facility (RTF) was operated jointly by the BNL Medical Department and the State University of New York at Stony Brook. The RTF was a high-energy, dual X-ray mode linear accelerator (LINAC) for radiation therapy of cancer patients. The RTF has been dismantled and is not operational.

Chemists and physicians teamed to view the inner workings of the brain in 1977 with the advent of Positron Emission Tomography (PET) cameras. Two more imaging techniques were added to the PET research efforts to form the Center for Imaging and Neuroscience in 1996. Except for the BMRR, all of these facilities are currently operating.

Figure 2-1. Aerial view of Brookhaven National Laboratory (BNL 2009a).

Particle Accelerators

High-energy particle physics research began in 1952 with the Cosmotron, the first particle physics accelerator to achieve billion-electro-volt energies. The Cosmotron operated from 1953 to 1966. In 1960, the Alternating Gradient Synchrotron (AGS), a large accelerator, was built to surpass the Cosmotron's capabilities. The AGS is capable of accelerating protons to energies up to 30 GeV and heavy ion beams to 15 GeV/amu. The AGS achieved full energy in 1960 and is still in use.

Between 1967 and 1970, the Tandem Van De Graaff, 60-inch Cyclotron, and Vertical Accelerator were used for medium-energy physics investigations and for special isotope production. The heavy ions from the Tandem Van De Graaff can be injected into the AGS for physics experiments. The Tandem Van De Graaff began operating in 1970 and continues operating to the present.

The Heavy Ion Transfer tunnel connects the coupled Tandem Van de Graaff and the AGS. The interconnection of these two facilities permits intermediate-mass ions to be injected into the AGS where they can be accelerated to an energy of 15 GeV/amu. These ions then are extracted and sent to the AGS experimental area for physics research. The AGS Booster is a circular accelerator with a circumference of 200 m that receives either a proton beam from LINAC or heavy ions from the Tandem Van De Graaff. The Booster accelerates proton particles and heavy ions before injecting them into the AGS ring. The Booster receives protons and heavy ions from the LINAC and Tandem Van De Graaff facilities to increase their intensity for delivery to the AGS.

The Brookhaven LINAC Isotope Producer (BLIP) became operational in 1973. Protons from the LINAC are sent through an underground beam tunnel to the BLIP facility where they strike target

metals. These metals, which become activated by the proton beam, are then processed at the Target Processing Laboratory for use in radiopharmaceutical development and production. The targets are cooled by a continuously recirculating water system. The BLIP facility underwent significant upgrades in 1994 in support of the Brookhaven Isotope Research Center program. The 200-MeV Proton Linear Accelerator serves as a proton injector for the AGS and supplies a continuous beam of protons for radionuclide production by spallation reactions in the BLIP.

In 1982, the National Synchrotron Light Source (NSLS) began operation. The NSLS guides charged particles in an orbit. As the electrons spin inside a hollow donut-shaped tube called an electron storage ring, they emit light called synchrotron light. This light, which can be detected by specialized instruments, is used to study the properties of matter. The NSLS utilizes a LINAC and booster synchrotron as an injection system for two electron storage rings that operate at energies of 750 MeV vacuum ultraviolet (VUV), and 2.5 GeV (X-ray). The synchrotron radiation produced by their stored electrons is used for VUV spectroscopy and for X-ray diffraction studies.

Brookhaven's newest accelerator facility is the Relativistic Heavy Ion Collider (RHIC), which was completed in 1999. The RHIC is designed to recreate a state of matter that scientists believe existed moments after the universe was formed.

Department of Applied Science
The Target Processing Laboratory (also call Hot Laboratory in 1993) officially opened on January 15, 1951. The original purpose of the central facility was to provide appropriately shielded areas for research with large amounts of radioactive material. The "hot" area of the Hot Laboratory included five hot cells, three chemical-processing hot cells, and three high-level hot cells for handling and processing of radioactivity in gaseous, liquid, or solid form.

In 1971 and 1972, the High Intensity Radiation Development Laboratory (HIRDL**),** which contained million-curie-range (in the early 1970s) ^{60}Co and ^{137}Cs sources, was used for source development and experimental process irradiations. A ^{60}Co pool in the HIRDL facility operated at lower activity levels into the 1990s.

Waste Management
The new Waste Management Facility (WMF) replaces the original Hazardous Waste Management Facility in its entirety and consolidates several waste management operations into functional buildings. The WMF also provides for significant expansion in a dedicated site suitable for handling and storing hazardous and radioactive wastes generated at BNL.

Figure 2-2 shows the location of the major sites where nuclear research activities were carried out at BNL.

Table 2-1 lists the major nuclear research facilities and their associated summary information.

The following subsections comprise further descriptions of the research facilities of significance on the BNL site and provide background information relevant to the dose reconstruction efforts.

2.4.1 Brookhaven Graphite Research Reactor, Building 701

The operational BGRR and its support systems were housed in Buildings 701, 704, 708, and 709.

Building 701
The BGRR was a graphite-moderated and -reflected, thermal-neutron, air-cooled research facility. The original fuel loading was natural uranium, which was replaced in later years by highly enriched fuel elements. The 25-ft, 700-ton graphite cube was built in two halves separated by a narrow vertical

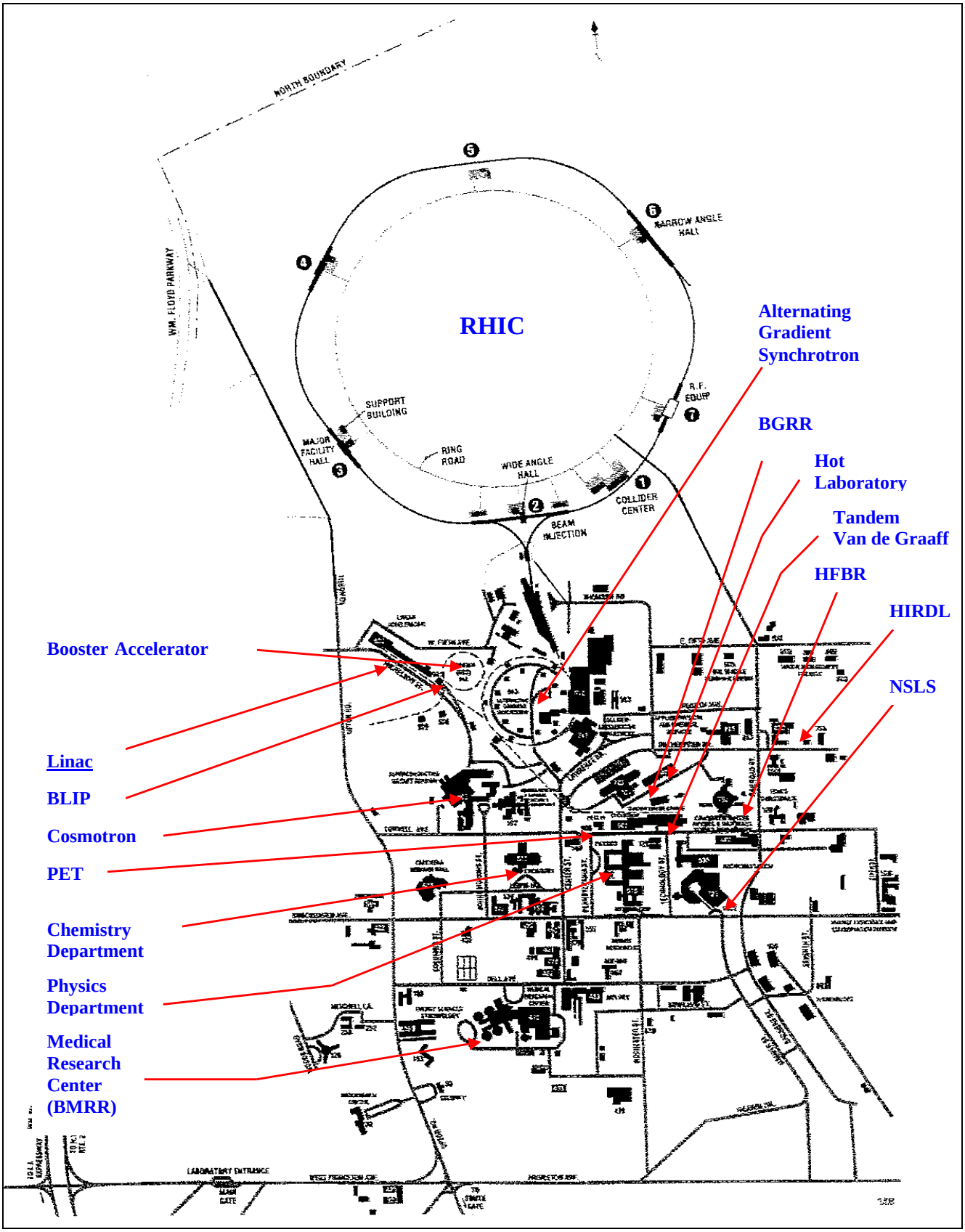

Figure 2-2. Nuclear and radioactivity sites at BNL [1].

Table 2-1. Site information of major nuclear research facilities at BNL.

Section	Name	Description	Period	Building No.	Note
2.4.1	BGRR	U-fueled, graphite-moderated and -reflected reactor 28 MW	1950–1968	701	
2.4.1	BGRR fuel canal	BGRR fuel storage	1950–1972	709	
2.4.1	BGRR exhaust fanhouse	Highly contaminated ducting and fans	1950–1972	704	
	BGRR exhaust filter house	Contaminated HEPA filter elements	1950–unknown	708	Filter elements were still in place in 1997.
2.4.2	HFBR	30–60 MW thermal heavy-water-moderated research reactor	1965–1999	750	Building ceased operation due to leak in spent fuel pool in 1997.
2.4.2	HFBR Stack	100-m stack and houses iodine filters	1965–1999	705	
2.4.2	CNF	Produce extremely low-energy neutron by moderate neutron with liquid hydrogen	1980–1996	751	
2.4.3	MRC	Medical Department	1959–present	490	Dispersible radioisotopes PuBe sources (removed)
2.4.4	BMRR	Enriched U-fueled, light-water-moderated and -cooled reactor	1959–2000	491	
2.4.5	PET Imaging Laboratory	PET scanners for nuclear medicine and neurosciences researches	1977–present	906	Use of positron emitters (carbon-11, fluorine-18, nitrogen-13, and oxygen-18)
2.4.6	Cosmotron	Proton accelerator	1949–1968	902	
2.4.7	AGS	A large accelerator capable of accelerating protons to energies up to 30 GeV and heavy ion beams to 15 GeV/amu	1960–present	913	AGS tunnel, short-lived activation products in tunnel.
2.4.7	200-MeV LINAC	Preaccelerator and LINAC providing proton source	1967–present	930	
2.4.7	LINAC cooling support service	Water-cooling services for the LINAC complex	1967–present	930 MER	Contains activated water
2.4.7	AGS Booster Tunnel	Accumulator booster ring	1960–present	942	Short-lived activation products in tunnel
2.4.7	AGS Experiment Area	Experimental target area for the AGS ring and later contains a proton beam switchyard system	1960–present	912	Activated components
2.4.7	AGS ventilation system fanhouses	Ventilation exhaust fans	1960–present	913A-E	High radiation area due to proximity to the tunnel. Activated water
2.4.7	AGS LINAC	Contains 50-MeV AGS LINAC	1960s	914	

Section	Name	Description	Period	Building No.	Note
2.4.7	E10 Power Supply Building	Houses an assortment of power supplies	1971–present	920	Radiation hazard from activated cooling water and oil in transformer.
2.4.7	Siemens motor generator house	Electrical equipment and lubricating equipment for the motor generator	1960–present	928, 929	Radiation hazard from activated cooling water
2.4.7	AGS Department	Office, field testing shops, machine shops, high bays	1960–present	911	Stored and repair activated components.
2.4.7	g-2/Bubble Chamber	Contains the 30-in. and 80-in. Bubble Chamber	1962–1978	919	A release of tritium occurred in 1973.
2.4.7	Proton Target	Proton target that produces secondaries for the g-2 ring	1962–present	949	Highly activated target
2.4.7	7-ft Bubble Chamber	High-energy physics experimental facility	1972–1979	960	Activated components
2.4.7	AGS Warehouses	Warehouses	1960–present	975, 918, 196, 209, 424, 178	Stored activated components
2.4.8	BLIP	Production of radioisotopes via irradiation in the LINAC beam (200-Mev protons)	1961–present	931B	Bldgs. 931A and C have no nuclear hazard.
2.4.9	Tandem Van de Graaff	Van de Graaff accelerators 60-in. proton Cyclotron producing 10-MeV protons, 20- MeV deuterons, and 40-MeV alpha particles for medical radionuclide research	1970–present	901	Dynamitron (positron accelerator) operations ceased in 1989.
2.4.10	NSLS	Produce intense sources of X-rays, ultraviolet and infrared radiation	1981–present	725	
2.4.10	NSLS Development Laboratory	Houses a linear accelerator.	1981–present	729	
2.4.11	RHIC Complex	High-energy particle accelerator and collider	1999–present	1002	Has prior radioactive works.
		BRAHMS experimental hall	1981–present	1004A	Uranium plate machining
		RHIC service building	1981–present	1004	Has prior radioactive works.
		Open area (future experimental area)	1996–present	1004B	
		RHIC support building	1994–present	1005	
		Beam tunnel	1981–present	1005S	
		Offices and tech shops	1981–present	1006	
		STAR Detector	1985–present	1006A	
		Service building	1981–present	1007	
		Beam tunnel	1981–present	1008	
		PHENIX experiment	1988–present	1008A	
		Experimental support building	1985–present	1010	
		PHOBOS experiment	1994–present	1012	
		Future experimental hall	1994–present		

Section	Name	Description	Period	Building No.	Note
2.4.12	Hot Laboratory	Target Processing Laboratory BLIP processing group	1951–present	801	There was an explosion of UF_6/BrF_3 on 5/15/1957. Few people injured.
2.4.13	HIRDL	Radioactive sources fabrication, irradiation cells and 1970-1990s, the GIF	1951–1990s GIF 1970–present	830	The GIF contained approximately 35,000 Ci of Co-60 (removed) and megacurie Co-60 and Cs-173 sources (removed)
2.4.14	Chemistry Department	Studies from chemical kinetics, to hot-atom effects, to nuclear chemical studies of nuclear decay schemes and nuclear reaction cross-sections, to solar neutrino studies and radiocarbon dating.	1966–present	555	
2.4.15	Physics Department	Laboratories, office space, machine shop, and basement area	1962–present	510	Radioactive material storage, counting labs
2.4.16.1	LMFR Support Facility	Research and development work for the LMFR	1957–1975	820	
2.4.16.2	Hot Machine Shop	Hot Machine Shop	1947–1975	530	
2.4.16.3	Instrument Division	Research and development of X-ray and neutron detectors and corresponding electronics, which are used at the NSLS, the HFBR, the AGS, and other worldwide scientific research facilities.	1964–present	535	
2.4.17	Radwaste Reclamation Building	Located in the WMF for processing of radwaste	1997–present	865	
2.4.17	Tritium Evaporator Facility	Reduce tritium release by evaporation.	(Closed)	802B	
2.4.17	Waste Management Incinerator	Low-level waste incinerator	1970s–early 1990s	444	Animal carcasses with no radiological content were incinerated.
2.4.18	Radiological Decontamination Facility	Decontamination of radiological items and Hot Laundry operated until 1989	1959–1996	650	

gap running east-west. Filtered cooling air was drawn into this gap and flowed through north-south channels removing heat from the fuel elements and graphite, and then flowed out of the reactor through underground concrete ducts, passing through filters, coolers, and primary exhaust fans that discharged into a 100-m high stack (BNL 1997a, p. 3).

The BGRR achieved criticality on August 22, 1950, and operated at power levels up to 28 MW with natural uranium fuel. In April 1958, the reactor was reloaded with highly enriched uranium fuel

elements and operated at power levels of up to 20 MW. On June 10, 1968, the use of the reactor for experimental purposes ended and initial decommissioning operations began. The last fuel was shipped to the Savannah River Site in June 1972 and the canal was pumped dry (BNL 1997a, p. 4).

Building 709
Building 709 is the fuel transfer and storage canal of the BGRR. During the 1950s, before the replacement of the natural uranium fuel slugs, there was a substantial problem with corrosion of fuel elements in the canal. This fuel was subject to deterioration and oxidation while in storage, making the slugs "dusty" when they were eventually prepared for shipment. The new type of fuel elements, which replaced the natural uranium elements in 1958, eliminated this problem. The new elements were aluminum-clad enriched uranium.

During the early years of operation of the BGRR, fuel failures occurred that resulted in radioactive materials being released to the air stream that cooled the reactor. There were 28 reported ruptures of BGRR fuel during the period from 1952 to 1957. These all occurred with the natural uranium fuel. There was one rupture of a uranium oxide (U_3O_8) sample that was being irradiated for the radioiodine production program. Aside from ^{41}Ar, ^{131}I was the most important radionuclide that would contribute to a potential dose that was discharged to the atmosphere from the BGRR. Bromine-82 and ^{133}I were released in somewhat larger concentrations (Meinhold and Meinhold 2001).

More than 2,414 fuel elements, generated in a 12-year period, were shipped from the canal. The contaminated water, filter media, and backflushing from the ion exchange columns were pumped to the storage tanks at the Waste Concentration Facility, Building 811.

By 1972, the canal was finally drained, cleaned with detergents and water, and covered with concrete slabs for shielding (BNL 1997b, p. 8).

Building 704
The BGRR was shut down in 1968 and partially decommissioned in 1972. The exhaust ducts from the reactor and to the stack have been sealed from the fans. The fans remain in their cells and are contaminated. The intake duct, exhaust duct, and fans are grossly contaminated from fuel failures that occurred with the natural uranium fuel (BNL 1997b, p. 6).

Building 708
Radioactive hot air was filtered and discharged from the reactor through underground concrete ducts between the reactor, Building 701, the instrument house, Building 708, and the fanhouse, Building 704. The north and south exit air ducts were contaminated as a result of fuel ruptures with the original natural uranium fuel. Due to decay over some 30 years since use of uranium metal fuel, the major remaining fission products should be ^{137}Cs and ^{90}Sr. On August 18, 1988, a radiological survey was conducted on each exhaust duct upstream of the filters. Results indicated 20,000 to 30,000 dpm in the ducting. This indicates 40 to 70 times higher than the unrestricted limit of 500 dpm. Filter elements and exhaust coolers have been removed (BNL 1997b, p. 6).

2.4.2 High Flux Beam Reactor, Building 750

The BGRR capacity was replaced and surpassed in 1965 by the HFBR (BNL 2001a). The HFBR is a 30-MW thermal, heavy-water-moderated nuclear research reactor. The reactor is designed to provide intense beams of neutron radiation to be used in the study of a variety of neutron scattering research projects and to allow for the radiating of materials close to the reactor core by insertion through special tubes near the reactor core. The HFBR is fueled with fully enriched uranium and aluminum alloy, moderated and cooled by heavy water. Initial criticality was achieved on October 31, 1965. The HFBR was originally designed to operate at 40 MW. In 1979, a newer fuel design was employed that

provided increased uranium loading in anticipation of an overall facility upgrade. In 1982, several major modifications were completed that allowed operation at powers up to 60 MW.

In 1990, as a result of questions raised about the ability of natural circulation to cool the reactor during certain emergencies, reactor operations were limited to 30 MW. Heavy water flowing in the core is exposed to a dense neutron field that activates the deuterium atoms in the water to produce tritium. The primary mechanism by which tritium is transferred from the interior coolant system to the atmosphere is depressurization of the reactor vessel and evaporative losses during maintenance and refueling operations. During a scheduled maintenance shutdown in 1997, a leak in HFBR's spent fuel storage pool was discovered. In November 1999, the Secretary of Energy made a decision to permanently close the HFBR.

The HFBR Complex includes the following buildings:

Building 750
Building 750 is a domed cylindrical structure that contains the reactor and almost all associated process systems. The reactor, its beam lines, and laboratories are on the second main level known as the Experimental Level. The topmost level, the Operations Level, contains the Control Room and the Instrument Maintenance Shops.

Building 751
In 1980, the Cold Neutron Facility (CNF) was installed at beam line H9. This facility provided extremely-low-energy neutrons by moderating thermal neutrons with liquid hydrogen. Cooling of the liquid hydrogen was provided by liquid helium cooled by a large compressor in Building 751.

Building 705
Building 705 is a 100-m stack that provides the path for ventilation exhaust from the HFBR. A 30-in. underground duct exhausts air from Building 750 ventilation blowers to particulate and iodine filters and then up through the stack. Stack effluent downstream of the filters is monitored from the Stack Monitoring Facility in Building 715 (BNL 1997c, pp. 6, 7).

2.4.3 Medical Research Center, Building 490

The Medical Department (Building 490) was opened in 1956 and conducted research in the building. Active clinical research involving human volunteers is conducted in the Clinical Research Center and its satellite facilities. Animal research is conducted in the Brookhaven Laboratory Animal Facility (BLAF). Benchtop laboratory research is conducted in support of the various programs. Studies involving dispersible radioisotopes (used primarily as tracers) are carried out in the building.

There are several other facilities in the building, among them the Whole Body Neutron Irradiation Facility, the Prompt Gamma Neutron Facility, the Partial Body Neutron Activation Facility, the Inelastic Neutron Scattering Facility, the Whole Body Counter, and two SPECT cameras. Some of these facilities contain radiation sources (e.g., PuBe sources (removed) for the Whole Body Neutron Irradiation Facility were stored in a vault below the facility and were raised into the facility when in use). In addition, there are many fume hoods and other apparatus typically found in research laboratories (BNL 1997d, pp. 4, 5).

2.4.4 Brookhaven Medical Research Reactor, Building 491

The BMRR, Building 491, is the first nuclear reactor built exclusively for medical and biological research and came on line on March 15, 1959, and operated until October 2000. It is an integral part of the MRC and is in a 60-ft-diameter steel and concrete structure adjacent to the MRC (Building 490). It is fueled with enriched uranium, moderated and cooled by light water, and operated intermittently at

power levels up to 3 MW (thermal). The reactor is capable of operating for short periods at powers up to 5 MW. Air from the interior of the containment building is used to cool the neutron reflector surrounding the core of the BMRR vessel. When air is drawn through the reflector, it is exposed to a neutron field that causes the natural argon gas in the air to become radioactive (as ^{41}Ar). Due to a reduction of research funding, the BMRR conducted its last run on December 2000, and transition and stabilization activities began in 2001.

The research function of the reactor was to provide radiation beams of known, controllable character and strength at the designed sample and treatment locations. In 1997, its primary use was to provide neutron beams for Boron Neutron Capture Therapy research and patient treatment. Testing of neutron capture compounds and techniques was ongoing (BNL 1997e, p. 4).

2.4.5 Positron Emission Tomography, Building 906

Building 906 was constructed in 1981 and houses two state-of-the-art PET scanners for use in basic research in the fields of neurology, nuclear medicine, and neurosciences.

Radiopharmaceuticals labeled with short-lived positron emitters (^{11}C, ^{18}F, ^{13}N, and ^{15}O) are used for physiological and biochemical research.

In 1987, the research group acquired a new PET scanner and another in 1997. The name changes for Building 906 have been evolutionary in that today it is called the Pet Imaging Laboratory (BNL 1997f, p. 5).

2.4.6 Cosmotron, Building 902

The 902 Complex was originally built for the Cosmotron proton accelerator and experimental facilities. Some of the areas date back to Camp Upton. The Cosmotron was a very-low-intensity accelerator.

After the Cosmotron ceased operation, the Medical Department continued the operation of the Van de Graaff accelerator for a radiobiological program. The balance of the high bay area of Building 902 was used for research and development of superconducting magnets. Eventually, the Medical Department moved its equipment out and the high bay was devoted entirely to the development and fabrication of a superconducting magnet.

The operational chronology of the Building 902 High Bay is:

1949–1968	Cosmotron
1968–1980	Radiation effects facility in the south portion of the high bay
1968–present	Superconducting magnet development and fabrication and other equipment assembly (BNL 1997g, p. 2)

2.4.7 Alternating Gradient Synchrotron, 900 Series Buildings

The AGS achieved full energy in 1960 and was capable of accelerating protons to energies up to 30 GeV and heavy ion beams to 15 GeV/amu. When such accelerated particles collide and interact with nuclei, part of their energy is transformed into new particles, which fly off from the target nuclei. These particles are then detected or their paths are made visible by devices such as scintillation counters, Cerenkov counters, bubble chambers, spark chambers, and photographs. The AGS has been continuously upgraded and it now provides the highest intensity of protons per pulse and the highest intensity of polarized protons per pulse than any other synchrotron in the world. The AGS also accelerates heavy ion beams for experimental use as well as for the RHIC.

The AGS consists of three different accelerating systems: the 200-MeV LINAC, which is the source of the protons housed in Building 930, the 200-m-circumference rapid cycling Booster synchrotron in Buildings 914 and 942, and the 800-m AGS main ring designated as Building 913. The Tandem Van de Graaff accelerator, which is a separate facility, provides heavy ions for the Booster ring through a beam transfer line. The particles that are accelerated by the AGS facility are extracted into and stopped in various experimental areas around the ring, or are sent through a transfer line to the RHIC. Building 912 was the original experimental target area. The asphalt pad inside the AGS ring adjacent to Building 912 was an experimental area in the 1960s with two secondary beam lines. Since that time, activated components have been stored and repaired in the area. Figure 2-3 shows the buildings associated with the AGS Complex.

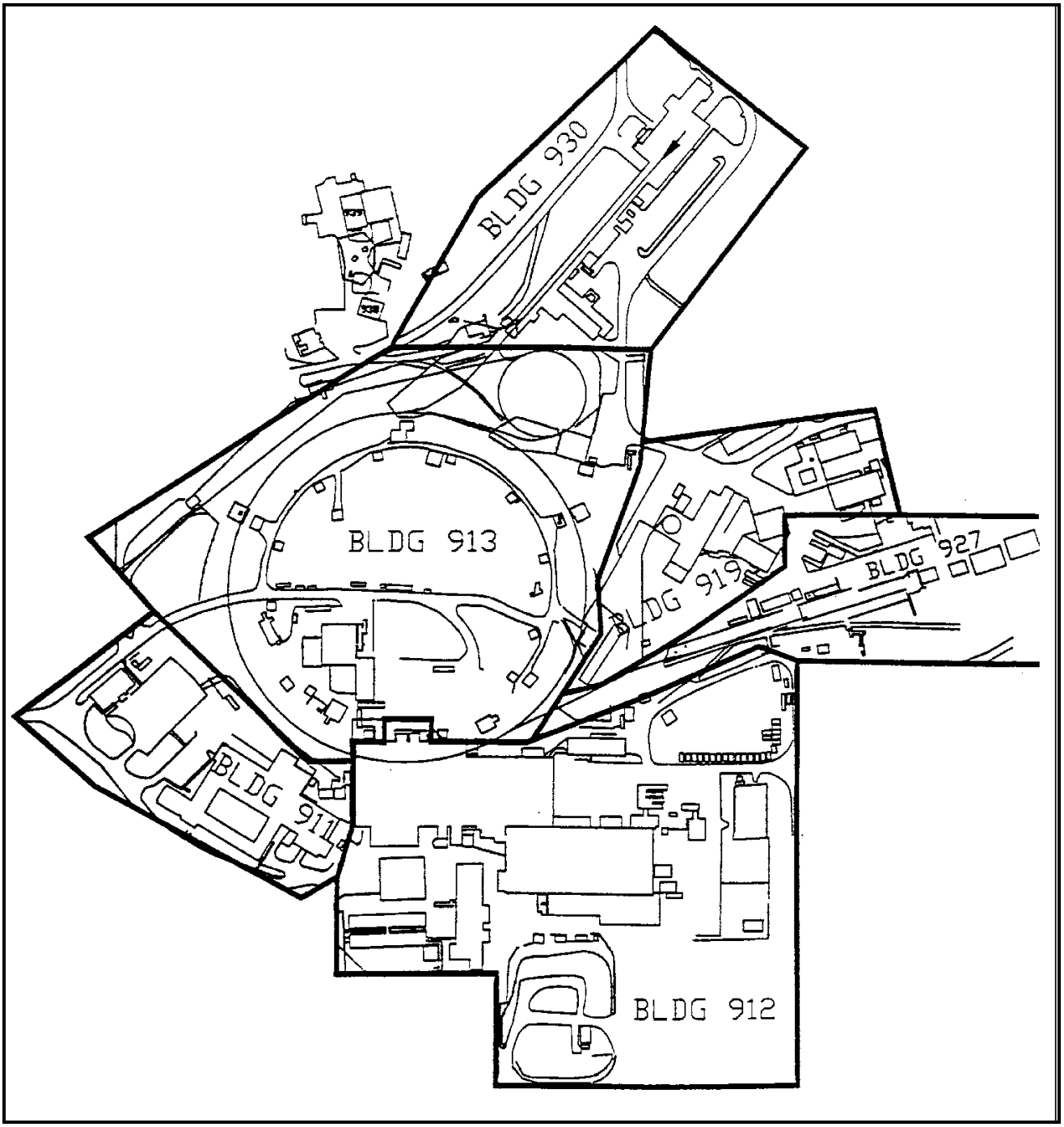

Figure 2-3. The AGS complex (BNL 1997h).

The AGS Linear Accelerator, Building 930 and Associated Facilities
The LINAC was designed and built in the late 1960s as part of a major upgrade to the AGS facility. The LINAC tunnel is 140 m long and consists of nine large accelerators. From the end of the LINAC, a 17-m-long spur tunnel injects the beam into the Booster accelerator. Another high-energy beam transport (HEBT) line extends 95 m to connect with the AGS. Another spur tunnel provides beam to the BLIP facility, the Chemistry LINAC Isotopes Facility (CLIF), the Radiation Effects Facility, the Neutral Beam Test Facility, and a beam stop. Only the BLIP facility is presently used, and it has recently undergone a significant upgrade to increase its intensity. The LINAC consistently produces a beam of 25 to 35 mA with a 0.5-ms pulse length or 1.0×10^{14} protons/pulse. Pulses are repeated at the rate of 7.5 per second, but at most only 1 in 7 pulses are transported to the Booster with the remainder transported to the BLIP facility.

Relevant buildings directly attached with building 930 are:

- Building 930 MER - provides water-cooling services for the LINAC complex and contains activated water. Associated with it is a large water-cooling tower and a compressor area.

- Building 930 Annex - was added in the 1970s and contains shops and storage areas. Building 930A was added on in the late 1980s as a service building for the Booster project. It contains power supplies and computer control equipment for the Booster (BNL 1997h).

The AGS Accelerator Rings, Buildings 913 and 914, and Associated Facilities
The AGS tunnel, Building 913, has a circumference of 800 m and is buried under a 7-m-thick berm of earth and concrete. There are 240 large alternating gradient dipole electromagnets, more than 100 supporting focus and beam tuning magnets as well as radiofrequency (RF) accelerating components, vacuum systems, water-cooling systems, etc., in the tunnel. Supporting the tunnel operation are the ventilation system fanhouses and multiple power supply houses. Some of these houses are designated 913A through R, while others have a separate plant engineering building number. The AGS tunnel (Building 913) is interrupted at the Experimental Hall, Building 912, for roughly 65 m. Here the AGS is under heavy concrete shielding blocks.

The Booster tunnel (Building 942) is directly adjacent to the AGS tunnel and the LINAC. It is connected to the LINAC and the Tandem Van de Graaff through the HEBT transfer tunnel. The original connecting tunnel is now used to transfer a beam from the Booster to the AGS. The Booster tunnel is 200 m in circumference and is buried under a 5-m thick berm.

The new section of the Booster tunnel was built in 1988. Some radioactive gases were created by activation of the ventilating air in the tunnel and experimental areas of the AGS. But, because they are short-lived (^{11}C, half-life 20.5 minutes; ^{13}N, half-life 10.0 minutes; ^{15}O, 2.1 minutes), they did not create a measurable radiation level beyond the immediately adjacent onsite area. All of the cooling water systems in the AGS and Booster tunnels are activated. This includes systems that use the AGS ring as a utility tunnel for piping that goes to the support buildings. In addition, there are activated components in the AGS and Booster rings, and activated spare parts are stored in the facility (BNL 1997h).

Other Related Buildings
Building 911. Building 911 is the main office for the AGS Department. It was one of the first structures built for the accelerator complex and has direct passageways to both the AGS tunnel (Building 913) and the AGS experimental area (Building 912). Building 911 also contains the main control room, the support building for the main magnet cooling system, the support building for the Westinghouse main magnet power supply (now the backup power supply for the ring magnets), a high bay assembly area with magnetic field testing shops, and other light electronics, vacuum, and machine shops. There are activated components from the AGS ring that have been stored and

repaired in the high bay area and shop areas of Building 911 in posted radiation work areas. Because it also contains a system to cool water from the AGS ring, it does contain activated water (BNL 1997h).

Building 912. Building 912 is the designation of the approximately 5 indoor acres of AGS experimental floor. It is not one building, but five connected structures constructed over a 30-year period. The initial portion of Building 912 was started in 1958 to enclose both a portion of the AGS ring and the first experiments.

Within this large area, a majority of the ~400 AGS experiments have been located. The AGS experimental floor also contains a section of the AGS ring. Surrounding the beam lines are concrete and steel shielding needed to maintain radiation levels to within the required limits outside the lines. Shielding around the proton target stations that produce secondary beams is much thicker due to the high levels of radiation generated in the targets. This shielding can have significant activation contained in the body of the material. Cooling water at these target stations has higher levels of activation than the magnet cooling water and is handled by closed cooling systems. Radiation safety is provided by security systems that prevent access to these target stations and primary beam lines when protons are being extracted to these areas. There are activated components in the beam lines, including highly activated targets. Steel cutting, including activated shielding steel, has been performed inside and outside Building 912. Depleted uranium was used in experimental areas in the past, but its use and disposition were tightly controlled. Small radioactive sources (nanocuries) are used. They are inventoried and stored in locked shielding boxes (BNL 1997h).

Building 913A-E. AGS ventilation system fanhouses were an original part of the AGS ring and provided air conditioning and heating for the tunnel enclosure. Because of their proximity to the tunnel, they are High Radiation Areas when there is beam in the AGS ring and must be kept secured during operations. The cooling water for the air-conditioning system is activated and there is a potential for release in the fanhouse. Air handled in the fanhouses is from the AGS tunnel air and can also be activated (BNL 1997h).

Building 914. Building 914 was the location for the original 50-Mev AGS LINAC. This facility contained power supplies, water-cooling systems, pumps and compressors, and a motor generator set. During the 1970s and 1980s, after the LINAC was decommissioned, this building housed a mechanical maintenance group for the AGS division. Activated components were repaired and stored in this facility and new components were assembled and cleaned there (BNL 1997h).

Building 919 (the g-2/Bubble Chamber and associated facilities). Building 919 was built in 1962 for an AGS experimental area and is still in use. The high bay area of Building 919 housed the 80–in. bubble chamber that was in operation until 1978. The bubble chamber had both a cryogenic component and a large mechanical component driven by a high-pressure oil hydraulic system. When the bubble chamber reached the end of its run, the high bay area and control room were used as shops and assembly areas. The cryogenic shop continued to be used to support liquid H_2 target in Building 912 and the other buildings became storage areas. This continued to the late 1980s, when the area was modified for the g-2 experiment and the water-cooling systems were used to support Booster operations. A release of tritium from a gas chronograph detector occurred in 1973 in the technician machine shop. The detector held approximately 250 mCi of tritium (BNL 1997h).

Building 920. Building 920 is the EI0 Power Supply building, and is above the AGS ring. It houses an assortment of power supplies used under different beam configurations, but is presently running only a few supplies. The radiological hazard in Building 920 is radiation from activated cooling water and oil in transformers (BNL 1997h).

Building 928 (Siemens motor generator house). Building 928 is directly adjacent to and at one corner connected to Building 929. Both buildings share a basement area. The basement area contains support electrical equipment and lubricating equipment for the motor generator set. Also in the basement is a mechanical equipment room with water-cooling equipment for power supplies in Buildings 928 and 929 and for systems in the AGS ring. There were potential radiation hazards from activated cooling water (BNL 1997h).

Building 949. This new building houses the proton target that produces secondaries for the g-2 ring. The water-cooled target is highly activated (>50 rem at contact immediately after the beam has been turned off). Building 949 is built into the side of the V-line and has extensive shielding. The beam line, which runs between the target building and Building 919, contains water-cooled magnets and vacuum pumps. The cooling water is shared with the target so it is activated (BNL 1997h).

Building 960. The building was the site of a large high-energy physics experimental facility, the Seven Foot Bubble Chamber (1972–1979). After the Bubble Chamber was removed from Building 960, the facility was used for storage and to test superconducting materials, in conjunction with a small cryogenic helium refrigerator (1979–1993). The testing of superconducting materials moved to Building 902 in 1993. From 1993 to 1997, the building was used for storage and then was abandoned. From a radiological standpoint, the particle beam delivered to the Bubble Chamber was very low intensity with respect to causing induced activity in the machine components (BNL 1997i, pp. 3, 6).

Buildings 912, 919, 975. The AGS Department has used warehouse space throughout the facility and the Laboratory. The AGS also stored materials outside, in the “inner Mongolia” area of the AGS, the southwest area, and the ISABELLE experimental buildings. One of the major issues confronting AGS storage is the storage of activated materials. When a part fails in service in the accelerator tunnels or the experimental lines, it is often replaced with a spare. After a radiation cooldown period, the component is repaired and stored until needed (BNL 1997h).

Building 918 (Warehouse). This building is adjacent to Building 912. It was built in 1957 and 1958. It was a warehouse from the start and always used for that purpose. It was doubled in size in 1962. Activated components are stored in it (BNL 1997h).

Building 196 (Warehouse). This wood-frame building was built in 1942. It was formally abandoned and demolished in 1995. The building was used by the AGS Department for storage from 1975 until it was abandoned in 1991–1992. The building housed depleted uranium, lead, activated copper magnet coils, vacuum pumps with oil, and other activated components (BNL 1997h).

Building 209 (Warehouse). This warehouse belongs to the Safety and Environmental Protection (S&EP) division. The AGS has been storing activated components (e.g., magnets, jacks/stands, and coils @ <5 mR) in the building since 1995 (BNL 1997h).

Building 424 (Warehouse). Building 424 was built in 1942 for Camp Upton as its theater. The AGS began storing activated components and power supplies with polychlorinated biphenyl capacitors there from 1973 until it collapsed in 1996. After the building collapsed, it was totally demolished (BNL 1997h).

Building 178 (Warehouses). This building was built in 1922 as a theater and lecture hall. The AGS began storing activated components there in the early 1970s. Because the building was wood frame and in a "populated" area, the levels of activation were low and much of the equipment was new spares. The AGS equipment was removed and the building was demolished in 1992 (BNL 1997h).

2.4.8 Brookhaven LINAC Isotope Producer, Building 931

In 1972 the BLIP (Building 931B) and the CLIF (Building 931A) were constructed on a large earthen mound. The CLIF was operated independently by the Chemistry Department until 1977, at which time it was incorporated into the BLIP operation. Building 931C was constructed in 1996 as part of a substantial facility upgrade.

The BLIP was designed for production of radioisotopes by irradiation in the LINAC beam. It consists of a main building that houses a "hot cell" over a shaft that descends approximately 30 ft. The shaft allows targets containing various substances to be lowered along a track to an area into which a beam from the LINAC is conducted. Irradiated materials are withdrawn, transported to, and processed in, the Target Processing Lab (TPL; Building 801).

A smaller structure (Building 931A) houses the control panel for BLIP operations and monitoring, as well as a single fume hood and a second LINAC beam access system (currently not in use).

Building 931C acts primarily as a garage to house the fork-lift truck used to deliver irradiated targets to the TPL.

In the BLIP, targets are irradiated with 200-MeV protons. In this process, high-energy secondary neutrons are created. These penetrating neutrons are absorbed in the shielding soil around the main BLIP containment tank. This leads to some activation of the shielding soil (BNL 1997j, pp. 3, 4).

Building 946 houses the water-cooling equipment for the BLIP target area. This area was upgraded to provide better containment and shielding for this activated water system (BNL 1997h, p. 1).

2.4.9 Tandem Van de Graaff, Building 901

The Tandem Van de Graaff is housed in Building 901. It consists of two Van de Graaff machines, arranged so they can be used independently or in tandem, each capable of accelerating atomic particles to energies of 10 MeV. A special device that changes negative ions to positive ions makes it possible to achieve a maximum total acceleration of 30 MeV.

Building 901 is divided into laboratories, accelerator vaults, and office space. The building is the home for research that includes medical radionuclide research, accelerator target development, synthetic organic chemistry of radiotracers, and analysis of a variety of materials. Areas inside the building include the cyclotron area, the Radio-Frequency Quadrupole (RFQ)-Drift-Tube-LINACS (DTL) area, laboratory space associated with the Department of Applied Science (DAS), and a mechanical shop area that is currently occupied as a storage area. The west end of the building contains the Dynamitron, which has been shut down, and a robot room dedicated to the analysis of biological samples.

Area 1 – Cyclotrons. Two cyclotrons housed in this area are used for the production of radiopharmaceuticals. The radiopharmaceuticals are processed in the adjacent hot chemistry laboratory suite (Rooms 108 to 112). The cyclotrons are operated remotely from Room 118. These machines are used almost exclusively for producing the short-lived, positron-emitting isotopes used in the PET program. The radioactivity produced by these cyclotrons is remotely transferred, as liquids or gases, from the vaults to the adjacent hot laboratory. The hot laboratory contains preparation and purification equipment as well as shielded hoods for the processing of the radioisotopes from the cyclotrons into radiopharmaceuticals (BNL 1997k, p. 5).

Area 2 -RFQ-DTL Accelerator. The BNL RFQ-DTL facility consists of the AccSys RFQ accelerator, associated electronics, and other support systems. The areas associated with the accelerator include

the vault (Room 130), where the accelerator is located, and the control room (Room 129), where the power supplies and control console are located. Since 1996, this facility has occupied space formally used for the 3.5-MeV Van de Graaff (BNL 1997k, pp. 4, 5).

Area 3 - Laboratory Space. This area is laboratory and office space devoted to DAS projects. Most of the space is used for data analysis and storage of materials to be analyzed at the NSLS. The former machine shop is used for storage of samples and unused electronic equipment associated with the 3.5-MeV Van de Graaff (BNL 1997k, p. 5).

Area 4 - 901W Dynamitron and Robot Room. This room in the southwestern corner of Building 901W is dedicated to the operation of a robot used by the BNL PET program to analyze plasma samples taken from subjects during the PET study. The rest of the area in Building 901W is occupied by the Dynamitron (BNL 1997k, p. 5).

Most of Building 901 was constructed in 1948 and 1949. It was originally constructed to house the cyclotron(s) and the 3.5-MeV Van de Graaff. The 3.5-MeV Van de Graaff was installed in the building in 1950.

In 1958, Building 901 W was constructed to house the 18-in. cyclotron, which, in 1959, was moved from the test shack in the rear of the Cosmotron and reassembled in the new building. The 18-in. cyclotron was capable of accelerating protons to energies of about 3 MeV. From 1960 to 1963, this accelerator was used to study elastic and inelastic scattering of polarized neutrons. The target material for the production of the neutrons was a T(p,n) ^{3}He reaction on a target of zirconium tritide. The accelerator was capable of consistent beam currents of 100 µA and occasionally reached beam currents of 200 µA.

The 60-in. cyclotron was installed in 1950 and became operational in 1951. The 60-in. cyclotron was capable of producing 10 MeV protons, 20 MeV deuterons, and 40 MeV alpha particles. It was used to produce a variety of radioisotopes for use in medicine, biology, chemistry and physics. Upgrading of the 60-in. cyclotron began in 1964 and was completed in 1968. The upgrade project resulted in the cyclotron becoming a variable-energy machine capable of producing 35-MeV protons, 23-MeV deuterons, 57-MeV ^{3}He and 46-MeV alpha particles. During the late 1950s and early 1960s, a number of radioisotopes were in development and/or production at what was known then as the Low Energy Accelerator Facility (LEAF), which included the cyclotrons, and the Van de Graaff accelerator. The isotopes were: ^{90}Y, ^{47}Ca, ^{67}Cu, ^{38}Ar, ^{28}Mg, ^{124}I, ^{133}I, ^{47}Sc, ^{210}Po, ^{83m}Kr, ^{68}Ga, ^{151}Sm, ^{132}Te-^{132}I generator, and ^{99}Mo-^{99m}Tc generator. The major purpose of these isotopes was medical research.

In 1965, the Dynamitron was installed in Building 901W. It was used as a positron accelerator until 1989 to study positron reactions. During this time, it used a large ^{22}Na source as the generator of positrons. This source was removed in 1996. At present, the facility is not in operation and there are no immediate plans for a restart. All activated items have been removed.

The Van de Graaff was installed in Building 901 in 1950. There were some problems during the early years and a reconstruction project was completed in 1954. In 1960 the first experiments with a ^{3}He beam were begun. The first test of the triton beam was carried out in June 1968. During 1968 and for a few years after, ^{28}Mg was being produced routinely on the Van de Graaff using the 26 Mg(t,p)28 Mg nuclear reaction. During the period from 1968 through the late 1970s, the 3.5-MeV Van de Graaff was being used to accelerate tritium for production of isotopes as well as basic physics studies. In 1985, the Van de Graaff was turned over to the DAS. Some experiments with tritium continued until the shutdown of the Van de Graaff in 1991 (BNL 1997k, pp. 6, 7).

2.4.10 National Synchrotron Light Source, Building 725

Building 725 is the NSLS. It is one of the most intense sources of X-ray, ultraviolet, and infrared radiation in the world. The beams of radiation are created by electrons circulating in two storage rings. The X-ray ring energy is 2.5 GeV and the VUV ring is 800 MeV. The radiation produced by the circulating electrons travel down 85 independent beamlines to targets on a variety of experiments. There are also wet laboratories available for the experimenters, storage space, offices, and a user machine shop in the building.

The sole occupant of Building 725, which was constructed in 1981, has been NSLS. In 1987, a major Phase II expansion of the facility (office space, beamlines, laboratory and setup space) was added, but the original function of the facility remained the same. Operations of the VUV ring commenced in 1982 and the X-ray ring in 1984 (BNL 1997l, pp. 1, 2).

Building 729 is the NSLS Source Development Laboratory. The building houses a linear accelerator coupled to a magnetic "wiggler" that produces an intense X-ray beam (BNL 1997m, p. 1).

2.4.11 Relativistic Heavy Ion Collider Complex, Building 1000 Series

The RHIC Complex is shown in Figure 2-4. It is a high-energy particle accelerator that was commissioned in 1999 and achieved its first successful operation in the summer of 2000. The RHIC is designed to achieve much higher reaction energies by colliding two accelerated beams head-on. When the ion beam is traveling at top speed in the AGS, it is taken down another beam line called the AGS-To-RHIC (ATR) transfer line. At the end of this line, there is a “fork in the road,” where a switching magnet sends the ion bunches down one of two beamlines. Bunches are directed either left to the clockwise RHIC ring or right to travel counter-clockwise in the second RHIC ring. From here on, the counter-rotating beams are accelerated, as in the Booster and AGS, and then circulate in RHIC where they will collide into one another at as many as six interaction points. These intersection points are described in Figure 2-5.

The chronology of the RHIC buildings (BNL 1997n, pp. 4–8):

Building 1002

1981–present	Experimental hall, assigned to BRAHMS experiment
1982–1992	AGS and ADD storage, some activated components
1990–1992	AGS experiment 813

Building 1004A (Service Building)

1981–present	Utilities, no usage before 1992
1992–present	RF System testing

Building 1004 Open Area

1981–present	Future experimental area
1994–present	RF cavities testing for Collider
1996 -present	Temporary beamstop for Sextant Test completed during January 1997

Building 1004B (Support Building)

1994–present	Power supplies, Cryogenic Valve Boxes, other system electronics

Building 1005 Beam Tunnel

1981–present	Commissioned in January 1997 as part of the Sextant Test

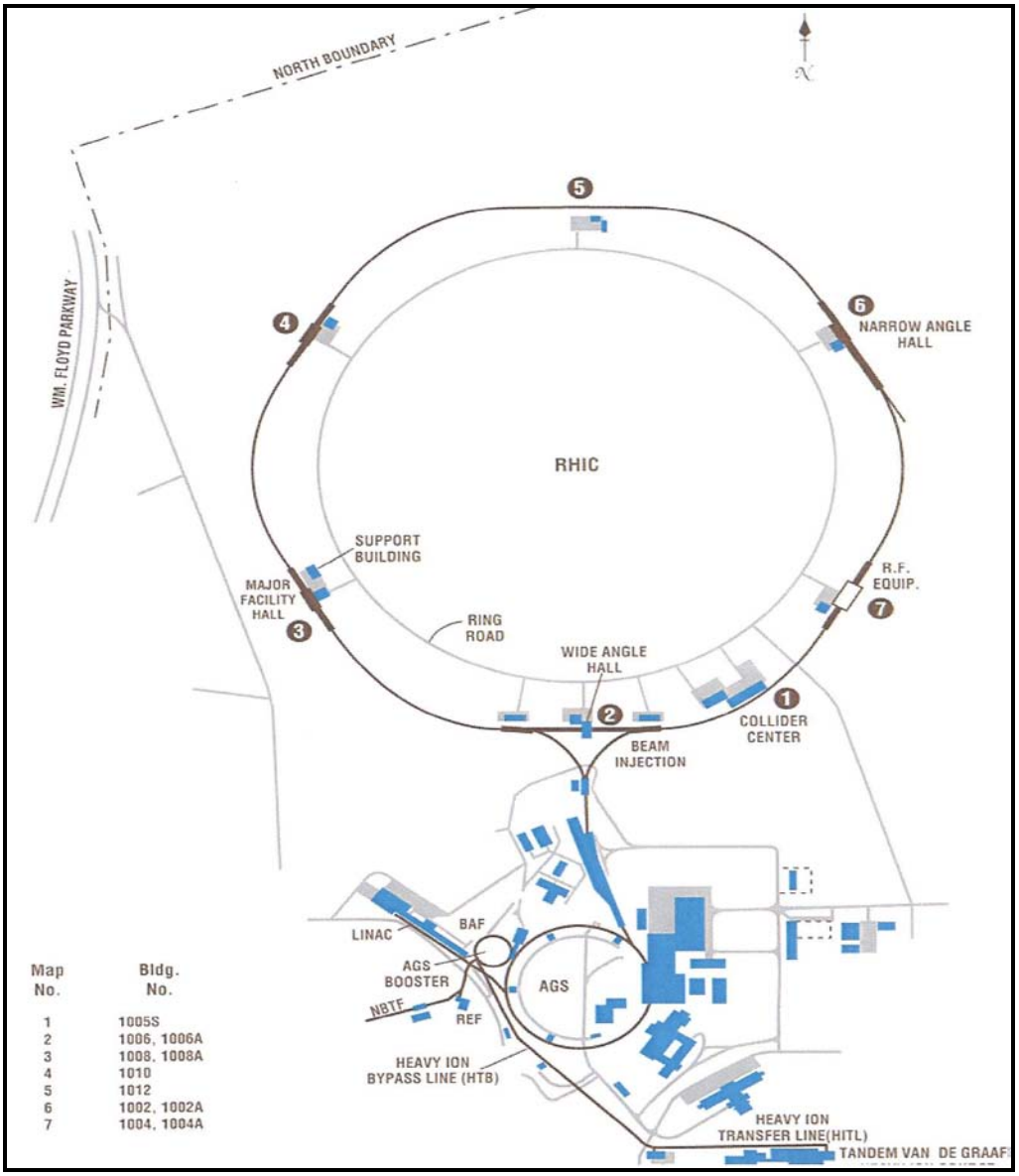

Figure 2-4. The Relativistic Heavy Ion Collider complex.

Building 1005S
1981-present Tech Shops on 1st Floor, Administrative Offices 2nd, 3rd, 4th Floors

Building 1006
1991–present STAR Detector
1985–1986 Machining of low-level radioactive steel for AGS Experiment 787
1981–1990 Other short-term uses, temporary storage

Building 1006A (Service Building)
1981–present Experimental support, tech shop, utilities, and center room occasional storage

Building 1007
1981–present Beam tunnel to be commissioned in 1999
1981–1995 Part of tunnel used as a calibration laboratory for Survey Group

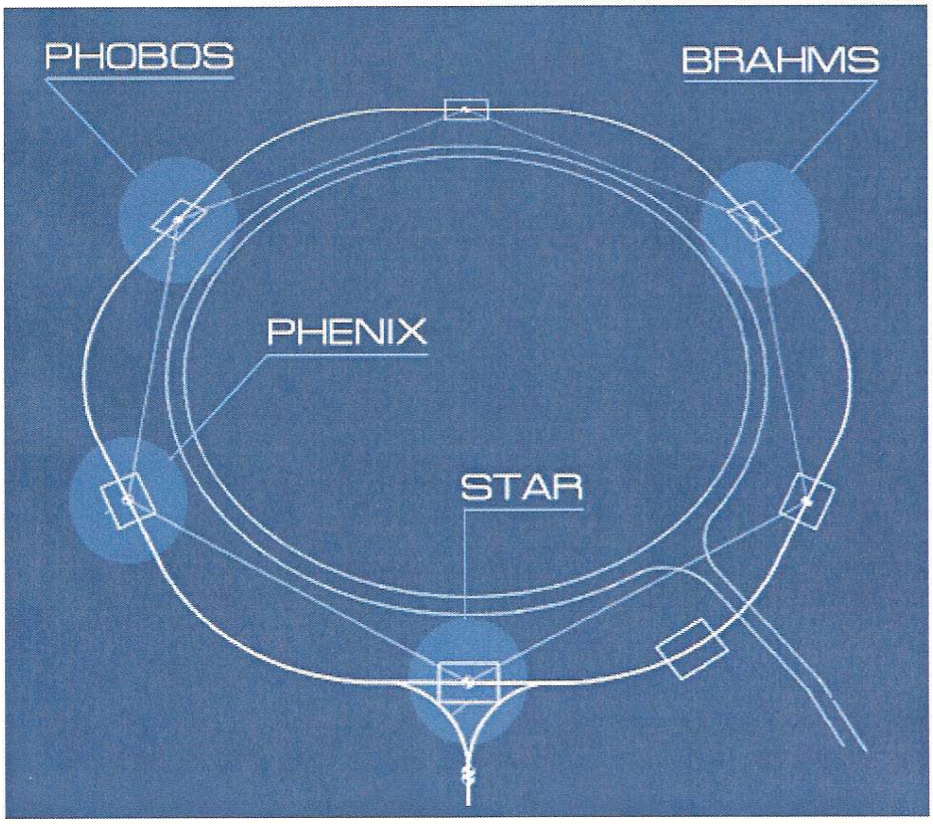

Figure 2-5. RHIC ring intersection points (BNL 2009b).

Building 1008

1991–present	PHENIX Experiment
1992–1995	Injection magnet fabrication
1988–1991	Uranium plate machining for Experiment DO at FNAL

Building 1008A

1981–present	Experimental Support Building, Utilities
1992–1995	Injection Magnet Group Shop/South Room
1990–1992	AGS/Physics Experiment Prep/South Room
1986–1987	Assembly of Wire Chambers for AGS Experiment 755
1985–1986	Cleaning of Depleted Uranium with TCA for CERN Experiment NA-34

Building 1010

1994–present	PHOBOS Experimental

Building 1012

1994–present	Future Experimental Hall

2.4.12 Hot Laboratory, Building 801

Building 801 has from its inception in 1949 been known as the Hot Lab. It consisted of a central laboratory, a fanhouse, a radioactive-liquid waste tank farm, and a liquid radioactive-waste concentration plant. The original purpose of the central facility was to provide appropriately shielded areas for research with large amounts of radioactive material. The building was designed as two separate but connected structures; a "Hot" (the western portion) and a "Cold" (the eastern) side. The Hot area of the Hot Laboratory included five hot cells, three chemical-processing hot cells, and three

high-level hot cells for handling and processing of relatively high levels of radioactivity in gaseous, liquid, or solid form. The cells were maintained at negative pressure with respect to their surroundings to minimize the possibility of radioactive releases to the building. Each has individual exhaust air filters as well as a backup filter preceding discharge to the BGRR stack.

Currently in the Cold area there are a number of chemistry laboratories that conduct basic research. On the Hot side, radioisotope processing and production (related to the BLIP), and radiopharmaceutical research is conducted by Medical Department staff.

There are Metallurgy Hot Cells [the Metallurgical Evaluation Lab (MEL)] in the Semi Works Area (Area 56) that were constructed in 1958. Metallurgical studies on highly radioactive reactor components were performed in this facility by Department of Applied Technology (DAT) personnel.

There are "D" and "F" waste systems (storage tanks and piping) in the building basement. The D waste system holds radioactive nonhazardous liquid waste. The "F" waste system holds nonradioactive, nonhazardous liquids. The Hazardous Waste Management Group of S&EP manages that facility.

Some additional special facilities in the building are the TPL (a series of six hot boxes in a separate, rad-monitored area (Room 66), the MEL, and three inactive Hot Cells. The 300-ft stack south of the building receives the ventilation from hoods on the hot side. The stack is monitored for radioactivity (BNL 1997o, p. 4).

There was a ^{60}Co irradiation pool in what is now the TPL (Laboratory 66). The pool, which was constructed of concrete, had depths of 4, 10, and 14 ft where large amounts of sealed ^{60}Co sources were stored under water. There was a drain to D waste in the deep portion of the pool. The pool was in operation from about 1952 until about 1960. The ^{60}Co pool was moved, water was drained, concrete was decontaminated, and the pool area was backfilled with sand (BNL 1997o, p. 7).

From March 1952 to June 1960, there was a program at the Hot Laboratory to produce ^{131}I by acid-dissolution of irradiated uranium samples. A separate exhaust system, which included NaOH scrubbers and backup charcoal filters, was installed in the hot cell and ducted to a stainless-steel pipe in the BGRR stack.

There are pneumatic tubes in the roadway connecting the BGRR to Building 801. These lines allowed quick transfer of short-lived isotopes from the reactor to Building 801 where they would be used. An interviewee reported that at times the rabbits containing the radioactive samples would break or get stuck in these tubes.

Incidents

On May 15, 1957, a serious incident occurred involving the reprocessing of uranium for the Volatility Project. UF_6/BrF_3 exploded and a few people were injured, one hospitalized. There was a release of about 13 lb of unirradiated uranium to the local environment. Damage occurred to nearby trees, automobiles, and building equipment. Environmental sampling of the appropriate areas might identify residual uranium contamination (BNL 1997o, p. 5).

In August 1960, some highly radioactive waste (reactor fuel elements) was dissolved in aqua regia and stored in plastic containers in the storage vault (Room 51). These containers cracked and leaked onto a stainless-steel tray containing the plastic containers. The solution was sucked up using an aspirator connected to the house vacuum system. The vacuum system became highly radioactive. The main vacuum chamber removed all standing liquid in the lines. However, because of the high contamination level and long half-life of the activity, the pipes remain residually contaminated. The system was moved to a remote location, but some of the piping in the floor is still contaminated as a

result of this incident. The piping is still in the concrete floor, which is labeled as a radioactive material area (BNL 1997o, p. 7).

2.4.13 High Intensity Radiation Development Laboratory, Building 830

Building 830 is an office and laboratory complex presently occupied by DAT and RHIC personnel. All of the RHIC personnel are housed in a modular structure, which is totally office space. The laboratory complex has always been used as an extensive experimental area, especially with regard to the use of radioactive and hazardous chemicals. This facility houses the Gamma Irradiation Facility (GIF), two inactive hot cells, analytical laboratories, electron microscopy, and associated offices.

In 1963, Building 830 commenced operations as the HIRDL. At that time, it consisted of the high bay area (which houses the two hot cells), laboratories, and offices. Cell 1 (Preparation Cell) was used to fabricate high-intensity ^{60}Co sources for food irradiation programs. Some of the sources were then moved to Cell 2 (Irradiation Cell) by means of a transfer canal. In the Irradiation Cell, the sources were stored in a 21-ft–deep, water-filled pit in the cell until needed. Items to be irradiated were moved in and out of the Irradiation Cell by means of two transfer tunnels under the cell. Sources were also kept in the two bays for storage and irradiation purposes.

In 1970, the Low Dosimetry Facility (currently known as the GIF) was added to the northeast end of the main building. This facility included the gamma irradiation pool and a machine shop. Sources were stored at the bottom of the pool and samples to be irradiated were lowered through air-filled tubes. In 1974, the last of the sources was removed from the pit in the Irradiation Cell. Since that time, the cells have been used for experiments with lower activity level materials, and storage of radioactive materials and contaminated equipment.

At present, the two hot cells in Building 830 have no mission-essential work. The Laboratory spaces are being used for experiments, and the GIF currently contains approximately 35,000 Ci of ^{60}Co (BNL 1997p, pp. 2-3).

2.4.14 Chemistry Department, Building 555

Building 555 is the home of BNL's Chemistry Department. It was built between 1963 and 1966. The only major modification was made in 1996 when the underground Center for Radiation Chemistry Research was added. The building contains three floors plus a partial basement and loft. There are many extra-large laboratories with at least two fume hoods per laboratory. There are pipe chases between rows of laboratories to deliver all services to the laboratories. Transparent glass piping in the basement carries wastewater from the sinks in the laboratories to the sewer system. Counting rooms constructed of specially selected low-activity materials are used for low background counting. There is a large chemical stockroom with separate storage rooms for acids, bases, and organic solvents, as well as a room devoted to the washing of laboratory glassware.

A large variety of research programs have been conducted during the past 31 years. Many different chemicals have been used, including inorganic acids and bases, inorganic compounds and metals, as well as a plethora of organic and organometallic compounds. A variety of specialized equipment and instrumentation is in use in different laboratories (e.g., there are several laser-based systems in operation).

In addition, research with radioactive isotopes has been done since the earliest days. Studies include chemical kinetics, hot-atom effects, nuclear chemical studies of nuclear decay schemes, nuclear reaction cross-sections, solar neutrino studies, and radiocarbon dating. Over the years, the mix of research projects in the Department has changed considerably, but virtually every chemical element in the Periodic Table has been used at one time or another in the building (BNL 1997q, p. 5).

Some radiological problems associated with the building are:

Disposition of sealed ^{60}Co irradiation sources in Laboratories 171–173. These sources are in stainless-steel containers that penetrate the laboratory floors and are in the ground below. There is evidence that one source (40-Ci source strength) was leaking small amounts of ^{60}Co into the water that surrounds the source to provide radiological shielding. This source has been removed and disposed of. Some of this contaminated water has gotten into the soil surrounding the buried containment vessel. The amount of ^{60}Co in the water and the soil is small. (The estimated ^{60}Co activity remaining in this soil is less than 35.)

Radioactive materials and counting samples are used and/or stored in many rooms: Laboratories 225, 227, 229, 233, 235, 236, 253, 367, 369, and 374 and counting rooms 103, 203, 204, and 205. Periodically, chemical manipulations are done with these materials in vented hoods that are posted as radioactive work areas in accordance with BNL procedures. Occurrence reports from 1990 to present were reviewed for Building 555. They indicated three separate reportable incidents involving small amounts of radioactivity. Two of these, one involving ^{32}P and the other, ^{238}U, were confined to the chemistry laboratories in which they occurred. The third involved a Kimwipe contaminated with ^{124}I that was inadvertently thrown into the trash and was subsequently detected in the garbage truck before it left the BNL site (BNL 1997q, p. 9).

2.4.15 Physics Department, Building 510

Building 510 was built in 1962 to house the Physics Department personnel and laboratories. It consists of approximately 400 offices and 100 laboratories in an area of about 200,000 ft^2. There is a large machine shop to support the research programs as well as a number of smaller machine shops. A high bay area is available for assembling equipment for experiments. The basement is used predominantly for storage but houses the building support facilities such as heating and air-conditioning units and power distribution systems. The northeast parking lot contains 11 trailers permanently placed for storage of solid materials. These are not climate controlled and no chemical or radioactive materials are stored there (BNL 1997r, p. 6).

The northeast corner of the building houses in the Health Physics Section (Room 1-136) where there are 35 vaults for storage of radioactive materials. There are nine Type A vaults that are 12 in. in diameter and penetrate 10 ft into the ground, six Type B vaults that are 8 in. in diameter and penetrate 10 ft into the ground, and 20 Type C vaults that are 8 in. in diameter and penetrate 3 ft into the ground. Vault 17 is contaminated because it contained a leaking radium source. The source has been placed in a sealed polyvinyl chloride pipe and is now stored in Vault 4 (BNL 1997r, pp. 4, 5).

2.4.16 Other Miscellaneous Radiological Research Facilities

2.4.16.1 LMFR Support, Building 820

Research and development on Liquid Metal Fuel Reactor (LMFR) technology took place in Building 820 from 1957 to 1975. A simulated reactor with a core of uranium dissolved in bismuth was studied (BNL 1997s, p. 4).

2.4.16.2 Hot Machine Shop, Building 530

Building 530 functioned as a Hot Machine Shop for the Central Shops Division. In 1975, Central Shops evacuated the building and relocated its equipment and function to Building 462. The building was then used as a storage area by Plant Engineering until 1988, at which time it was demolished (BNL 1997t, p. 3).

2.4.16.3 Health Physics and Safety Instrumentation, Building 535

Building 535 was constructed in 1962 and 1963 and was operational in 1964. The building is a multitenant, multifunctional facility consisting of a ground floor and a basement. The Instrumentation Division, which is responsible for the building, occupies a major part of the ground floor for research and development of X-ray and neutron detectors and corresponding electronics. These detectors and associated electronics are used at the NSLS, the HFBR, the AGS, and other worldwide scientific research facilities. A state-of-the-art electronic printed circuit design and fabrication facility and a microelectronics clean room facility are unique to the Laboratory. The Safety and Environmental Protection Division's Analytical Services Laboratory was in the basement of Building 535 until the 1990s, when it relocated to Building 490. Personnel Monitoring was also in this building until 2002, when it relocated to Building 490. Personnel Monitoring processed film badges and TLDs in the building (first floor). Also in the building was the equipment needed to operate the external monitoring program (X-ray machine, dark room, densitometer, microscopes, etc.).

In 1978, the NSLS Department moved into the rear section of the basement, occupying that space to the present. An underground walkway (tunnel) was constructed in 1986 between the basement of Building 535 and the main floor of Building 725 (NSLS Department).

In 1985, Instrumentation Division established the Optical Metrology Laboratory in the southeast section of the basement to conduct research for synchrotron radiation experiments. In 1987, an office module was added to the southwest corner of the building (BNL 1997u, pp. 5, 6).

2.4.17 Waste Management Facility, Radwaste Reclamation Building, Building 865

The WMF was opened in December 1997 for managing the wastes generated from BNL's research and operation activities. The new WMF replaces the original Hazardous Waste Management Facility in its entirety and its design ensures that all storage and transfer activities are accomplished inside buildings and on paved and curbed areas. A security fence around the cleared area and a berm 8 ft high around the perimeter of the radioactive waste portion of the facility ensures that incidental exposures meet the BNL design criteria of 25 mrem/yr to nonradiation workers.

The WMF includes an Operations Building (Building 860), a Resource Conservation and Recovery Act Waste Building (Building 855), a Radwaste (Radioactive Waste) Reclamation Building (Building 865), and a Mixed Waste Building (Building 870).

Radwaste Reclamation Building, Building 865. The Reclamation Building is the primary facility for radioactive waste handling, size reduction, and repackaging for subsequent offsite disposal for BNL. The goal is to size reduce the radioactive waste stream generated at BNL. This building receives bulk radioactive waste of various sizes and configurations to be disassembled, decontaminated, size-reduced, and packaged for temporary storage before shipment off site. To achieve the goal of waste reduction, Building 865 will house a 500–lb/d lead smelter, a trash compactor, and a shredder (BNL 1997v, pp. 2, 3).

Additional radioactive waste treatment facilities include:

Wastewater processing began in 1995. The Tritium Evaporator Facility (Building 802B) was constructed to reduce the total amount of tritiated water released to the Peconic River. The other room contains fans that exhaust Building 801 out the stack.

Building 811 was designed in the late 1940s and constructed in 1950 to support the radiological waste stream from the Nuclear Engineering Department and Medical Department in the 801 and 701 complexes. Liquid waste, which contains residual radioactive material and generated on site, is

processed at the Waste Concentration Facility (WCF), Building 811. At the WCF, suspended solids are removed from the liquid along with a high percentage of radionuclides using a reverse osmosis process. The only radionuclide that is not removed during this process is tritium. The tritiated water that remains following the waste concentration process is delivered to the Evaporator, where it is converted to steam and released as an airborne effluent.

The Waste Management Incinerator. The Laboratory incinerates certain low-level radioactive wastes at the HWMF incinerator, Building 444.

2.4.18 Radiological Waste Decontamination Facility, Building 650

The Waste Decontamination Facility was constructed in 1957 and occupies the western half of Building 650. It replaced the yard decontamination operations at Building 446. Decontamination of large pieces continued until the 1980s. The process slowed and is now idle.

The facility consists of an office, showers, decontamination showers, airlock, and high bay. The decontamination showers were once used for decontamination of equipment. They drain to the basement then to the D waste tanks (removed). The high bay houses a lead melter (contaminated vent pipe; out of service), two vapor blaster talc/water abrasive blasters (internally contaminated; out of service), one walk-in shot blaster (internally contaminated; out of service), sample hood, and limited storage (one B-25 container holding film badge records at the time of the walkthrough). Already removed were two wet decontamination tanks (a 20-ft × 4-ft × 4-ft top tank used for acid/base/detergent wash).

Associated with the Waste Decontamination Facility is an outside decontamination pad. From 1957 to 1981, the 20-ft × 20-ft pad was used for washing off surface contamination from large pieces of equipment. Drainage from the pad used to go to the underground storage tanks (now removed). The surface of the pad has low-level radiological contamination. About 1994, an asphalt cap was laid by the Office of Environmental Restoration (OER) to contain the radiological materials. Soil in the vicinity of the pad has been characterized by OER and is in its remedial plan (1993 Survey, ^{137}Cs, ^{152}Eu, ^{154}Eu, depth of 0.5 ft, exceeding OER cleanup goals). The low level contaminants are fixed in the soil and are unlikely to migrate.

From 1959 to 1996, the Plant Engineering portion of the building was used as a laundry facility for contaminated and clean laundry. In 1996, laundry services were subcontracted and the facility is now being used for storage of custodial supplies. Building 650T has been used as offices since it was first acquired in 1994 (BNL 1997w, pp. 4-7).

2.5 ISOTOPES OF CONCERN

Table 2-2 identifies the potential radiological contaminants associated with the specific nuclear operations at BNL in terms of isotopes of concern. Due to the wide variety of research activities in a single multiple-laboratory building and a significant number of programs that handle and/or create practically all of the isotopes of the elements in the Periodic Table, the isotopes of concern are identified forensically from the airborne radionuclide releases by the facility. This method is considered adequate for the purpose of this section of the BNL site profile; that is, to provide background information only.

Table 2-2. Area information and parameters.

Section	Name	Description	Period	Building No.	Radionuclide
2.4.1	BGRR	U-fueled, graphite-moderated and -reflected reactor	1950–1969	701	Ba-140
					Ce-144

Section	Name	Description	Period	Building No.	Radionuclide
		28 MW			Cs-137
					La-140
					Nb-95
					Ru-103
					Ru-106
					Sr-89
					Sr-90
					Zr-95
					U-235
					U-238
					U-234
					Pu-239
2.4.1	BGRR fuel canal	BGRR fuel storage	1950–1972	709	Same as above
2.4.1	BGRR exhaust fanhouse	Highly contaminated ducting and fans	1950–1972	704	Cs-137
					Sr-90
2.4.1	BGRR exhaust filter house	Contaminated HEPA filter elements	1950–unknown	708	Cs-137
					Sr-90
2.4.2	HFBR	30-to-60-MW thermal, heavy-water-moderated research reactor	1965–1999	750	Be-7
					Br-77
					Br-82
					Cs-137
					H-3
					I-126
					Mn-54
					Xe-133
					Xe-135
2.4.2	HFBR Stack	100-m stack and houses iodine filters	1965–1999	705	I-131
					I-132
					I-133
					I-134
					I-135
2.4.2	CNF	Produce extremely-low-energy neutron by moderating neutrons with liquid hydrogen	1980–1996	751	
2.4.3	MRC	Medical Department	1959–present	490	
2.4.4	BMRR	Enriched U-fueled, light-water-moderated and -cooled reactor	1959–2000	491	Ar-41
					Al-26
					As-76
					Ba-128
					Ba-140
					Br-82
					Ce-141
					Ce-144
					Co-60
					Fe-59
					Hg-203
					I-124
					I-131
					I-133
					La-140
					Mo-99
					Na-24
					Sb-122

Section	Name	Description	Period	Building No.	Radionuclide
					Sc-46
					Se-75
					Sr-91
					Tc-99m
					Ti-44
					Xe-133
					Xe-135
					Zn-65
					Zn-69m
2.4.5	PET Imaging Laboratory	PET scanners for nuclear medicine and neurosciences research	1977–present	906	C-11
					N-13
					O-15
					F-18
					Ge-68
2.4.6	Cosmotron	Proton accelerator	1949–1968	902	C-11
					N-13
					O-15
2.4.7	AGS	A large accelerator capable of accelerating protons to energies up to 30 GeV and heavy ion beams to 15 GeV/amu	1960–present	913	C-11
					N-13
					O-15
2.4.7	200-MeV LINAC	Preaccelerator and linear accelerator providing proton source	1967–present	930	H-3
2.4.7	LINAC cooling support service	Provides water-cooling services for the LINAC complex	1967–present	930 MER	
2.4.7	AGS Booster Tunnel	Accumulator booster ring	1960–present	942	
2.4.7	AGS Experiment Area	Experimental target area for the AGS ring and later contains a proton beam switchyard system	1960–present	912	Radiation sources and activated targets
2.4.7	AGS ventilation system fanhouses	Ventilation exhaust fans	1960–present	913A-E	
2.4.7	AGS LINAC	Contains 50-MeV AGS LINAC	1960s	914	H-3
2.4.7	E10 Power Supply Building	Houses an assortment of power supplies	1971–present	920	
2.4.7	Siemens motor generator house	Electrical equipment and lubricating equipment for the motor generator	1960–present	928, 929	
2.4.7	AGS Department	Office, field testing shops, machine shops, high bays.	1960–present	911	Radiation sources and activated targets
2.4.7	g-2/Bubble Chamber	Contains the 80-in. Bubble Chamber	1962–1978	919	H-3
2.4.7	Proton Target	Proton target that produces secondaries for the g-2 ring	1962–present	949	Ni-63
2.4.7	7-ft Bubble Chamber	High-energy physics experimental facility	1972–1979	960	H-3
2.4.7	AGS Warehouses	Warehouses	1960–present	975,918,196,209,424,178	
2.4.8	BLIP	Production of radioisotopes by	1961–1962	931B	As-72

Section	Name	Description	Period	Building No.	Radionuclide
		irradiation in the LINAC beam (200-MeV protons) C-11, F-18, N-13 and O-18			As-74
					Be-7
					Co-57
					Co-58
					Co-60
					Cs-132
					Cs-137
					H-3
					Mn-54
					Na-22
					O-15
					Sc-46
2.4.9	Tandem Van de Graaff	Van de Graaff accelerators 60-in. proton Cyclotron producing 10-MeV protons, 20-MeV deuterons, and 40-MeV alpha particles for medical radionuclide research	1970–present	901	Yt-90
					Ca-47
					Cu-67
					Ar-38
					Mg-28
					I-124
					I-133
					Sc-47
					Po-210
					Kr-83m
					Ga-68
					Sm-151
					Te-132
					I-132
					Na-22
					H-3
					Mo-99
					Tc-99m
2.4.10	NSLS	Produce intense sources of X-ray, ultraviolet, and infrared radiation	1981–present	725	
2.4.10	NSLS Development Laboratory	Houses a linear accelerator	1981–present	729	
2.2.11	RHIC Complex	High-energy particle accelerator and collider	1999–present	1002	
		BRAHMS experimental hall	1981–present	1004A	
		RHIC service building	1981–present	1004	
		Open area (future experimental area)	1996–present	1004B	
		RHIC support building	1994–present	1005	
		Beam tunnel	1981–present	1005S	
		Offices and tech shops	1981–present	1006	
		STAR Detector	1985–present	1006A	
		Service building	1981–present	1007	
		Beam tunnel	1981–present	1008	
		PHENIX experiment	1988–present	1008A	
		Experimental support building	1985–present	1010	
		PHOBOS experiment	1994–present	1012	
		Future experimental hall	1994–present		
2.4.12	Hot Laboratory	Target Processing Laboratory	1951–present	801	As-72
					As-74

Section	Name	Description	Period	Building No.	Radionuclide
					Be-7
					Co-57
					Co-58
					Co-60
					Cs-132
					Cs-137
					H-3
					Mn-54
					Na-22
					Au-199
					Bi-213
					Br-77
					Br-82
					Se-75
					V-48
					I-126
					Se-75
					Ge-69
2.4.13	HIRDL	Radioactive sources fabrication, irradiation cells and since 1970, the GIF	1951–present GIF 1970–present	830	Co-60
					Cs-137
2.4.14	Chemistry Department	Studies from chemical kinetics, to hot-atom effects, to nuclear chemical studies of nuclear decay schemes and nuclear reaction cross-sections, to solar neutrino studies and radiocarbon dating.	1966–present	555	H-3
					Co-60
2.4.15	Physics Department	Laboratories, office space, a machine shop, and basement area	1962–present	510	
2.4.16.1	LMFR Support Facility	Research and development work for the LMFR	1957–1975	820	
2.4.16.2	Hot Machine Shop	Hot Machine Shop	1947–1975	530	
2.4.16.3	Instrument Division	Research and development of X-ray and neutron detectors and corresponding electronics, which are used at the NSLS, the HFBR, the AGS, and other worldwide scientific research facilities.	1964–present	535	
2.4.17	Radwaste Reclamation Building	Located in the WMF for processing of radwaste.	1997–present	865	
2.4.17	Tritium Evaporator Facility	Reduce tritium release by evaporation	1995–present	802B	I-133
					Rb-83
					Rb-86
					Be-7
					Co-56
					Co-57
					Co-58
					Co-60
					Cs-137

Section	Name	Description	Period	Building No.	Radionuclide
					H-3
					Mn-54
					Na-22
					Se-75
					Zn-65
2.4.17	Waste Management Incinerator	Low-level waste incinerator	Torn down	444	H-3
					Sr-85
					I-125
					Co-57
					Sc-47
					Zn-65
					C-14
					P-32
					S-35
					Fe-59
					Sn-117m
					Sn-113
					Cr-51
					Be-7
2.4.18	Radiological Waste Decontamination Facility	Decontamination of radiological waste; hot laundry services	1959–1996	650	

In the absence of measurements or studies, NIOSH guidance requires the use of default solubility classes and particle size values from the International Commission on Radiological Protection (ICRP; NIOSH 2002, pp. 15, 16).

2.6 MAGNITUDE OF SITE ACTIVITY

Table 2-3 provides a perspective of the magnitude of the nuclear operations at BNL. The Site Profile preparation guide (ORAUT 2007) requires the magnitude of the operations be expressed in radioactivity (Ci) of the isotope of concerns. The same information is also required in Section 5, Internal Dosimetry. Therefore, radioactivity values in Section 5 should be used for dose reconstruction. In cases where available information does not allow the estimation of the radioactivity at the time of the operations, the activity fraction of each isotope is listed. Activity fractions listed in the table are the ratios of the activity of the individual isotope released and the total activity released of all the isotopes. In cases where numeric data are not available, the table provides the descriptive text that gives a perspective on the magnitude of the radiological impact on personnel.

Table 2-3. Magnitude of site activity.

Section	Name	Description	Period	Building No.	Radionuclide
2.4.1	BGRR	U-fueled, graphite-moderated and -reflected reactor 28 MW	1950–1969	701	Ba-140
					Ce-144
					Cs-137
					La-140
					Nb-95
					Ru-103
					Ru-106
					Sr-89
					Sr-90
					Zr-95

Section	Name	Description	Period	Building No.	Radionuclide
					U-235
					U-238
					U-234
					Pu-239
2.4.1	BGRR fuel canal	BGRR fuel storage	1950–1972	709	Same as above
2.4.1	BGRR exhaust fanhouse	Highly contaminated ducting and fans	1950–1972	704	Cs-137
					Sr-90
2.4.1	BGRR exhaust filter house	Contaminated HEPA filter elements	1950–unknown	708	Same as above
2.4.2	HFBR	30-to-60-MW thermal, heavy-water-moderated research reactor	1965–1999	750	Be-7
					Br-77
					Br-82
					Cs-137
					H-3
					I-126
					Mn-54
					Xe-133
					Xe-135
2.4.2	HFBR Stack	100-m stack and houses iodine filters	1965–1999	705	I-131
					I-132
					I-133
					I-134
					I-135
2.4.2	CNF	Produce extremely-low-energy neutron by moderate neutron with liquid hydrogen	1980–unknown	751	
2.4.3	MRC	Medical Department	1959–present	490	
2.4.4	BMRR	Enriched U-fueled, light-water-moderated and -cooled reactor	1959–2000	491	Ar-41
					Al-26
					As-76
					Ba-128
					Ba-140
					Br-82
					Ce-141
					Ce-144
					Co-60
					Fe-59
					Hg-203
					I-124
					I-131
					I-133
					La-140
					Mo-99
					Na-24
					Sb-122
					Sc-46
					Se-75
					Sr-91
					Tc-99m
					Ti-44
					Xe-133
					Xe-135

Section	Name	Description	Period	Building No.	Radionuclide
					Zn-65
					Zn-69m
2.4.5	PET Imaging Laboratory	PET scanners for nuclear medicine and neurosciences researches	1977–present	906	C-11
					N-13
					F-18
					O-15
					Ge-68
2.4.6	Cosmotron	Proton accelerator	1949–1968	902	C-11
					N-13
					O-15
2.4.7	AGS	A large accelerator capable of accelerating protons to energies up to 30 GeV and heavy ion beams to 15 GeV/amu	1960–present	913	C-11
					N-13
					O-15
2.4.7	200-MeV LINAC	Preaccelerator and linear accelerator providing proton source		930	
2.4.7	LINAC cooling support service	Provides water-cooling services for the LINAC complex		930 MER	
2.4.7	AGS Booster Tunnel	Accumulator booster ring		942	C-11
					N-13
					O-15
2.4.7	AGS Experiment Area	Experimental target area for the AGS ring and later contains a proton beam switchyard system	1960–present	912	
2.4.7	AGS ventilation system fanhouses	Ventilation exhaust fans	1960–present	913A-E	
2.4.7	AGS LINAC	Contains 50 MeV-AGS LINAC	1960s	914	H-3
2.4.7	E10 Power Supply Building	Houses an assortment of power supply	1971–present	920	
2.4.7	Siemens motor generator house	Electrical equipment and lubricating equipment for the motor generator	1960–present	928, 929	
2.4.7	AGS Department	Office, field testing shops, machine shops, high bays.	1960–present	911	
2.4.7	g-2/Bubble Chamber	Contains the 80-in. Bubble Chamber	1962–1978	919	H-3
2.4.7	Proton Target	Proton target that produces secondaries for the g-2 ring	1962–present	949	
2.4.7	7’ Bubble Chamber	High-energy physics experimental facility	1972–1979	960	
2.4.7	AGS Warehouses	Warehouses	1960–present	975, 918, 196, 209, 424, 178	
2.4.8	BLIP	Production of radioisotopes by irradiation in the LINAC beam (200-MeV protons) C-11, F-18, N-13 and O-18	1961–1962	931B	As-72
					As-74
					Be-7
					Co-57
					Co-58
					Co-60

Section	Name	Description	Period	Building No.	Radionuclide
					Cs-132
					Cs-137
					H-3
					Mn-54
					Na-22
					O-15
					Sc-46
					Co-56
					Ga-68
					Ge-69
					I-126
					Xe-127
					Zn-65
2.4.9	Tandem Van de Graaff	Van de Graaff accelerators 60-in. proton Cyclotron producing 10-MeV protons, 20-MeV deuterons, and 40-MeV alpha particles for medical radionuclide research	1970–present	901	Sr-90/Y-90
					Ca-47
					Cu-67
					Ar-38
					Mg-28
					I-124
					I-133
					Sc-47
					Po-210
					Kr-83m
					Ga-68
					Sm-151
					Te-132
					I-132
					Na-22
					H-3
					Mo-99
					Te-99m
2.4.10	NSLS	Produce intense sources of X-ray, ultraviolet, and infrared radiation	1981–present	725	
2.4.10	NSLS Development Laboratory	Houses a linear accelerator	1981–present	729	
2.4.11	RHIC Complex	High-energy particle accelerator and collider	1999–present		
		BRAHMS experimental hall	1981–present	1002	
		RHIC service building	1981–present	1004A	
		Open area (future experimental area)	1996–present	1004	
		RHIC support building	1994–present	1004B	
		Beam tunnel	1981–present	1005	
		Offices and tech shops	1981–present	1005S	
		STAR Detector	1985–present	1006	
		Service building	1981–present	1006A	
		Beam tunnel	1981–present	1007	
		PHENIX experiment	1988–present	1008	
		Experimental support building	1985–present	1008A	
		PHOBOS experiment	1994–present	1010	
		Future experimental hall	1994–present	1012	

Section	Name	Description	Period	Building No.	Radionuclide
2.4.12	Hot Laboratory	Target Processing Laboratory	1951–present	801	As-72
					As-74
					Be-7
					Co-57
					Co-58
					Co-60
					Cs-132
					Cs-137
					H-3
					Mn-54
					Na-22
					Au-199
					Bi-213
					Br-77
					Br-82
					Se-75
					V-48
					I-126
					Se-75
					Ge-69
					U-natural
2.4.13	HIRDL	Radioactive sources fabrication, irradiation cells and, since 1970, the GIF	1951–present GIF 1970–present	830	Co-60
					Cs-137
2.4.14	Chemistry Department	Studies from chemical kinetics, to hot-atom effects, to nuclear chemical studies of nuclear decay schemes and nuclear reaction cross-sections, to solar neutrino studies and radiocarbon dating	1966–present	555	
2.4.15	Physics Department	Laboratories, office space, a machine shop, and basement area	1962–present	510	
2.4.16.1	LMFR Support Facility	Research and development work for the LMFR	1957–1975	820	
2.4.16.2	Hot Machine Shop	Hot Machine Shop	1947–1975	530	
2.4.16.3	Instrument Division	Research and development of X-ray and neutron detectors and corresponding electronics, which are used at the NSLS, the HFBR, the AGS, and other worldwide scientific research facilities.	1964–present	535	
2.4.17	Radwaste Reclamation Building	Located in the WMF for processing of radwaste	1997–present	865	
2.4.17	Tritium Evaporator Facility	Reduce tritium release by evaporation		802B	I-133
					Rb-83
					Rb-86
					Be-7
					Co-56

Section	Name	Description	Period	Building No.	Radionuclide
					Co-57
					Co-58
					Co-60
					Cs-137
					H-3
					Mn-54
					Na-22
					Se-75
					Zn-65
2.4.17	Waste Management Incinerator	Low-level waste incinerator		444	H-3
					Sr-85
					I-125
					Co-57
					Sc-47
					Zn-65
					C-14
					P-32
					S-35
					Fe-59
					Sn-117m
					Sn-113
					Cr-51
					Be-7
2.4.18	Radiological Waste Decontamination Facility	Decontamination of radiological waste		650	

2.7 MAJOR INCIDENTS

Table 2-4 describes major site incidents that might have significant potential for internal or external exposure to personnel.

Table 2-4. Major incidents.

Facility/building	Year	Description
BGRR, Building 701	1952–57	During the early years of operation of the BGRR, fuel failures occurred that resulted in radioactive materials being released to the air stream that cooled the reactor. There were 28 reported ruptures of BGRR fuel during the period 1952–1957. These all occurred with natural uranium. There was one rupture of a uranium oxide (U_3O_8) sample that was being irradiated for the radioiodine production program. Aside from Ar-41, I-131 was the most important radionuclide that would contribute to a potential dose that was discharged to the atmosphere from the BGRR. Bromine-82 and I-133 were released in somewhat larger concentrations (Meinhold and Meinhold 2001).
Hot Laboratory, Building 801	5/15/1957	There was a serious incident involving the Volatility Project where uranium reprocessing was the objective. There was an explosion of UF_6/BrF_3 and a few people were injured, one hospitalized. There was a release of about 13 lb of unirradiated uranium to the local environment. Apparently, the UF_6 combines with moisture readily to form an oxide. The BrF_3 is very corrosive and damaged nearby trees and automobiles and equipment in the building (BNL 1997o).
	8/1960	There were some highly radioactive waste reactor fuel elements dissolved in aqua regia stored in plastic containers in the storage vault (Room 51). These containers cracked and leaked onto a stainless-steel tray containing the plastic containers. It was decided to suck up the solution with an aspirator connected

Facility/building	Year	Description
		to the house vacuum system. The vacuum system became very highly radioactive. The main vacuum chamber removed all standing liquid in the lines. However, because of the high level and long half-life of the activity, the pipes remain residually contaminated. Thereafter, the system was moved to a remote location but some of the piping in the floor is still contaminated as a result of this incident. The piping is still in the concrete floor, which is labeled as a radioactive area (BNL 1997o).
HFBR, Building 750	1997	During a scheduled maintenance shutdown in 1997, a leak in HFBR's spent fuel storage pool was discovered. In November 1999, the Secretary of Energy made a decision to permanently close the HFBR (BNL 2001a).

2.8 RADIOLOGICAL ACCESS CONTROLS

Radiological access controls were exercised locally at the site where activities involving radioactive materials are performed. Radiological Control Areas are established for each specific laboratory, facility, or building in which nuclear operations were conducted at the BNL site. Entry to those areas was controlled (i.e., hand-and-shoe counters, dosimeters, and training requirements).

3.0 OCCUPATIONAL MEDICAL DOSE

3.1 PURPOSE

AEC-funded work at BNL began in 1948. BNL occupational medical physicians prescribed chest X-rays as part of the preemployment and periodical physical examination of employees from the very beginning of operations (Sunderman 1947b; Cowan 1948). These radiographs caused exposure of the lungs and other organs and tissues of the body. Exposure of the radiographed workers came primarily from the primary X-ray beam and from scattered radiation.

The purpose of this section is to describe the occupational medical X-ray screening program over time at BNL, and to provide organ and tissue doses associated with these exposures.

3.2 SCOPE

Substantial information regarding the historical BNL occupational medical X-ray program has been located. The current medical director and two BNL X-ray technicians were interviewed and some older X-ray films were reviewed to gain insight into the occupational medical program and collimation practices (Morris 2006a,b,c,d). A peer-reviewed publication (Handloser and Love 1951) provided exposure data specific to the BNL radiographic equipment and techniques in use in 1950. A transcript of interviews conducted in preparation for an epidemiology study (Brodsky 1964) included discussions with BNL's first medical director regarding the early radiographic examination practices, equipment, and exposure rates.

3.3 EXAMINATION FREQUENCY

The occupational medical program at BNL began in 1947. Sunderman (1947b) mentions that the recommended X-ray screening protocol should include a preemployment fluororoentgenogram (otherwise known as photofluorography or PFG), a preemployment anterior-posterior (AP) and LAT lumbar spine, and an X-ray of one forearm. The recommended annual physical should include a PFG; and the termination examination should include a PFG, AP and LAT lumbar spine, and the same forearm radiographed on the preemployment examination. It was also recommended that beryllium workers under contract with the AEC receive a chest X-ray at preemployment, 6-month intervals, and at termination. These recommendations specifically referred to chest X-rays on 14-in. × 17-in. film (Hardy 1948).

The X-ray records in the claim files submitted by BNL do not bear out the recommendations specified by Sunderman (1947b). While there are some PFGs in the claim files, there are very few lumbar spine examinations, and no X-rays of forearms were found in the sample of cases reviewed [2]. Because no lumbar spine or forearm X-rays were found in claim files records in this early period, it is assumed that BNL occupational medical physicians did not implement the protocol recommended by Sunderman [3].

It is also clear from the claim file records that PFG was not used exclusively in the early years of BNL. Beginning in 1947 and continuing until at least 1964, all workers, including pile (reactor) operators, were subjected to a preemployment and an annual physical examination, including a PA chest X-ray on 14-in. × 17-in. film, but no X-ray on termination (Love 1957, 1959, 1963, 1964; Bond 1963). No PFG records were found in the claim files after 1955 [4].

Dose reconstructors should assign dose according to the number of PFG and 14-in. x 17-in. PA chest X-rays in the claim file records if they are provided. If these records are not provided, the dose reconstructor should assign dose from a preemployment PFG for start dates between 1947 and 1955,

and annual 14-in. × 17-in. PA chests during this period. The default X-ray examination frequencies are found in Table 3-1.

Table 3-1. Default frequency of chest X-rays at BNL.

Period	Type of chest X-ray	Applicability	Frequency
1947–1955	PFG	All workers	Preemployment Periodic per the records No termination examination
1947–1955	14-in. × 17-in. PA	All workers	Preemployment if no PFG in the records Annual No termination examination
1956–1978	14-in. × 17-in. PA	All workers	Preemployment Annual No termination examination
1979–present	14-in. × 17-in. PA and LAT	All workers	Preemployment Every 7 years, unless records indicate otherwise No termination examination

The screening protocol policy seems to have stayed fairly constant (Flood 1976), although the actual interval between "annual" X-ray examinations seems to have increased in the mid-1960s, to an average of every 2.5 years (Brodsky 1964, pp. 38–39 and p. 72). It is assumed this examination frequency pattern continued through 1978. Dose reconstructors should assign dose according the number of 14-in. × 17-in. PA chests in the claim file records if they are provided. If these records are not provided, the dose reconstructor should assign dose from a preemployment 14-in. × 17-in. PA chest, and annual 14-in. × 17-in. PA chests during this period (1965–1978). The default X-ray examination frequencies are found in Table 3-1. In 1978, a Presidential Recommendation to Federal agencies advised the discontinuation of routine or screening radiographic examinations, including chest X-rays, on patients for whom no prior clinical evaluation is made (Carter, J. 1978). This recommendation, at least in part, was incorporated into BNL practice and the average time between radiographic examinations increased. Starting with 1979, the chest X-ray reexamination cycle for all employees might have decreased to once every 7 years (Morris 2006b). Preemployment radiographic examination is assumed to have continued as a condition of employment. At some date in the 1980s (probably around 1981), the typical radiographic examination expanded to include both PA and LAT chest films (Morris 2006a). For expedience, this is assumed to start in 1979 coinciding with the extended reexamination frequency. Current (as of 2009) preemployment X-ray examination practice is to offer PA and LAT chest X-ray to all employees and it appears that most new employees choose to have that examination. For new employees who test positive to tuberculosis, preemployment PA and LAT chest X-ray are required. The time between screening chest X-rays has been extended over the years and now occurs on a 7-to-10-year cycle (Morris 2006b,c).

Dose reconstructors should use the number of X-rays in the Energy Employee's X-ray records if provided by DOE for the period from 1979 to the present. If records have not been provided, the default X-ray examination frequency from Table 3-1 can be used by dose reconstructors in assigning dose.

3.4 EQUIPMENT AND TECHNIQUES

Sunderman (1947c) states that "arrangements have been made with the Powers X-ray Service for chest roentgenograms for each employee attached to our Laboratory." Powers X-ray Service was a well-known provider of PFG services on Long Island. Conrad (1948) mentions the continuation of the use of Powers X-ray Service for 1948, and further mentions the exposure as a constant 3,000 mrep. This is consistent with the information in a retrospective interview, during which the medical director stated each examination caused a 4,000-mR exposure (Brodsky 1964, p. 36). Handloser and Love (1951) state that the approximate exposure range from the PFG at BNL was 0.7 to 1.2 R. It is

assumed that this value is for a single PFG exposure, while the other exposure values reported by Conrad and Brodsky are for stereo exposures. Because these values are consistent with the dose values in ORAUT-OTIB-0006 (ORAUT 2005), the dose values from that document will be used for dose reconstruction of PFG for BNL workers.

Sunderman (1947a) mentions that a decision was made to purchase Westinghouse X-ray equipment. It is assumed this equipment was purchased, because Westinghouse X-ray equipment is referred to in the published article by Handloser and Love (1951).

By 1951, the occupational X-ray program was well established and data regarding the equipment and exposure had been published in the *Journal of Radiology* (Handloser and Love 1951). That paper listed X-ray tube data for a PFG unit, a fluoroscopic unit, and a radiographic unit. However, it is concluded that only the radiographic unit was used for occupational medical screening examinations (Brodsky 1964). The 14-in. × 17-in. PA chest radiographic technique used for employee screening was 200 mA and 0.10 second at 72 in. with 0.5 mm Al added filtration in the beam. The nominal tube potential used was 72 kV and only the tube potential was adjusted to compensate for patient size (Handloser and Love 1951). The half-value layer (HVL) of the X-ray beam is assumed to be 1.5 mm Al for an X-ray tube with 0.5 mm Al eq. inherent filtration, 0.5 mm Al added filtration, and operated at 72 kVp (NCRP 1989, Table B.2).

An interview (Morris 2006a) with a registered X-ray technician who worked at BNL from 1960 to 1993 revealed that a well-maintained Picker machine was in use for chest exposures in 1960. In 1973, phantom measurements were made on the Picker machines for various technique factors (Nelson 1973). In 1978, more measurements were made on the Picker machines, which provide information on the HVL and entrance exposures for this period (Carter, N. 1978).

An interview (Morris 2006b) with a registered X-ray technician who worked at BNL from 1993 to the present (March 2006) revealed that the equipment currently in service is a single-phase Picker model BCX with a measured HVL of 3.2 mm Al. The unit is automatically collimated. A grid cassette film holder is routinely used. This unit has been in service since 1991. The unit is tested routinely by a medical physicist in accordance with New York State Department of Health Guidelines. Test records estimate tube filtration as 4.06 mm Al and the HVL as 3.3 mm Al (Astarita Associates 1998–2004). For a PA chest film, the nominal technique in current use is 110 kVp and 3.2 mAs at 72 in. No measurements were found for the LAT chest film technique but the technique is similar to PA, except it is performed at 6 mAs.

A sample of 26 PA chest films spanning 1949 through 1971 was reviewed to determine past beam collimation practices [5]. The equipment in use appears to have allowed the technician to manually set the collimation. In some films before the early 1970s, collimation is evident. In other films from the same period, no evidence of collimation is visible. That does not necessarily mean collimation was not used. It might indicate that collimation was established just at the edges of the film cassette and was, therefore, not visible on the film, which would be consistent with the practice described by the technician employed in that timeframe. The earliest film in this sample with obvious collimation was made in 1959 (Morris 2006b). Based on this inspection and the statement of the retired technician, it is reasonable to assume that all exposures after 1960 were collimated [6].

3.5 ENTRANCE AIR KERMA IN AIR

BNL medical personnel adopted the unusual (possibly unique) practice of recording the entrance skin exposure (ESE) for some examinations. Such information is found on the radiologist's interpretation form "Report of X-ray Examination" that is included in the employee's medical chart. These ESE data were based on measurements made during the annual calibration of the X-ray machine. This practice of recording ESE was still occurring in 1964 (Brodksy 1964, p. 67). These contemporary data reflect

the exposure for a specific machine and a nominal, not individual-specific, technique. It is not known if this exposure included backscatter, and it does not appear to adjust for the worker's chest thickness. Therefore, although it might be a more accurate assessment of the machine output at the time of the exposure, it is not likely to significantly improve the accuracy of the dose reconstruction.

1947 to 1955 PFG
PFG doses are based on the doses in ORAUT-OTIB-0006 (ORAUT 2005).

1947 to 1959, 14-in. × 17-in. PA Chest
The entrance air kerma in air for the 14-in. × 17-in. radiographs are based on the techniques in Handloser and Love (1951), information in National Council on Radiation Protection and Measurements (NCRP) Report 102 (NCRP 1989), and ORAUT-OTIB-0006 (ORAUT 2005). The calculation follows:

1. From NCRP Report 102 (NCRP 1989), Table B-3, the air kerma rate for a single-phase X-ray machine with 2.5 mm Al eq. total filtration and operated at 75 kVp is 0.45 cGy/100 mAs at 100 cm.

2. Correcting for total filtration of 1.5 mm Al eq using the information in ORAUT-OTIB-0006 (ORAUT 2005, pg. 10), the air kerma rate is 0.67 cGy/100 mAs at 100 cm.

3. Correcting for the actual mAs (20 mAs) used at BNL according to Handloser and Love (1951), the air kerma is 0.134 cGy at 100 cm.

4. Correcting for a source to skin distance of 154 cm, the entrance air kerma in air is 0.06 cGy. This is comparable to the 0.055-R value in Handloser and Love (1951).

1960 to 1978
The entrance air kerma for this period is based on the measurements on X-ray equipment reported by Carter, N. (1978). Carter reports the following:

1. Measured entrance skin exposure of 11 mR for the PA chest at 115 kV, 100 mA, 1/30 sec (Carter 1978).

2. Measured HVL of approximately 3.0 mm Al eq. (Carter 1978).

1979 to 1986
In 1983, measurements of the X-ray machine in Room 2 were made at 120 kVp and 300 mA at various exposure times (Zukas 1983). It is clear from these measurements compared to those made in 1978 that a grid was probably introduced because the entrance exposures are higher. The entrance exposure measurements range from 25.6 mR to 73.0 mR, without distinction between PA and LAT. For dose reconstruction, the entrance exposure for the PA chest for this period will be assumed to be 30 mR, and 60 mR for the LAT.

1987 to 1995
In 1987, measurements of the X-ray machine in Room 2 were made at 100 kVp, 200 and 300 mA at various exposure times (Zukas 1987). The entrance exposures listed are lower than those determined in 1983, so possibly there was a change in technique factors and/or screen/film combination to produce the lower exposures. The entrance exposures range from 8 mR to 35.6 mR, with no indication of PA or LAT. For dose reconstruction, the entrance exposure for the PA chest for this period will be assumed to be 15 mR, and 30 mR for the LAT.

1996 to present
Between 1996 and 2004, the PA chest ESE from the Picker unit in Room 1 was measured at least five times by American Board of Radiology/American Board of Medical Physics-certified radiation physics consultants during the course of routine inspection. The technique factors were similar to those used for nominal PA and LAT chest examination in current use, namely 110 kVp, 3.2 mAs on the large focal spot with a 72-in. source-to-image distance and 23-cm phantom. The ESE ranged from 6.7 to 8.1 mR. For 1996 to the present (2010), the ESE for PA chest is rounded up to 10 mR to account for the possibility that the actual technique used was set to a slightly higher tube potential. No measured ESE is available for the LAT view. Therefore, the ESE for the LAT chest was calculated to be 25 mR based on the rule of thumb that the ESE for LAT chest is conservatively estimated to be 2.5 times the ESE for PA chest (ORAUT 2005, p. 20).

3.6 ORGAN DOSE CALCULATIONS

ICRP Publication 34 Method for collimated exposures
The methodology of ICRP Publication 34 (ICRP 1982) is used to estimate the organ doses when the tabulated dose conversion factors (DCFs) for collimated X-ray beams are applicable. The method is described in Section 3.6.1, Organ Dose from Collimated Exposure. Modifications to this method to account for poorly collimated X-ray beams are described in Section 3.6.2, Organ Dose from Poorly Collimate Exposure. Calculation of skin dose is described in Section 3.6.3, Skin Dose.

Organ doses are found in Tables 3-2 and 3-3 for various periods at BNL. In these tables, the remainder organs are assigned the same dose as the female lung, which is the organ with the highest DCF.

3.6.1 Organ Dose from Collimated Exposure

In ICRP Publication 34 (ICRP 1982) methodology, organ dose (OD) is the product of entrance kerma (EK) and a DCF. Entrance kerma is defined in ICRP Publication 34 as “air kerma in air without backscatter.” For practical application it is numerically the same as, and can be used interchangeable with, ESE (ORAUT 2005, p. 16). For organs other than skin, organ dose is calculated as shown in Equation 3-1.

$$OD = EK \times DCF \tag{3-1}$$

DCF values are a function of beam quality, expressed as the HVL, and of the X-ray projection and organ of interest, assuming that the primary beam is properly collimated.

DCFs for some organs are not tabulated in ICRP Publication 34 (ICRP 1982) but are needed for the Interactive RadioEpidemiological Program (IREP). In those cases a dosimetric analogy to a nearby organ is assumed and the missing DCF is assigned the same value as the analogue organ. ICRP reference organs and their IREP organ analogues have been defined (ORAUT 2005, Table 3-2). For some organs ICRP Publication 34 lists gender-based DCFs and, in that situation, the larger of the two values is assigned as the DCF to the IREP organ analogues.

3.6.2 Organ Dose from Poorly Collimated Exposure

Organ doses from poorly collimated radiographs are calculated in a similar manner as those for collimated exposures. However, in those cases where the DCFs are not available or are not applicable, guidance is provided in ORAUT (2005). Overriding any default guidance is the preference for actual measurement data when available (ORAUT 2005, p. 15).

Some organs, specifically the thyroid, ovaries, uterus, and testes, are not in the primary beam of a properly collimated PA chest projection. But if the beam is poorly collimated, those organs might be in the primary beam. Therefore, a DCF from a different projection is substituted to avoid underestimation of the organ dose. ORAUT (2005, Table 9-11) defines appropriate substitutions. These substitutions are incorporated in the data shown in Table 3-2.

3.6.3 Skin Dose

Skin doses from PA and LAT chest projections are calculated differently than organ doses depending on proximity of predefined areas of skin to the primary beam. The primary beam entrance skin dose (ENSD), primary beam exit skin dose (EXSD), entrance skin dose outside but near the primary beam (ENSDNPB), exit skin dose outside but near the primary beam (EXSDNPB), and remote skin dose (RSD) can be calculated.

ENSD is the product of ESE and a backscatter factor BF, as shown in Equation 3-2. The BF is from Table B-8 of NCRP Report 102 (NCRP 1989). The ENSD applies to all skin surfaces in the beam on the entrance side of the body.

$$ENSD = ESE \times BF \tag{3-2}$$

EXSD is the ENSD divided by a adjusted absorption factor AFF, which is the absorption factor AF for the technique tabulated in Table B.7 of NCRP Report 102 (NCRP 1989) decreased by 10% as shown in Equations 3-3 and 3-4, respectively. This dose applies to all skin surfaces in the beam on the exit side of the body.

$$EXSD = {ENSD}/{AFF} \tag{3-3}$$

$$AFF = AF \times 0.9 \tag{3-4}$$

ENSDNPB is 10% of the ENSD as shown in Equation 3-5. This equation is based on the tabulated values in ICRP Publication 34 (ICRP 1982) showing that the dose to the testes is 10% of the dose in the primary beam when the testes are located just outside the primary beam.

$$ENSDNPB = ENSD \times 0.1 \tag{3-5}$$

Similarly, EXSDNPB is 10% of the EXSD as shown in Equation 3-6.

$$EXSDNPB = \times 0.1 \tag{3-6}$$

RSD, shown in Equation 3-7, is a function of:

- ENSD,
- Square of the distance from the center of the primary beam to the location of interest on the skin,
- The ratio of scattered-to-incident exposure based on the exposure at 1 m due to 90-degree scattering of 70-kVp radiation per Table B-2 of NCRP Report 49 (NCRP 1976),
- Average depth dose (ADD) at 12 cm (mid-chest depth) for the technique tabulated in NCRP Report 102 (NCRP 1989, Table B.8), and

- A bias factor of 1.1, which is favorable to the claimant, allows for 10% uncertainty in tabulated values of ADD.

$$RSD = ENSD \times 0.0005 \times ADD \times 1.1 \times \left(\frac{1}{R}\right)^2 \quad (3\text{-}7)$$

Skin doses from PFG, PA, and LAT chests are found in Table 3-3.

3.7 DOSE RECONSTRUCTION

The medical records provided by DOE might include adequate information to define the date, type, and count of X-ray examinations that were administered to the claimant as a condition of employment. Only radiographs made as a condition of employment are to be included in dose reconstructions. Such exposures are limited to PA and LAT chest films and were required or recommended as part of a preemployment examination or a routine reexamination.

If confusion about the radiographic exposure record exists, consider requesting that the notes on the exterior of the envelope(s) containing the worker's X-ray films be transcribed and provided. These notes should give insight to the reason the exposures were made, for example preemployment examination, routine surveillance, or diagnosis of injury. Assume that any radiograph that was not a PA chest or LAT chest was diagnostic, not to be included in dose reconstruction. If the X-ray envelope notes associate the annotation "LMD" or "industrial" with a particular exposure, that means the radiograph was a diagnostic exposure (i.e., associated with a workplace injury). LMD radiographs are not included in dose reconstruction.

Depending on equipment and technique, the photon energy associated with occupational medical X-ray dose is in the 30-to-250-keV energy group. Assignment of all BNL occupational medical doses to the 30-to-250-keV energy group is favorable to the claimant and recommended.

3.8 UNCERTAINTY

ORAUT (2005) analyzed uncertainties in the occupational medical X-ray organ doses. The document considered several major sources of uncertainty: measurement errors; variations in applied voltage (peak voltage), beam current, and exposure time; and uncertainties due to worker size and placement. However, at SRS entrance skin dose measurements were made on nine workers of varying chest thicknesses (builds) (Cooley 1967). While Cooley (1967) does not report the measured chest thicknesses for these nine workers, the entrance skin doses are reported and reflect the increases in exposure needed to radiograph thicker body parts, in this case, chests. The standard uncertainty of the range of measurements is 5.6, resulting in an uncertainty of 21% from this source. Substituting this value into the calculation for combined uncertainty described in ORAUT-OTIB-0006 (ORAUT 2005) instead of the 10% value used in that document, the resultant standard uncertainty is 35% from these five sources. For further conservatism, it may be appropriate to assume that errors are all positive and that only +35% should be used as suggested in ORAUT-OTIB-0006 (ORAUT 2005). ORAUT (2005) assesses the relative error in an individual ESE or organ dose to be ±30% at 1 standard deviation.

Table 3-2. Organ doses (rem) for PFG, PA, and LAT 14-in. × 17-in. chest radiography.

Organ	Projection	1947–1955 PFG[a]	1947–1959 14-in. × 17-in.	1960–1978	1979–1986	1987–1995	1996 to present
Thyroid	PA	5.22E-01	7.26E-03	5.06E-04	1.38E-03	6.90E-04	6.20E-04
	LAT				7.98E-03	3.99E-03	3.78E-03
Eye/brain	PA	9.60E-02	7.26E-03	5.06E-04	1.38E-03	6.90E-04	6.20E-04

Organ	Projection	1947–1955 PFG[a]	1947–1959 14-in. × 17-in.	1960–1978	1979–1986	1987–1995	1996 to present
	LAT				7.98E-03	3.99E-03	3.78E-03
Ovaries	PA	2.50E-02	2.50E-02[b]	1.98E-05	5.40E-05	2.70E-05	3.20E-05
	LAT				5.40E-05	2.70E-05	4.00E-05
Urinary/bladder	PA	2.50E-02	2.50E-02[b]	1.98E-05	5.40E-05	2.70E-05	3.20E-05
	LAT				5.40E-05	2.70E-05	4.00E-05
Colon/rectum	PA	2.50E-02	2.50E-02[b]	1.98E-05	5.40E-05	2.70E-05	3.20E-05
	LAT				5.40E-05	2.70E-05	4.00E-05
Testes	PA	5.00E-03	5.00E-03	1.10E-07	3.00E-07	1.50E-07	1.00E-07
	LAT				6.00E-06	3.00E-06	2.50E-06
Lungs (male)	PA	1.26E+00	1.46E-02	5.46E-03	1.49E-02	7.44E-03	5.65E-03
	LAT				1.42E-02	7.08E-03	6.90E-03
Lungs (female)	PA	1.35E+00	1.50E-02	5.89E-03	1.61E-02	8.03E-03	6.10E-03
	LAT				1.60E-02	8.01E-03	7.75E-03
Thymus	PA	1.35E+00	1.50E-02	5.89E-03	1.61E-02	8.03E-03	6.10E-03
	LAT				1.60E-02	8.01E-03	7.75E-03
Esophagus	PA	1.35E+00	1.50E-02	5.89E-03	1.61E-02	8.03E-03	6.10E-03
	LAT				1.60E-02	8.01E-03	7.75E-03
Stomach	PA	1.35E+00	1.50E-02	5.89E-03	1.61E-02	8.03E-03	6.10E-03
	LAT				1.60E-02	8.01E-03	7.75E-03
Bone surface	PA	1.35E+00	1.50E-02	5.89E-03	1.61E-02	8.03E-03	6.10E-03
	LAT				1.60E-02	8.01E-03	7.75E-03
Liver/gall bladder/ spleen	PA	1.35E+00	1.50E-02	5.89E-03	1.61E-02	8.03E-03	6.10E-03
	LAT				1.60E-02	8.01E-03	7.75E-03
Remainder organs	PA	1.35E+00	1.50E-02	5.89E-03	1.61E-02	8.03E-03	6.10E-03
	LAT				1.60E-02	8.01E-03	7.75E-03
Breast	PA	1.47E-01	1.08E-03	7.59E-04	2.07E-03	1.04E-03	9.10E-04
	LAT				1.72E-02	8.61E-03	7.90E-03
Uterus	PA	2.50E-02	2.50E-02[b]	2.53E-05	6.90E-05	3.45E-05	3.00E-05
	LAT				5.40E-05	2.70E-05	3.50E-05
Bone marrow (male)	PA	2.76E-01	2.94E-03	1.29E-03	3.51E-03	1.76E-03	1.46E-03
	LAT				2.88E-03	1.44E-03	1.53E-03
Bone marrow (female)	PA	2.58E-01	2.58E-03	1.23E-03	3.36E-03	1.68E-03	1.41E-03
	LAT				2.28E-03	1.14E-03	1.20E-03
Entrance skin[c]	PA	4.05E+00	7.80E-02	1.54E-02	4.20E-02	2.10E-02	1.40E-02
	LAT				8.40E-02	4.20E-02	3.50E-02

a. All organ doses from ORAUT-OTIB-0006 (ORAUT 2005). The doses are for stereo PFG (i.e., two exposures).
b. Based on measured doses from ORAUT-OTIB-0006 (ORAUT 2005).
c. Entrance skin dose is the entrance air kerma in air multiplied by the backscatter factor of 1.35 or 1.4 for HVLs of 1.5 or 4.0 mm Al, respectively, from NCRP Report 102 (NCRP 1989).

Table 3-3. Skin dose guidance for various chest projections and periods.

Area of skin	PFG	<1970 PA chest	>1970 PA chest	>1970 LAT chest
Right front shoulder	EXSD	EXSD	EXSD	ENSD
Right back shoulder	ENSD	ENSD	ENSD	ENSD
Left front shoulder	EXSD	EXSD	EXSD	EXSD
Left back shoulder	ENSD	ENSD	ENSD	EXSD
Right upper arm to elbow	10% ENSD	ENSD	10% ENSD	ENSD
Left upper arm to elbow	10% ENSD	ENSD	10% ENSD	EXSD
Left hand	ENSD	ENSD	10% ENSD	10% ENSD
Right hand	ENSD	ENSD	10% ENSD	10% ENSD
Left elbow, forearm, wrist Right elbow, forearm, wrist	10% ENSD	ENSD	10% ENSD	10% ENSD

Area of skin	PFG	<1970 PA chest	>1970 PA chest	>1970 LAT chest
Right elbow, forearm, wrist Right elbow, forearm, wrist	10% ENSD	ENSD	10% ENSD	10% ENSD
Right side of head (including ear)	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Left side of head (including ear)	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Front left thigh	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
Back left thigh	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
Front right thigh	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
Back right thigh	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
Left knee and below	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)
Right knee and below	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)
Left side of face	Eye/Brain	Eye/Brain	Eye/Brain	10% ENSD
Right side of face	Eye/Brain	Eye/Brain	Eye/Brain	10% ENSD
Left side of neck	10% ENSD	ENSD	10% ENSD	10% ENSD
Right side of neck	10% ENSD	ENSD	10% ENSD	10% ENSD
Back of head	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Front of neck	Eye/Brain	Eye/Brain	Thyroid	10% ENSD
Back of neck	10% ENSD	ENSD	10% ENSD	10% ENSD
Front torso: base of neck to end of sternum	EXSD	EXSD	EXSD	Lung
Front torso: end of sternum to lowest rib	EXSD	EXSD	EXSD	Lung
Front torso: lowest rib to iliac crest	EXSD	EXSD	10% EXSD	10% Lung
Front torso: Iliac crest to pubis	10% EXSD	10% EXSD	10% EXSD	10% Lung
Back torso: base of neck to midback	ENSD	ENSD	ENSD	Lung
Back torso: midback to lowest rib	ENSD	ENSD	ENSD	Lung
Back torso: lowest rib to iliac crest	ENSD	ENSD	10% ENSD	10% Lung
Back torso: buttocks (Iliac crest and below)	10% ENSD	10% ENSD	10% ENSD	10% Lung
Right torso: base of neck to end of sternum	ENSD	ENSD	ENSD	ENSD
Right torso: end of sternum to lowest rib	ENSD	ENSD	ENSD	ENSD
Right torso: lowest rib to iliac crest	ENSD	ENSD	10% ENSD	10% ENSD
Right torso: Iliac crest to pubis (right hip)	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Left torso: base of neck to end of sternum	ENSD	ENSD	ENSD	EXSD
Left torso: end of sternum to lowest rib	ENSD	ENSD	ENSD	EXSD
Left torso: lowest rib to iliac crest	ENSD	ENSD	10% ENSD	10% EXSD
Left torso: iliac crest to pubis (left hip)	10% ENSD	10% ENSD	10% ENSD	10% EXSD

Table 3-4. Skin dose (rem) from various chest projections.[a]

Area of skin	PFG 1947–1955	PA chest 1947–1959	PA chest 1960–1978	PA chest 1979–1986	LAT chest 1979–1986	PA chest 1987–1995	LAT chest 1987–1995	PA chest 1996–present	LAT chest 1996–present
Right front shoulder	8.82E-02	6.E-04	4.E-04	1.1E-03	8.40E-02	5.E-04	4.20E-02	4.E-04	3.50E-02
Right back shoulder	4.05E+00	7.80E-02	1.54E-02	4.20E-02	8.40E-02	2.10E-02	4.20E-02	1.40E-02	3.50E-02
Left front shoulder	8.82E-02	6.E-04	4.E-04	1.1E-03	4.E-04	5.E-04	2.E-04	4.E-04	2.E-04
Left back shoulder	4.05E+00	7.80E-02	1.54E-02	4.20E-02	4.E-04	2.10E-02	2.E-04	1.40E-02	2.E-04
Right upper arm to elbow	4.05E-01	7.80E-02	1.5E-03	4.2E-03	8.40E-02	2.1E-03	4.20E-02	1.4E-03	3.50E-02
Left upper arm to elbow	4.05E-01	7.80E-02	1.5E-03	4.2E-03	4.E-04	2.1E-03	2.E-04	1.4E-03	2.E-04
Left hand	4.05E+00	7.80E-02	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Right hand	4.05E+00	7.80E-02	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Left elbow, forearm, wrist Right elbow, forearm, wrist	4.05E-01	7.80E-02	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Right elbow, forearm, wrist Right elbow, forearm, wrist	4.05E-01	7.80E-02	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Right side of head (including ear)	4.05E-01	7.8E-03	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Left side of head (including ear)	4.05E-01	7.8E-03	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Front left thigh	1.2E-03	1.E-05	5.E-06	1.E-05	1.E-05	7.E-06	7.E-06	5.E-06	7.E-06
Back left thigh	1.2E-03	1.E-05	5.E-06	1.E-05	1.E-05	7.E-06	7.E-06	5.E-06	7.E-06
Front right thigh	1.2E-03	1.E-05	5.E-06	1.E-05	1.E-05	7.E-06	7.E-06	5.E-06	7.E-06
Back right thigh	1.2E-03	1.E-05	5.E-06	1.E-05	1.E-05	7.E-06	7.E-06	5.E-06	7.E-06
Left knee and below	4E-04	4.E-06	2.E-06	5.E-06	5.E-06	2.E-06	3.E-06	2.E-06	2.E-06
Right knee and below	4E-04	4.E-06	2.E-06	5.E-06	5.E-06	2.E-06	3.E-06	2.E-06	2.E-06
Left side of face	9.60E-02	7.3E-03	5.E-04	1.4E-03	8.4E-03	7.E-04	4.2E-03	6.E-04	3.5E-03
Right side of face	9.60E-02	7.3E-03	5.E-04	1.4E-03	8.4E-03	7.E-04	4.2E-03	6.E-04	3.5E-03
Left side of neck	4.05E-01	7.80E-02	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Right side of neck	4.05E-01	7.80E-02	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Back of head	4.05E-01	7.8E-03	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Front of neck	9.60E-02	7.3E-03	5.E-04	1.4E-03	8.4E-03	7.E-04	4.2E-03	6.E-04	3.5E-03
Back of neck	4.05E-01	7.80E-02	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Front torso: base of neck to end of sternum	8.82E-02	6.E-04	4.E-04	1.1E-03	1.60E-02	5.E-04	8.0E-03	4.E-04	7.8E-03
Front torso: end of sternum to lowest rib	8.82E-02	6.E-04	4.E-04	1.1E-03	1.60E-02	5.E-04	8.0E-03	4.E-04	7.8E-03
Front torso: lowest rib to iliac crest	8.82E-02	6.E-04	4.E-05	1.E-04	1.6E-03	5.E-05	8.0E-04	4.E-05	8.E-04
Front torso: iliac crest to pubis	8.8E-03	6.E-05	4.E-05	1.E-04	1.6E-03	5.E-05	8.0E-04	4.E-05	8.E-04
Back torso: base of neck to midback	4.05E+00	7.80E-02	1.54E-02	4.20E-02	1.60E-02	2.10E-02	8.0E-03	1.40E-02	7.8E-03
Back torso: midback to lowest rib	4.05E+00	7.80E-02	1.54E-02	4.20E-02	1.60E-02	2.10E-02	8.0E-03	1.40E-02	7.8E-03
Back torso: lowest rib to iliac crest	4.05E+00	7.80E-02	1.5E-03	4.2E-03	1.6E-03	2.1E-03	8.0E-04	1.4E-03	8.E-04

Area of skin	PFG 1947–1955	PA chest 1947–1959	PA chest 1960–1978	PA chest 1979–1986	LAT chest 1979–1986	PA chest 1987–1995	LAT chest 1987–1995	PA chest 1996–present	LAT chest 1996–present
Back torso: buttocks (Iliac crest and below)	4.05E-01	7.8E-03	1.5E-03	4.2E-03	1.6E-03	2.1E-03	8.0E-04	1.4E-03	8.E-04
Right torso: base of neck to end of sternum	4.05E+00	7.80E-02	1.54E-02	4.20E-02	8.40E-02	2.10E-02	4.20E-02	1.40E-02	3.50E-02
Right torso: end of sternum to lowest rib	4.05E+00	7.80E-02	1.54E-02	4.20E-02	8.40E-02	2.10E-02	4.20E-02	1.40E-02	3.50E-02
Right torso: lowest rib to iliac crest	4.05E+00	7.80E-02	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Right torso: iliac crest to pubis (right hip)	4.05E-01	7.8E-03	1.5E-03	4.2E-03	8.4E-03	2.1E-03	4.2E-03	1.4E-03	3.5E-03
Left torso: base of neck to end of sternum	4.05E+00	7.80E-02	1.54E-02	4.20E-02	4.E-04	2.10E-02	2.E-04	1.40E-02	2.E-04
Left torso: end of sternum to lowest rib	4.05E+00	7.80E-02	1.54E-02	4.20E-02	4.E-04	2.10E-02	2.E-04	1.40E-02	2.E-04
Left torso: lowest rib to iliac crest	4.05E+00	7.80E-02	1.5E-03	4.2E-03	4.E-05	2.1E-03	2.E-05	1.4E-03	2.E-05
Left torso: Iliac crest to pubis (left hip)	4.05E-01	7.8E-03	1.5E-03	4.2E-03	4.E-05	2.1E-03	2.E-05	1.4E-03	2.E-05

a. Values less than 1 mrem shown to one significant digit.

4.0 OCCUPATIONAL ENVIRONMENTAL DOSE

4.1 INTRODUCTION

Ambient external gamma radiation outside radiologically controlled areas is the result of ubiquitous background radiation, or gamma emissions from stack effluent such as ^{41}Ar, or skyshine due to air scatter from an otherwise well-shielded radiation source.

During the early years (1950 to 1973), BNL used an ion chamber and dynamic capacitor electrometer assembly to measure ambient external radiation. The ion chamber/dynamic capacitor electrometer assemblies and thermoluminescent dosimeters (TLDs) were used concurrently during 1973 and 1974. Information on the specific type of TLD used was not published until 1980 when the use of CaF2:Dy TLDs was noted (Naidu and Olmer 1981). The site changed to LiF:Mg Tl technology in 2000 (BNL 2001a).

Monitoring results from as many as four onsite stations are available for some years between 1967 and 1984. If available, these data are included in the average dose estimates. Beginning in 1985, the perimeter and onsite monitoring program was expanded to approximately 20 onsite stations and steadily increased to more than 50 onsite stations as of 2004 [7].

4.2 PURPOSE

The purpose of this section is to identify the sources and quantify the magnitude of the radiation dose received by BNL employees due to ambient radiation on the BNL site.

4.3 SCOPE

This section evaluates the ambient external radiation based on the monitoring results from four perimeter stations surrounding the BNL site at the northwest, southwest, southeast, and northeast coordinates.

Doses due to inhalation and ingestion are evaluated using stack emissions and the results of BNL environmental reports.

4.4 AMBIENT EXTERNAL RADIATION

4.4.1 Use of Offsite Monitoring

Before 1962, average and maximum environmental external gamma doses are derived from summary data published in retrospect (Meinhold and Meinhold 2001). During the period from 1962 through 1966, doses are derived from measurements at three or four continuous onsite monitoring stations as published in annual environmental monitoring reports. The standard deviation of the data for these years assumes a normal distribution. Table 4-1 provides average and maximum external gamma radiation results that have been adjusted to reflect a 2,000 hr/yr occupancy. After 1966, onsite monitoring results were no longer reported and the only data available are fenceline measurements that, in general, are remote from areas occupied by employees. The site averages for 1962 through 1966 have a mean of 71.4 mrem/yr. The maximum value for these years is 141 mrem/yr, which is approximately twice the average. The average is exceeded only once during this 5-year period. Based on this data, a reasonable average that is favorable to the claimant for years beyond 1966 is 75 mrem/yr with a maximum of twice the average, suggesting a 100% uncertainty if the average is assigned as a normal distribution.

4.4.2 Applicability for Dose Reconstruction

For dose reconstruction, the ambient external dose should be applied to all unmonitored workers. For monitored workers, external dose should be based on the dosimetry records without assignment of ambient external dose.

Table 4-1. External gamma radiation dose (mrem/yr).

Year	Monitoring location P-9[a]	Monitoring location S-10[b]	Monitoring location S-11[b]	Monitoring location S-12[b]	Site average	Error 1 standard deviation[c]	Maximum
1947[d]					0		0
1948[d]					0		0
1949[d]					0		0
1950[e]					0.18		0.27
1951[e]					6.4		9.2
1952[e]					8.0		11
1953[e]					8.5		12
1954[e]					8.9		13
1955[e]					8.9		13
1956[e]					8.5		12
1957[e]					7.3		11
1958[e]					21		30
1959[e]					27		39
1960[e]					32		50
1961[e]					27		39
1962[f]	44	35	59	74	53	17	74
1963[f]	135	141	125	127	132	8	141
1964[f]	42		64	41	49	13	64
1965[f]	40		97	38	58	34	97
1966[g]	40		128	28	65	54	128
1967–present[g]					75		150

a. Monitoring location P-9 was originally known as E-9.
b. Monitoring locations S-10, S-11, and S-12 were originally known as E-10, E-11, and E-12.
c. Error term includes only counting uncertainty and does not include sampling uncertainty.
d. Data before 1950 are assumed based on site activities in those years.
e. Data from 1950 to 1961 are from Meinhold and Meinhold (2001).
f. Data from 1962 to 1965 are extracted from annual environmental monitoring reports (Hull 1963, 1964, 1966; Hull and Gilmartin 1967).
g. Data after 1965 are assumed based on personnel dosimetry program criteria.

4.5 INHALATION OF ONSITE AIRBORNE RADIONUCLIDES

BNL has monitored releases to the environment since 1950 when the first stack became operational (Meinhold and Meinhold 2001). Stack release points and principal radionuclides in the airborne effluent are contained in the site annual environmental reports.

4.5.1 Stack Monitoring

With the exception of tritium, the intake for each radionuclide is the product of the highest annual average concentration reported for that radionuclide at any stack or perimeter sampling location during the year and the assumed breathing rate of $3.3 \times 10\text{-}4\ m^3/s$ (ICRP 1975) based on a 2,000-hr/yr exposure.

The individual stacks and their period of operation are:

Stack ID	Period of operation	Stack ID	Period of operation
BGRR	1950–1969	Chem	1973–1993
HFBR	1966–2004	BMRR	1996–1997
Hot Lab & HFBR	1986	Incinerator	1981–1996
Hot Lab	1987–2004	Evaporator	1995–2000
BLIP/LINAC	1973–2004		

The following isotopes were identified:

H-3	Co-60	Cs-137
Na-22	Zn-65	Ba-140
Na-24	Rh-106	La-140
Ar-41	Ru-106	Ce-141
Mn-54	I-125	Ce-144
Co-58	I-131	Eu-152
Fe-59	Cs-134	Eu-155

4.5.2 Estimates of Potential Inhalation Intake

The intake of each radionuclide that substantially contributes to personnel dose is tabulated by year. In Table 4-2, the maximum annual intakes are provided. These values are then assigned as a lognormal distribution with a GSD of 3.

As stated above, with the exception of tritium, the intake for each radionuclide is the product of the highest annual average concentration reported for that radionuclide at any stack or perimeter sampling location during the year and the assumed breathing rate of 3.3×10^{-4} m^3/s (ICRP 1975) based on a 2,000-hr/yr exposure. The ^3H intake, assumed to be in the form of water vapor, is determined as described for other radionuclides, and then increased by a factor of 1.5 to account for direct absorption through the skin [8].

In most years, stack effluent sampling shows that some radionuclides were released but not specifically monitored at ground-level site or perimeter sampling points. In those instances, the highest annual average stack concentration was reduced by a factor of 0.01 to account for the lessened overall intake due to contribution from multiple widely spaced facilities, atmospheric dispersion, and building wake, and the result was used as though it were a ground-level site or perimeter sample. Most radionuclides released from the stacks were not subsequently detected by ground-level monitoring stations. Therefore, a reduction factor could not be calculated from the data, so a reduction factor of 0.01 was applied to the stack air concentrations to provide a bounding ground-level concentration [9].

No measurements of particle size or solubility are available. Solubility and particle size for environmental intake calculations should be assumed to be the same as those used in Section 5.0 of this document. If no data are available, default solubility classes and particle size values from the ICRP should be used (NIOSH 2002, pp. 15–16).

4.6 INGESTION

Potable water, supplied from onsite wells, provides the most likely pathway for radionuclide ingestion at BNL. Environmental reports include the radionuclide concentration in potable water. Most of the observed radionuclides are naturally occurring and consistent with concentrations found in offsite regional water supplies.

Table 4-2. Maximum annual environmental occupational radionuclide inhalation (Bq/yr).[a,b]

Year	Radionuclide												
	H-3	I-131	1-125	Na-22	Na-24	Mn-54	Co-58	Fe-59	Co-60	Zn-65	Sr-90	Nb-95 Zr-95	Tc-99[c]
1950	3.01E+04	2.70E-01	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1951	3.01E+04	4.73E+01	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1952	3.01E+04	6.09E+01	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1953	3.01E+04	6.42E+01	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1954	3.01E+04	6.76E+01	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1955	3.01E+04	6.76E+01	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1956	3.01E+04	6.42E+01	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1957	3.01E+04	5.41E+01	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1958	3.01E+04	6.15E+02	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1959	3.01E+04	6.15E+02	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1960	3.01E+04	6.15E+02	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1961	3.01E+04	6.15E+02	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1962	3.01E+04	7.03E+02	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	2.11E+02	N/A
1963	3.01E+04	6.15E+02	4.84E+04	5.51E-02	1.19E+03	3.78E+01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	8.30E+02	N/A
1964	3.01E+04	5.71E+02	4.84E+04	5.51E-02	1.19E+03	3.52E+00	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	5.27E+00	N/A
1965	3.01E+04	7.45E+02	4.84E+04	5.51E-02	1.19E+03	6.15E-01	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	5.27E+00	N/A
1966	3.01E+04	8.11E+02	4.84E+04	5.51E-02	1.19E+03	8.79E-02	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	8.79E-01	N/A
1967	2.11E+05	3.16E+02	4.84E+04	5.51E-02	1.19E+03	8.79E-02	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	4.84E+00	N/A
1968	1.71E+06	7.47E+05	4.84E+04	5.51E-02	1.19E+03	8.79E-02	3.22E-01	1.22E+04	1.49E-03	1.05E-01	3.52E-01	4.84E+00	N/A
1969	1.71E+06	1.32E+01	4.84E+04	5.51E-02	1.19E+03	8.79E-02	3.22E-01	1.22E+04	1.49E-03	2.64E-01	3.52E-01	6.68E+00	N/A
1970	3.96E+06	2.64E-01	4.84E+04	5.51E-02	1.19E+03	8.79E-02	3.22E-01	1.22E+04	1.49E-03	7.91E-01	3.52E-01	8.79E+00	N/A
1971	1.05E+03	8.79E-02	4.84E+04	5.51E-02	1.19E+03	8.79E-02	3.22E-01	1.22E+04	1.49E-03	3.52E-01	1.76E-01	8.09E+00	N/A
1972	7.91E+02	8.79E-02	4.84E+04	5.51E-02	1.19E+03	8.79E-02	3.22E-01	1.22E+04	1.49E-03	8.79E-02	1.76E-01	1.58E+00	N/A
1973	3.41E+06	8.79E-02	4.84E+04	5.51E-02	1.19E+03	8.79E-02	3.22E-01	1.22E+04	1.49E-03	8.79E-02	1.76E-01	2.64E-01	N/A
1974	4.46E+06	1.76E-02	4.84E+04	5.51E-02	1.19E+03	8.79E-02	3.22E-01	1.22E+04	1.49E-03	1.26E+01	1.76E-01	3.08E+00	N/A
1975	3.42E+06	1.76E-02	4.84E+04	5.51E-02	1.19E+03	8.79E-02	3.22E-01	1.22E+04	1.49E-03	8.79E-02	1.76E-01	1.05E+00	N/A
1976	4.08E+06	1.76E-02	4.84E+04	5.51E-02	1.19E+03	4.88E+02	3.22E-01	1.22E+04	1.49E-03	8.79E-02	1.76E-01	1.05E+00	N/A
1977	4.11E+03	8.79E-01	4.84E+04	5.51E-02	1.19E+03	4.88E+02	3.22E-01	1.22E+04	1.49E-03	8.79E-02	1.76E-01	8.88E+00	N/A
1978	5.32E+05	8.79E-01	4.84E+04	5.51E-02	1.19E+03	4.88E+02	3.22E-01	1.22E+04	1.49E-03	8.79E-02	1.76E-01	8.88E+00	N/A
1979	1.37E+06	8.79E+00	4.84E+04	5.51E-02	1.19E+03	4.88E+02	3.22E-01	1.22E+04	1.49E-03	3.42E+04	1.76E-01	8.88E+00	N/A
1980	2.05E+06	8.79E+00	4.84E+04	5.51E-02	1.19E+03	4.88E+02	3.22E-01	1.22E+04	1.49E-03	3.42E+04	1.76E-01	8.88E+00	N/A
1981	1.32E+07	4.88E+03	4.84E+04	5.51E-02	1.19E+03	4.88E+02	3.22E-01	1.22E+04	1.49E-03	3.42E+04	1.76E-01	8.88E+00	4.88E+03
1982	2.05E+07	4.88E+03	6.35E+04	5.51E-02	1.19E+03	4.88E+02	3.22E-01	4.88E+03	1.49E-03	3.42E+04	1.76E-01	8.88E+00	4.88E+03
1983	1.90E+07	4.88E+03	8.30E+04	5.51E-02	1.19E+03	4.88E+02	3.22E-01	4.88E+03	1.49E-03	3.42E+04	1.76E-01	3.52E-03	4.88E+03
1984	6.91E+06	1.47E+04	4.88E+04	5.51E-02	1.19E+03	4.88E+02	3.22E-01	4.88E+03	2.37E-03	3.42E+04	1.76E-01	3.52E-03	4.88E+03
1985	9.66E+05	1.37E+00	2.98E+04	5.51E-02	1.19E+03	4.88E+02	3.22E-01	1.47E+02	2.64E-02	1.40E-02	1.76E-01	3.52E-03	4.88E+03
1986	6.92E+06	1.03E+03	2.54E+04	5.51E-02	1.19E+03	4.88E+02	3.22E-01	1.47E+02	1.15E+00	1.40E-02	1.76E-01	3.52E-03	4.88E+03
1987	1.15E+07	8.30E+03	4.35E+03	5.51E-02	1.19E+03	1.70E-03	3.22E-01	4.88E+01	1.15E+00	1.40E-02	1.76E-01	3.52E-03	2.05E+03
1988	1.71E+06	4.88E+02	9.52E+02	5.51E-02	1.19E+03	5.37E-01	3.22E-01	4.88E+01	4.36E-01	3.24E-01	1.76E-01	3.52E-03	2.44E-01

Year	Radionuclide												
	H-3	I-131	1-125	Na-22	Na-24	Mn-54	Co-58	Fe-59	Co-60	Zn-65	Sr-90	Nb-95 Zr-95	Tc-99[c]
1989	2.70E+06	8.88E-02	1.03E+04	1.03E+00	1.19E+03	5.37E-01	3.22E-01	4.88E+01	6.44E-01	8.16E+00	1.76E-01	3.52E-03	2.44E-01
1990	4.63E+05	6.94E+02	2.30E+03	1.03E+00	1.19E+03	3.81E-02	3.22E-01	4.88E+01	6.55E+00	5.37E-03	1.76E-01	3.52E-03	2.44E+02
1991	6.44E+05	6.94E+02	4.75E+03	5.11E+00	1.19E+03	4.75E-02	1.34E+00	4.88E+01	2.83E-01	2.22E+00	1.76E-01	3.52E-03	2.44E+02
1992	4.44E+05	6.94E+02	2.59E+03	5.11E+00	1.19E+03	2.44E+01	1.34E+00	4.88E+01	2.77E+00	2.22E+00	1.76E-01	3.52E-03	2.44E+02
1993	5.33E+05	3.61E-02	2.44E+04	3.11E-01	1.19E+03	7.89E+00	6.83E+00	1.99E+01	6.65E-01	2.22E+00	1.76E-01	3.52E-03	2.44E+02
1994	5.92E+05	3.61E-02	2.44E+04	3.11E-01	1.19E+03	2.19E-01	6.83E+00	1.99E+01	9.49E-04	1.17E-01	1.76E-01	3.52E-03	2.44E+02
1995	7.15E+05	3.21E+00	1.95E+03	2.52E-03	1.19E+03	2.78E-02	6.74E-01	1.99E+01	3.84E-02	1.17E-01	1.76E-01	3.52E-03	2.44E+02
1996	3.52E+05	3.21E+00	1.47E+03	1.12E-01	1.19E+03	4.30E-02	6.74E-01	1.99E+01	4.88E-03	1.01E+02	1.76E-01	3.52E-03	2.44E+02
1997	1.98E+05	1.72E+02	1.47E+03	4.55E-03	1.19E+03	7.42E-02	4.18E-01	1.99E+01	1.37E+01	1.01E+02	1.76E-01	3.52E-03	N/A
1998	2.73E+05	1.72E+02	1.47E+03	6.59E-03	1.19E+03	1.21E-02	1.99E-01	1.99E+01	7.03E-03	3.92E-01	1.76E-01	3.52E-03	N/A
1999	1.33E+05	1.72E+02	7.86E+00	6.59E-03	1.19E+03	9.33E-02	8.84E-02	1.99E+01	1.18E-01	2.17E+00	1.76E-01	3.52E-03	N/A
2000	3.52E+04	1.72E+02	7.86E+00	1.08E-03	1.19E+03	1.53E-02	1.45E-02	1.99E+01	1.93E-02	3.56E-01	1.76E-01	3.52E-03	N/A
2001	2.64E+04	3.83E-05	7.86E+00	1.08E-03	1.19E+03	1.53E-02	1.45E-02	1.99E+01	1.93E-02	3.56E-01	1.76E-01	3.52E-03	N/A
2002	2.37E+04	3.83E-05	7.86E+00	1.08E-03	1.19E+03	1.53E-02	1.45E-02	1.99E+01	1.93E-02	3.56E-01	1.76E-01	3.52E-03	N/A
2003	5.92E+05	3.83E-05	7.86E+00	1.08E-03	1.19E+03	1.53E-02	1.45E-02	1.99E+01	5.25E-08	3.56E-01	1.76E-01	3.52E-03	N/A
2004	5.92E+05	3.83E-05	7.86E+00	1.08E-03	1.19E+03	1.53E-02	1.45E-02	1.99E+01	5.25E-08	3.56E-01	1.76E-01	3.52E-03	N/A

Year	Radionuclide												
	Tc-99m[d]	Ru-103	Rh-106 Ru-106	Cs-134[e]	Cs-137	Ba-140	La-140	Ce-141	Ce-144	Eu-152	Eu-155[d]	Ra-226	Th-228
1950	N/A	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	N/A	6.07E-03	2.55E-01	1.76E-01
1951	N/A	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	N/A	6.07E-03	2.55E-01	1.76E-01
1952	N/A	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	N/A	6.07E-03	2.55E-01	1.76E-01
1953	N/A	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	N/A	6.07E-03	2.55E-01	1.76E-01
1954	N/A	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	N/A	6.07E-03	2.55E-01	1.76E-01
1955	N/A	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	N/A	6.07E-03	2.55E-01	1.76E-01
1956	N/A	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	N/A	6.07E-03	2.55E-01	1.76E-01
1957	N/A	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	N/A	6.07E-03	2.55E-01	1.76E-01
1958	N/A	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	N/A	6.07E-03	2.55E-01	1.76E-01
1959	9.82E+03	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1960	9.82E+03	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1961	9.82E+03	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1962	9.82E+03	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1963	9.82E+03	6.51E+01	5.27E+01	N/A	2.02E+01	1.23E+00	1.23E+00	8.79E-01	6.33E+01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1964	9.82E+03	8.79E-01	1.23E+01	N/A	7.03E+00	1.23E+00	1.23E+00	8.79E-01	6.33E+01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1965	9.82E+03	8.79E-01	2.20E+00	N/A	2.37E+00	1.23E+00	1.23E+00	8.79E-01	6.33E+01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1966	9.82E+03	6.15E-01	5.27E-01	N/A	7.03E-01	1.23E+00	1.23E+00	4.40E-01	6.33E+01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1967	9.82E+03	1.05E+00	5.27E-01	N/A	7.03E-01	1.23E+00	1.23E+00	4.40E-01	6.33E+01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1968	9.82E+03	1.05E+00	5.27E-01	N/A	6.15E-01	5.27E-01	5.27E-01	4.40E-01	6.33E+01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1969	9.82E+03	1.05E+00	2.11E+00	N/A	5.27E-01	1.76E-01	1.76E-01	4.40E-01	1.58E+01	8.76E-07	6.07E-03	2.55E-01	1.76E-01

Year	Radionuclide												
	Tc-99m[d]	Ru-103	Rh-106 Ru-106	Cs-134[e]	Cs-137	Ba-140	La-140	Ce-141	Ce-144	Eu-152	Eu-155[d]	Ra-226	Th-228
1970	9.82E+03	1.05E+00	2.11E+00	N/A	1.23E+00	1.76E-01	1.76E-01	4.40E-01	2.46E+00	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1971	9.82E+03	1.05E+00	2.11E+00	N/A	1.05E+00	8.79E-02	8.79E-02	4.40E-01	6.15E-01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1972	9.82E+03	1.05E+00	2.11E+00	N/A	4.40E-01	2.64E-01	2.64E-01	4.40E-01	2.37E+00	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1973	9.82E+03	1.05E+00	1.23E+00	1.23E-01	8.79E-02	2.64E-01	2.64E-01	4.40E-01	2.37E+00	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1974	9.82E+03	1.05E+00	1.23E+00	1.23E-01	8.79E-02	2.64E-01	2.64E-01	4.40E-01	4.22E+00	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1975	9.82E+03	1.05E+00	6.15E-01	1.23E-01	8.79E-02	3.52E-01	2.64E-01	4.40E-01	6.68E+00	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1976	9.82E+03	4.88E+03	6.15E-01	1.23E-01	8.79E-02	3.52E-01	3.52E-01	4.40E-01	8.00E+00	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1977	9.82E+03	4.88E+03	7.91E-01	1.23E-01	8.79E-01	3.52E-01	3.52E-01	3.52E-02	1.32E+00	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1978	9.82E+03	4.88E+03	7.91E-01	1.23E-01	8.79E-01	3.52E-01	3.52E-01	3.52E-02	3.52E-01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1979	9.82E+03	4.88E+03	7.91E-01	1.23E-01	8.79E-01	2.20E-01	2.20E-01	3.52E-02	2.02E+00	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1980	9.82E+03	4.88E+03	7.91E-01	1.23E-01	8.79E-01	2.20E-01	2.20E-01	3.52E-02	7.91E-01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1981	9.82E+03	4.88E+03	7.91E-01	1.23E-01	3.96E-01	2.20E-01	2.20E-01	3.52E-02	7.91E-01	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1982	9.82E+03	4.88E+03	9.67E-02	1.23E-01	2.64E+00	2.20E-01	2.20E-01	3.52E-02	5.36E-03	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1983	9.82E+03	4.88E+03	9.67E-02	1.23E-01	2.99E-01	2.20E-01	2.20E-01	3.52E-02	5.36E-03	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1984	9.82E+03	4.88E+03	9.67E-02	1.23E-01	1.77E-01	3.70E-03	2.20E-01	3.52E-02	5.36E-03	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1985	9.82E+03	5.86E+02	9.67E-02	1.23E-01	2.81E-01	3.70E-03	2.20E-01	3.52E-02	5.36E-03	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1986	9.82E+03	5.86E+02	7.03E-02	1.23E-01	2.81E-01	3.70E-03	2.20E-01	3.52E-02	5.36E-03	8.76E-07	6.07E-03	2.55E-01	1.76E-01
1987	4.88E+02	5.86E+02	7.03E-02	9.58E-03	2.17E-01	3.70E-03	2.20E-01	3.52E-02	5.36E-03	8.76E-07	6.07E-03	2.55E-01	5.27E-02
1988	4.88E+02	1.12E+00	7.03E-02	9.58E-03	2.00E-01	3.70E-03	1.86E+02	3.52E-02	5.36E-03	8.76E-07	6.07E-03	8.44E-01	8.79E-02
1989	7.33E+03	1.12E+00	1.28E+02	2.60E-02	4.48E-01	3.70E-03	1.86E+02	3.52E-02	5.36E-03	8.76E-07	8.79E-03	6.15E-01	8.79E-02
1990	7.33E+03	1.52E+01	1.28E+02	2.60E-02	6.15E-01	3.70E-03	1.86E+02	3.52E-02	1.86E+00	8.76E-07	8.79E-03	1.03E+00	3.52E-02
1991	7.33E+03	1.52E+01	1.28E+02	2.60E-02	7.77E-01	3.70E-03	1.86E+02	3.52E-02	1.86E+00	8.76E-07	8.79E-03	1.86E-01	3.52E-02
1992	7.33E+03	1.52E+01	1.28E+02	2.60E-02	2.50E-01	7.76E+01	1.86E+02	9.41E-01	1.86E+00	8.76E-07	8.79E-03	1.86E-01	1.55E-01
1993	7.33E+03	1.52E+01	1.28E+02	2.60E-02	4.55E-01	7.76E+01	1.86E+02	9.41E-01	1.86E+00	8.76E-07	8.79E-03	1.86E-01	1.55E-01
1994	3.03E+02	1.52E+01	1.28E+02	4.49E-03	1.38E+00	7.76E+01	1.86E+02	9.41E-01	1.86E+00	8.76E-07	8.79E-03	5.07E+00	1.55E-01
1995	3.03E+02	1.52E+01	1.28E+02	4.49E-03	2.76E+01	7.76E+01	1.86E+02	9.41E-01	1.86E+00	8.76E-07	8.79E-03	5.07E+00	1.55E-01
1996	3.03E+02	1.52E+01	1.28E+02	4.49E-03	5.86E-01	7.76E+01	1.86E+02	9.41E-01	1.86E+00	8.76E-07	8.79E-03	5.07E+00	1.55E-01
1997	3.03E+02	1.52E+01	1.28E+02	4.49E-03	1.47E-01	8.07E+02	4.27E+03	9.41E-01	7.34E+00	8.76E-07	8.79E-03	5.07E+00	1.55E-01
1998	3.03E+02	1.52E+01	1.28E+02	4.49E-03	1.31E-02	8.07E+02	4.27E+03	9.41E-01	7.34E+00	8.76E-07	8.79E-03	5.07E+00	1.55E-01
1999	3.03E+02	1.52E+01	1.28E+02	4.49E-03	2.59E-01	8.07E+02	4.27E+03	9.41E-01	7.34E+00	8.76E-07	8.79E-03	5.07E+00	1.55E-01
2000	3.03E+02	1.52E+01	1.28E+02	4.49E-03	4.25E-02	8.07E+02	4.27E+03	9.41E-01	7.34E+00	8.76E-07	8.79E-03	5.07E+00	1.55E-01
2001	3.03E+02	1.52E+01	1.28E+02	4.49E-03	4.25E-02	8.07E+02	4.27E+03	9.41E-01	7.34E+00	8.76E-07	8.79E-03	5.07E+00	1.55E-01
2002	3.03E+02	1.52E+01	1.28E+02	4.49E-03	5.44E-04	8.07E+02	4.27E+03	9.41E-01	7.34E+00	8.76E-07	8.79E-03	5.07E+00	1.55E-01
2003	3.03E+02	1.52E+01	1.28E+02	4.49E-03	5.44E-04	8.07E+02	4.27E+03	9.41E-01	7.34E+00	8.76E-07	8.79E-03	5.07E+00	1.55E-01
2004	3.03E+02	1.52E+01	1.28E+02	4.49E-03	1.81E-09	8.07E+02	4.27E+03	9.41E-01	7.34E+00	8.76E-07	8.79E-03	5.07E+00	1.55E-01

a. Highlighted values are bounded by available data. Missing years are filled in with nearest results (highest value if uneven interval).
b. Values not highlighted are from closest available result.
c. Tc-99 reported only for incinerator, which operated from 1981 to 1996.
d. Tc-99m and Eu-155 are reported for the BMRR, which began operating in 1959; Tc-99m is also reported for incinerator.
e. Cs-134 reported for the BLIP, which began operating in 1973; it is also reported for evaporator.

Neither potable groundwater nor soil ingestion has been found to be a pathway of exposure. No ingestion dose is indicated [10].

4.7 UNCERTAINTY

A high degree of uncertainty is associated with environmental monitoring. Uncertainty is the result of many factors listed here in approximate order of importance: atmospheric dispersion models used to describe dilution of radionuclide concentration from the stack to the receptor; location of ground-level monitoring stations to represent the unmonitored worker adequately; efficiency of radioactive iodine sampling media before use of charcoal collectors; average water intake; occupancy factors for workers on the site; average breathing rate; measurement detection limits; and accuracy of measurement results. Additional factors could be listed. The error associated with each factor is unknown, but can be reasonably expected to range from more than a factor of 10 for atmospheric dilution, to about 20% for accuracy of measurement [11].

Although the historical uncertainty cannot be substantially reduced without a great deal of effort, importance of uncertainty in dose reconstruction is reduced by the fact that many of the doses are small. Both the maximum and average annualized concentrations are used to estimate intakes and other assumptions are biased to be favorable to the claimant. An example is the dilution factor used to adjust stack effluent concentrations for use as ground-level exposures. Actual data would suggest that roof-level stacks tend to create dilution factors of 0.001 or more (ORAUT 2004, p. 28), but in this instance a factor of 0.01 is assumed, which results in higher ground-level exposure to an unmonitored worker.

5.0 OCCUPATIONAL INTERNAL DOSE

5.1 INTRODUCTION

BNL has played an important role in the development of the U.S. nuclear program. It has conducted applied research in nuclear and high-energy physics, chemistry and physics of materials, environmental and energy research, nonproliferation, neurosciences and medical imaging, and structural biology. Methods and concepts of measuring occupational internal doses to workers have evolved since the beginning of BNL operations. This section describes BNL internal dosimetry systems and practices.

5.2 PURPOSE

The purpose of this section is to describe internal dosimetry systems and practices at BNL. This section provides supporting technical data to evaluate internal occupational doses that can reasonably be associated with worker radiation exposures covered by EEOICPA.

5.3 SCOPE

This section presents historical and current practices as they relate to the evaluation of internal exposure data for monitored and unmonitored workers. It describes plant facilities and processes, and historical information in relation to dose reconstruction for BNL workers. In addition, it contains supporting documentation to assist in the evaluation of occupational internal doses from these processes in accordance with the *Internal Dose Reconstruction Implementation Guideline* (NIOSH 2002) and addresses the evaluation of dose for unmonitored and monitored workers.

The section presents the technical basis of methods used to prepare dose information for input to the NIOSH IREP computer code, and evaluates the uncertainty for BNL exposure and dose records.

NIOSH has determined, and the Secretary of Health and Human Services has concurred, that it lacks sufficient personnel or area monitoring data, or sufficient source or source term information, associated with BNL operations to bound potential internal exposures for the period from January 1, 1947, through December 31, 1979 (other than tritium after December 31, 1964).

NIOSH found that while it is not possible to completely reconstruct internal radiation doses for employees who worked at BNL from January 1, 1947, through December 31, 1979, NIOSH intends to use any reliable internal monitoring data that may be available for an individual claim (and that can be interpreted using existing NIOSH dose reconstruction processes or procedures) to support a partial dose reconstruction for nonpresumptive cancers and/or cases that have less than 250 work days of employment.

5.4 BIOASSAY RECORDS IN THE INDIVIDUAL FILES

5.4.1 Bioassay Record (Form 1720)

The BNL bioassay record, Form 1720, contains one line (record) per sample. The record includes the following fields:

1. NO. (number, i.e., the sequential number of the sample),
2. DATE RECV'D (date sample was received),
3. I or S (code for incident or survey. Survey is assumed to be a routine sample),
4. COLLECTION DATE/TIME,
5. COUNT DATE,

6. TOTAL SAMPLE (volume in milliliters or X for a spot sample), and
7. SAMPLE TYPE (U for urine, F for feces, B for blood, H for hair, and WB for whole-body).

The results portion of the form is filled in according to the analysis. Columns are provided for MFPs (mixed fission products in dpm/day beta activity), ^{90}Sr (in dpm/day beta activity), and ^{3}H (in µCi/L beta activity). Additional columns are provided for NUCLIDE, AMOUNT, and UNITS for alpha activity. Results for ^{90}Sr appeared only with MFP results, indicating a sequential analysis. This form appears to have been used from 1967 to the 1980s. Data from as far back as 1952 appear to have been transferred to these forms in 1967.

5.4.2 Tritium Exposure Evaluation Form

This form was used to calculate the whole-body dose from tritium bioassay results. Results for the bioassay sample under evaluation that were above some threshold (probably around 1 µCi/L) were transferred to this form. Each row was used to calculate the dose (if any) from one urine result. The column headings are:

1. No. of Intervening Days (since last sample)
2. Gross µCi/L Current Date
3. Gross µCi/L Previous Date
4. Fraction Present of Previous Concentration
5. µCi/L Remaining from Previous Date
6. Net µCi/L Current Date
7. Tritium Body Dose for Current Date MREM
8. Cumulative Tritium Body Dose MREM

Doses were not calculated if the Net µCi/L Current Date (Gross µCi/L Current Date minus µCi/L Remaining from Previous Date) was less than some threshold. The threshold might have been 0.3 µCi/L. The form was used from the fourth quarter of 1968 until at least 1986. The doses were totaled for each quarter for comparison to the limits in place at the time. This form could be a secondary source of information should the BNL Bioassay Record (Form 1720) discussed above be missing or illegible. Based on the review of site records and personnel interviews, tritium dose was recorded on the external dosimetry cards (in the employee records) until the committed dose era starting in 1989.

5.4.3 Summary of Whole-Body Counting Results

Summaries of the whole-body counting results might be included in some employees' records for the 1970s and possibly earlier. The summaries currently list several employees on a single page. Cover letters included with the results provided an interpretation of positive results. For example, the letters discuss cesium results believed to be from fallout, results attributed to clothing contamination, results due to an intake with a body burden calculated, etc. [12].

5.4.4 Individual Whole-Body Counting Results

By the 1980s, whole-body counting results for each count were included in the records. The earliest results were titled "NAI Results" and consisted of a one- or two-page computer printout. The counts appeared to be done with a single detector and were 15 minutes long. The printout contains:

1. ACQUISITION DATE, date and time of the count

2. ELAPSED LIVE TIME, length of the count

3. NUCLIDE, a table of results listing the radionuclide

4. CONCENTRATION (UNITS), activity

5. ERROR, error

By 1993, the site had changed to the Canberra ABACOS-plus software package. The ABACOS printout contained:

1. COUNT STARTED, the date and time of the count

2. ELAPSED LIVE TIME, length of the count

3. NUCLIDE, a table of results listing the radionuclide

4. ACTIVITY (nCi), the activity

5. %ERROR (2 SD), and the error

Initially the ABACOS printouts displayed "<" and the minimum detectable activity (MDA) in the results column for results below the MDA. Due to software limitations, an MDA and decision level could not both be displayed. In preparation for DOE Laboratory Accreditation Program (DOELAP) accreditation, in 1999 the number displayed was changed to the decision level, but the printout incorrectly stated that the number displayed was the MDA (i.e., "MDA activity reported"). A list of MDAs was published separately. This was corrected when the software was upgraded and subsequently both a decision level and an MDA were reported [13].

5.5 *IN VITRO* MINIMUM DETECTABLE ACTIVITIES, COUNTING METHODS, AND REPORTING PROTOCOLS

5.5.1 *In Vitro* Urine Analysis

In January 1949, a chemistry laboratory was organized under the Health and Safety Branch, Medical Division, New York Operations Office (NYOO) of the AEC to provide analytical and spectrographic facilities for dealing with hazards arising from NYOO facilities (e.g., uranium, beryllium, fluorine, thorium, and radium). In April 1949, the NYOO chemistry laboratory began an investigation into the feasibility of using the levels of uranium excretion in urine as a control measure in production plants and processing facilities (AEC 1949). In 1953, this organization became the Health and Safety Laboratory (HASL) and in 1977 the Environmental Measurements Laboratory (EML). In 2002, it became part of the Department of Homeland Security.

5.5.2 History of *In Vitro* Urine Analysis

Initially, support was also obtained from Oak Ridge National Laboratory to perform urinalysis for plutonium, polonium, mixed fission products, barium-lanthanum, yttrium, and strontium. By 1951, BNL was doing its own research and development on urine sample preparation (BNL 1951). In 1952, an analysis procedure for fission products in urine was successful using an adaptation of the Chalk River method (BNL 1952). However, in 1955, some uranium in urine at BNL was still analyzed fluorometrically by EML (AEC 1955). In 1958, a vibrating reed electrometer and chambers suitable for tritium urinalysis were set up in Building T-145 (Bishop 1958). In 1965, enriched uranium in urine was analyzed by EML. The analysis appears to have used both liquid scintillation counting (perhaps as a screening measurement) and electroplating for counting or autoradiography (Steimers 1965). The uranium fusion photofluorimetry urinalyses performed by the NYOO were similar to those performed at other AEC facilities. The default detection threshold for uranium urinalysis is assumed to be 10 µg/L based on a reported sensitivity of 5 to 10 µg/L for uranium fluorometric urinalysis in the early

years (ORAUT 2005). During the period from 1956 to 1964, the reporting level for uranium in urine by fluorometric analysis by HASL appears to have been 1.0 µg/L (see for example AEC 1957). Determination of ^{233}U and ^{235}U in urine was by fluorometry and alpha counting (AEC 1958, 1961, 1962). It is uncertain whether the analyses were for direct support, verification, or only for specific analyses needed. In May 1963, 112 urine samples were processed by the in-house bioassay laboratory. Gross beta and ^{90}Sr activity was measured in one individual who had been contaminated in April during reloading of spent fuel elements for shipment (BNL 1963).

In 1973, bioassay analyses were performed by an Analytical Chemistry section (BNL 1973). In 1977, the Health Physics and Safety Division housed an analytical chemistry and bioassay laboratory (ERDA 1977). In 1999, Eberline was contacted for bioassay analyses, with the exception of ^{3}H, which remained in-house until 2004 (~April 2004). Due to some problems with meeting the contractual MDAs, Eberline was replaced by the Severn-Trent (ST) Laboratory in December 2001. ST also did the H-3 analyses when they were discontinued on site. The current BNL bioassay program is accredited by DOELAP.

During the operation of the BGRR, some workers apparently were routinely sampled for mixed fission products and ^{90}Sr. No program documentation was recovered but this seems to be the case from a limited review of the individual files. Sampling frequency varied from as short as monthly to as long as annually. After 1965, when the HFBR started operation, the most prevalent bioassay sampling was for tritium. During the operation of the HFBR, the concentrations of radionuclides other than tritium were not considered to be significant. The rationale was that concentration of tritium in the primary cooling water was several million times its "tolerance limit" where fission products from fuel uranium surface contamination and activations products, such as ^{24}Na, were present at less than 100 times tolerance (BNL undated, p. 14).

During most of the site's existence, it appears that department/division safety representatives or managers designated personnel for participation in the internal dosimetry program [whole-body counters (WBCs) and/or urinalysis] using guidance provided by Personnel Monitoring. This could have included the frequency of monitoring (BNL 1995; Holeman 1999). Therefore, it might be difficult to determine if monitoring should have occurred by job title. For example, in the 1950s, several references mentioned that personnel described as "janitors" were involved in the cleanup of radioactive contamination. It was not clear if this was a specially designated crew or random site janitors being supervised by health physics personnel.

As some of the site's older facilities have undergone decontamination and decommissioning (D&D) in recent years, D&D workers were sampled for ^{90}Sr, ^{241}Am, ^{238}Pu, $^{239/240}$Pu, ^{234}U, ^{235}U, and ^{238}U.

5.5.3 Fecal Sample Analysis

Although fecal sampling might have been used in response to specific events, no evidence of a comprehensive fecal sampling program was located.

Table 5-1 lists the frequencies for *in vitro* monitoring.

Table 5-1. Internal dose control program (*in vitro*).

Routine monitoring type	Period	Frequency
Spot urine sample for H-3	Before 1993	No comprehensive documentation was located. It appeared to vary from weekly to monthly over time. The majority of samples after 1965 were from workers at the HFBR
Urine samples for H-3[a]	1993–2000	Weekly for reactor operators, supervisors, maintenance technicians, and S&EP building safety services technicians

24-hr urine samples for fission, activation, uranium, and transuranics		No comprehensive documentation was located. In 1984, an annual program of urine sampling was in place for reactor workers. The analysis included Cd-109, Sr-85, Ga-68, Na-22, and Co-58[b].

a. BNL (1993).
b. Miltenberger and Steimers (1984).

5.6 *IN VIVO* MINIMUM DETECTABLE ACTIVITIES, COUNTING METHODS, AND REPORTING PRACTICES

5.6.1 Whole-Body Counting

Whole-body counting was established in 1960. It was first used as a research tool, but it became evident that it was also of use when someone was potentially involved in an incident. After confirmed intakes, WB counting was repeated daily and the results were correlated with daily urine excretion results. Pile operators were the first group to be routinely counted. Some of the pile operators had been working before WB counting started. Later, all new pile operators received a WB count before they started working and, starting in about 1962, annually thereafter. Other groups were apparently counted in the WBC as time permitted. Background counts were taken on unexposed individuals as a check on fallout radionuclides (e.g., cesium) in the general population (Brodsky 1964, p. 40). The counting facility, which is still in existence in the Medical Department, includes a counting bed with an array of sodium iodide thallium-activated [NaI(Tl)] scintillation crystals.

By 1963, a portable "shadow shield" WBC was developed to measure the fission product body burdens of the Marshallese people who were exposed to the fallout from nuclear test Bravo on March 1, 1954, and to the subsequent uptake of radioactive material in crops. The detector was a 10-cm-thick by 28-cm-diameter NaI(Tl) crystal. The detector was stationary and was fixed in a position over the thorax of the subject. For more than 25 years, BNL had a contract for the long-term medical surveillance of the Marshallese. In 1977, the responsibility for providing body burden measurements was transferred from the Medical Department to the Safety and Environmental Protection Division. In 1980, the minimum detection limit of the system was 1 nCi of ^{137}Cs or ^{60}Co for a 15-minute count (Miltenberger, Greenhouse, and Lessard 1980). Between these measurement trips, the counter was used at BNL as part of the health and safety program and eventually performed the routine counts (Miltenberger 1981a). For positive results, additional counts could be done at the medical WB counting facility to localize the contamination (Miltenberger 1981a). The MDL for the shadow shield arrangement was calculated in µCi by:

$$MDL = \frac{4.65\sqrt{Ct_b}}{900 * 37 * K} \quad (5\text{-}1)$$

where:

Ct_b = blank counts (background for region of interest)
900 = count time (seconds)
37 = unit conversion factor
K = product of gamma abundance and counting efficiency for the radionuclide

By 1981, ^{137}Cs body burdens of 2 nCi or less were considered to be the result of fallout from atmospheric weapons testing environmental sources (Miltenberger 1981b).

In 1989, the MDA reported for thyroid counts for ^{131}I using a NaI counting system was "on the order of 10 nanocuries" (Miltenberger 1989).

The shadow shield was replaced by a standup counter, but the date of this transition was not recovered. The NaI detectors were replaced by germanium detectors and eventually by broad energy germanium detectors.

In 2003, Canberra ABACOS 2000 software was used with the WBC. The MDA for each radionuclide was calculated by:

$$MDA = \frac{3.29 * S_b + 3}{KT} \quad (5\text{-}2)$$

where:

S_b = sample standard deviation of background counts in the region of interest
K = efficiency at the centroid energy channel as determined arithmetically from the calibration efficiency equation times the yield abundance of the energy emission
T = count time

The ABACOS 2000 software produced a printout with the MDA and decision level for each result (Michel and Sun 2003; Michel 2003, 2004, 2005).

5.6.2 Chest Counting

Chest counts and thyroid counts were not done routinely. These counts were done as a result of incidents involving iodine (thyroid) and certain gamma emitters (^{127}Xe, lung) (Miltenberger and Lessard 1987). Only one person who does iodinations was on a thyroid counting program in 2006.

Table 5-2 lists the frequencies for *in vivo* monitoring.

Table 5-2. Internal dose control program (*in vivo*).

Routine monitoring type	Period	Frequency
Preemployment and annual WBC[a]	1962–unknown	Annual for pile operators. Other workers designated by the facility health physics staff of the various facilities.
WBC[b]	1993–2000	Start of service in Bldg. 750, and termination of service for Reactor Division and S&EP personnel with offices in the HFBR building (750). Annual for reactor operators, supervisors, maintenance technicians, S&EP building safety services technicians and research coordination group technicians, BLIP personnel, facility support, others on prejob basis.

a. Brodsky (1964)
b. BNL (1993)

5.7 UNCERTAINTY

At BNL, the uncertainty for a single bioassay measurement was not reported consistently. Uncertainties associated with the analysis of MFPs, ^{90}Sr, or ^{3}H performed on site during the period from 1952 to 1986 were not included on the BNL Bioassay Record. From the 1980s to about 1998, uncertainties are reported on WBC sheets and are believed to be consistently reported as 2-sigma errors. Reviewed statements of work for bioassay services do not contain any specification for reporting uncertainty. Eberline reported a 1-sigma total error with its bioassay results. At present, the ST contract laboratory reports results with both a 1-sigma counting error and a 1-sigma total error [14].

5.8 DETECTION LIMITS

Table 5-3 lists the MDAs and reporting levels for periods corresponding to the bioassay methods discussed in Sections 5.5 and 5.6. The reporting levels are listed in the units quoted in the references, which are generally the units of the results. Detection limits are to be taken from the individual reports when available.

5.9 EXCRETA SAMPLE KIT CODES

No codes have been found. Table 5-4 lists sample kit information summarized from site documents.

Table 5-3. Detection limits.

Radionuclide	Method/ description	Period	MDA (nCi)[a]	Reporting level (nCi)[b]
Be-7 (dual detector)	WBC	1993	50	50
Mn-54 (dual detector)	WBC	1993	4.7	4.7
Cs-137 (dual detector)	WBC	1993	5	5
Co-60 (dual detector)	WBC	1993	5	5
Zn-65 (dual detector)	WBC	1993	8.5	8.5
I-131 (dual detector)	WBC	1993	3.8	3.8
Be-7 (single detector)	WBC	1993	82	82
Mn-54 (single detector)	WBC	1993	7.5	7.5
Cs-137 (single detector)	WBC	1993	8.5	8.5
Co-60 (single detector)	WBC	1993	9.2	9.2
Zn-65 (single detector)	WBC	1993	17.6	17.6
I-131 (single detector)	WBC	1993	8.8	8.8

a. Values from Murray (1993).
b. Reporting level was the MDA.

Radionuclide (keV)	Method/ description	Period	MDA (nCi)[a]	Reporting level[b]
Na-22 (1,274.54)	WBC	1999	3	
Mn-54 (834.83)	WBC	1999	3	
Co-57 (122.06)	WBC	1999	7	
Co-58 (810.76)	WBC	1999	4	
Fe-59 (1,099.22)	WBC	1999	4	
Co-60 (1,332.49)	WBC	1999	5	
Zn-65 (1,115.52)	WBC	1999	5	
Cs-134 (604.7)	WBC	1999	3	
Cs-137 (661.65)	WBC	1999	4	

a. Values from Murray (1999).
b. Reporting levels shown on lung count results reports are from ABACOS-Plus software.

Radionuclide (keV)	Method/ description	Period	MDA (nCi)[a]	Reporting level
Be-7 (477.59)	WBC	2003	21.96, 22.2	
Na-22 (1274.54)	WBC	2003	2.58, 3.21	
K-40 (1,460.81)	WBC	2003	36.50, 131.54	
Mn-54 (834.83)	WBC	2003	2.22, 3.74	
Co-57 (122.06)	WBC	2003	3.37, 2.44	
Co-58 (810.76)	WBC	2003	2.49, 3.23	
Fe-59 (1,099.22)	WBC	2003	4.04, 6.07	
Co-60 (1,332.49)	WBC	2003	1.83, 3.65	
Zn-65 (1,115.52)	WBC	2003	5.18, 6.45	
Sr-85 (513.99)	WBC	2003	2.38, 5.14	
I-129 (29.62)	WBC	2003	7.97, 3.01	

Radionuclide (keV)	Method/ description	Period	MDA (nCi)[a]	Reporting level
I-131 (364.48)	WBC	2003	2.51, 3.47	
Cs-134 (604.7)	WBC	2003	2.09, 3.08	
Cs-137 (661.65)	WBC	2003	2.64, 4.77	
Ce-139 (165.85)	WBC	2003	3.48, 2.93	
Ce-144 (133.54)	WBC	2003	27.12, 22.11	
Bi-214 (609.31)	WBC	2003	7.00, 9.65	
Pb-214 (351.92)	WBC	2003	7.02, 8.5	
Am-241 (59.54)	WBC	2003	9.06, 4.94	

a. Values for 2003 from Michel (2003) and Michel and Sun (2003); MDAs are for each calibration.

Radionuclide (keV)	Method/ description	Period	MDA (nCi)[a]	Reporting level
Be-7 (477.59)	WBC	2004	23.35	
Na-22 (1,274.54)	WBC	2004	3.97	
K-40 (1460.81)	WBC	2004	147.04	
Mn-54 (834.83)	WBC	2004	2.50	
Co-57 (122.06)	WBC	2004	1.40	
Co-58 (810.76)	WBC	2004	2.39	
Fe-59 (1099.22)	WBC	2004	6.10	
Co-60 (1332.49)	WBC	2004	4.12	
Zn-65 (1115.52)	WBC	2004	5.09	
Sr-85 (513.99)	WBC	2004	2.21	
I-129 (29.62)	WBC	2004	78.83	
I-131 (364.48)	WBC	2004	2.20	
Cs-134 (604.7)	WBC	2004	2.29	
Cs-137 (661.65)	WBC	2004	3.62	
Ce-139 (165.85)	WBC	2004	1.94	
Ce-144 (133.54)	WBC	2004	13.59	
Bi-214 (609.31)	WBC	2004	11.69	
Pb-214 (351.92)	WBC	2004	8.32	
Am-241 (59.54)	WBC	2004	5.73	

a. Values for 2004 from Michel (2004) published for each calibration.

Radionuclide (keV)	Method/ description	Period	MDA (nCi)[a]	Reporting level
Be-7 (477.59)	WBC	2005	20.13	
Na-22 (1274.54)	WBC	2005	2.76	
K-40 (1460.81)	WBC	2005	42.99	
Mn-54 (834.83)	WBC	2005	2.79	
Co-57 (122.06)	WBC	2005	1.91	
Co-58 (810.76)	WBC	2005	2.91	
Fe-59 (1099.22)	WBC	2005	4.92	
Co-60 (1332.49)	WBC	2005	2.90	
Zn-65 (1115.52)	WBC	2005	5.54	
Sr-85 (513.99)	WBC	2005	3.41	
I-129 (29.62)	WBC	2005	81.99	
I-131 (364.48)	WBC	2005	1.92	
Cs-134 (604.7)	WBC	2005	2.89	
Cs-137 (661.65)	WBC	2005	3.12	
Ce-139 (165.85)	WBC	2005	1.76	
Ce-144 (133.54)	WBC	2005	14.63	
Bi-214 (609.31)	WBC	2005	7.72	

Radionuclide (keV)	Method/ description	Period	MDA (nCi)[a]	Reporting level
Pb-214 (351.92)	WBC	2005	7.60	
Am-241 (59.54)	WBC	2005	4.42	

a. Values for 2005 from Michel (2005) published for each calibration.

Radionuclide	Method/ description	Period	MDA[a]	Reporting level[b]
Am-241 (Eberline)	Urinalysis	1999–2000	6.0×10^{-2} pCi/L	No threshold
Am-241	Urinalysis	2001–2006	8.4×10^{-8} µCi/24 hr	No threshold
Br-77	Urinalysis	1975		5 µCi/L[c]
H-3 (in house lab)[d]	Urinalysis	1965–1979		2.0×10^{-2} µCi/L
H-3 (in house lab)	Urinalysis	1996	4.0×10^{-3} µCi/L	
H-3 (in house lab)	Urinalysis	1999	3.3×10^{-3} µCi/L	
H-3 (in house lab)[e]	Urinalysis	2000	5.0×10^{-3} µCi/L	
H-3 (required by TBD)	Urinalysis	2001–2006	1.0×10^{-2} µCi/L	
Mixed fission products[d]	Urinalysis	1952–1969		5.0 dpm/24 hr
Pu-238 (Eberline)	Urinalysis	1999–2000	6.0×10^{-2} pCi/L	No threshold
Pu-238	Urinalysis	2004–2006	8.4×10^{-8} µCi/24 hr	No threshold
Pu-239	Urinalysis	2001–2006	8.4×10^{-8} µCi/24 hr	No threshold
Pu-239/240 (Eberline)	Urinalysis	1999–2000	6.0×10^{-2} pCi/L	No threshold
Sr-90[c]	Urinalysis	1950–1998		5.0 dpm/24 hr
Sr-90 (Eberline)	Urinalysis	1999–2000	1.0 pCi/L	No threshold
Sr-90 (required by TBD)	Urinalysis	2001–2006	3.54×10^{-2} µCi/24 hr	No threshold
Uranium (fluorometric)	Urinalysis	Up to 1955		10 µg/L
Uranium (fluorometric)	Urinalysis	1956–1965		1 µg/L
U-238	Urinalysis	2001–2006	8.4×10^{-8} µCi/24 hr	No threshold
U-238 (Eberline)	Urinalysis	1999–2000	1.0×10^{-1} pCi/L	No threshold
U-235	Urinalysis	2001–2006	8.4×10^{-8} µCi/24 hr	No threshold
U-235 (Eberline)	Urinalysis	1999–2000	1.0×10^{-1} pCi/L	No threshold
U-234 (Eberline)	Urinalysis	1999–2000	1.0×10^{-1} pCi/L	No threshold

a. Values from BNL (2001b) and Sun, Reciniello, and Sengupta (2004), except as noted. Values could be applicable earlier, but documentation was not located.
b. Reporting levels shown were not documented as the MDA but can be interpreted as the MDA in lieu of other information.
c. Value below which "no exposure was assigned" from O'Connell (1975).
d. Values from a reactor employee's bioassay data.
e. Value from Scarpitta (2001).

Table 5-4. Excreta sample kit codes.

Kit code[a]		Media	Sample description
D/R	P/U		
NA	NA	Urine	Routine samples for H-3 were collected as grab samples (1993) to be collected weekly or within 4 hr of completion of a task that required bioassay. Twenty-four-hour samples could also be collected when other radionuclides were suspected.[a] In 1984, 24-hour kits consisted of three 500-mL bottles.[b] In 1999, spot samples were collected in 60-cc plastic bottles.[c]

a. BNL (1993).
b. Miltenberger and Steimers (1984).
c. Holeman (1999).

5.10 SOLUBILITY TYPE, FRACTION ACTIVITY, AND PARTICLE SIZE BY FACILITY

In the absence of measurements or studies, NIOSH guidance requires the use of default solubility classes and particle size values from the ICRP (NIOSH 2002, pp. 15, 16). Facility-specific solubility and particle size data for BNL have not been found. Activity fractions for occupational exposure were

generally not available. For some facilities, stack emissions or other measurements could be useful for dose reconstructions. Table 5-5 lists this information.

Table 5-5. Solubility type, fraction activity, and particle size by facility.

Facility[a]	Compound[b]	RN	Solubility[c] type	Particle size[d] (µm AMAD)	Activity fraction
Sewage Treatment Plant (1962)	Unknown. Measured at the outfall from the Imhoff tank (Stubbings 1962)	Sr-90			0.20
		Cs-137			0.80
Sewage Treatment Plant (1973)	Unknown. Fractions based on activities measured at the input to the sand filter beds (ERDA 1977, p. 126).	H-3			9.87E-01
		Be-7			7.33E-03
		Na-22			6.01E-05
		Na-24			3.59E-03
		Cr-51			2.49E-04
		Co-58			9.02E-05
		Co-60			2.58E-05
		Zn-65			3.44E-05
		Sr-90			5.58E-05
		I-131			1.37E-03
		Cs-134			1.72E-05
		Cs-137			1.07E-04
		Ce-144			1.98E-04
BGRR Bldgs. 701-703, 704 (fanhouse), 708 (instrument house), 709 (canal house), 709A (canal water treatment facility) (1950–1957)	Natural uranium metal fuel, 1-in, × 4–in. cylinders in 11-ft finned aluminum cartridges. (Activity fractions based on estimates of core activity at the time of 28 fuel ruptures and one irradiated uranium sample failure) (Meinhold and Meinhold, 2001)	Ba-140			1.70E-01
		Ce-144			1.08E-01
		Cs-137			7.19E-03
		La-140			1.95E-01
		Nb-95			1.62E-01
		Ru-103			7.28E-02
		Ru-106			6.09E-03
		Sr-89			1.17E-01
		Sr-90			7.78E-03
		Zr-95			1.53E-01
		U-235			8.35E-08
		U-238			1.81E-06
		U-234			1.81E-06
		Pu-239			2.86E-04
BGRR Bldgs. 701-703 (1958–1969)	Enriched uranium fuel, in the form of curved plates of uranium-aluminum alloy, clad on all surfaces by 0.5 mm of Al. Routine releases of fission products occurred due to U contamination on the fuel's surface and trapped in the cladding. Based on I-131 and gross beta measurements in the 1967–1969 EMRs.	Co-60			8.05E-02
		Zr-95			3.79E-01
		Ru-103			2.30E-01
		Ce-141			1.26E-01
		Ce-144			1.15E-01
		Cs-137			6.90E-02
		I-131			2.86E-03
BGRR Bldgs. 701-703 (1970–2006)	Residual contamination resulting from fission, activation, and transuranic radionuclides produced in the core and spread primarily by contact with the cooling water (Musolino 2000). Fuel storage canal was decommissioned in 1973.	Pu-238			6.66E-06
		Pu-239/40			5.86E-04
		Pu-241			2.59E-04
		Am-241			5.05E-05
		Fe-55			9.79E-01
		Co-60			4.89E-04
		Sr-90			9.09E-03
		Cs-137			1.08E-02
		U-235			1.37E-07
		U-238			3.57E-06

Facility[a]	Compound[b]	RN	Solubility[c] type	Particle size[d] (µm AMAD)	Activity fraction
BMRR Bldgs. 490-491 (1959–2000)	Enriched uranium fuel, in the form of curved plates of uranium-aluminum alloy, containing 12% by weight of fully enriched uranium. Estimates are for 1997 routine releases of isotopes likely to be of dosimetric importance (Meinhold and Meinhold 2001, Table 5, p. 57) 99.9% of activity release to sewer from labs was H-3 (ERDA 1977, p. 123)	Ce-141			2.99E-03
		Ce-144			2.33E-02
		Co-60			4.35E-02
		Fe-59			6.32E-02
		I-131			5.47E-01
		Zn-65			3.20E-01
Chemistry Hot Chemistry Polonium Facility T-137 1954–1961	Polonium source used in chemistry apparatus; also separated as a by-product of the production of At-211 for medical purposes	Po-210			
Cosmotron Bldg. (1953–1966)	Activation of short-lived isotopes in the ventilating air in the tunnel and experimental areas. See ”Accelerators & RHIC” below.	C-11			
		N-13			
		O-15			
AGS Bldgs. 905-912 (1960–2006)	Activation of short-lived isotopes in the ventilating air in the tunnel and experimental areas. Processing of irradiated targets (Meinhold and Meinhold, 2001, p. 58; ERDA 1977, p. 310). See ”Accelerators & RHIC” below.	C-11			
		N-13			
		O-15			
AGS Bubble Chamber Bldg. 919	Handling of tritium sources up to 100 mCi (1977)	H-3			1
Accelerators and RHIC 1953–2006	Posted contamination areas primarily in the vicinity of fixed targets (Lessard, Schaefer, and Karol 2001). Based on recent information, but is assumed to apply to earlier routine operations. Before 1987, beam intensities were less but some uncontained targets (e.g., tungsten) were used.	Be-7			5.50E-01
		Na-22			1.40E-01
		Mn-54			1.40E-01
		Co-57			1.40E-01
		Co-60			3.00E-02
Hot Laboratory (central lab, fanhouse, liquid waste tank farm, liquid waste concentration plant) Bldg. 801, 802 (1951–2006)	Acid dissolution of irradiated uranium samples to recover radioiodines (March 1952 to June 1960) In 1957, there was an accidental release of unirradiated natural uranium hexafluoride due to an explosion (Meinhold and Meinhold, 2001, p. 59). Radioactive solutions up to mCi amounts, 200 Ci/yr of H-3 fabricated into accelerator targets (1977). 87% of the liquid waste in 1973 was H-3 (ERDA 1977, p. 125) Fractions based on environmental releases of isotopes of dosimetric importance, 1983–1991	Co-58			9.33E-02
		Co-60			1.30E-03
		Cs-137			1.92E-02
		Eu-155			3.37E-03
		I-131			8.67E-02
		Mn-54			1.88E-03
		Zn-65			7.91E-01
		Zr-95			2.95E-03
		U			Unknown
		H-3			Unknown

Facility[a]	Compound[b]	RN	Solubility[c] type	Particle size[d] (µm AMAD)	Activity fraction
Hot Laboratory (1955–1966)	Polonium contamination; Po-210 sources manufactured in alpha facility	Po-210			
Nuclear Engineering T-197, 480 (1954–1962)	Unspecified polonium use requiring urinalysis (1954); and air sampling (1962)	Po-210			
Physics T-248, T-109, others before (1947–1951)	Polonium used in physics experiments	Po-210			
Physics Bldg. 510 (1962–present)	Processing irradiated targets, up to 1 mCi; 5,000 Ci of Co-60 in the gamma irradiation facility (1977)				
Radiation and Chemical Technology Bldgs. 526-527	Unknown uranium of various enrichments. Originally housed a criticality facility for reactor physics (ERDA 1977, p. 48). Monomer processing (ERDA 1977). Concrete dried and impregnated with monomers.				
HIRDL Bldg. 528 (1963–1972)	Contained million-Ci Co-60 and Cs-137 sources. The HIRDL was used for the development and testing of these sources. Operations were curtailed in 1972 due to lack of funding. In 1977, only a water-tank Co-60 gamma irradiation facility was still in operation.	Cs-137 Co-60			
Radiation Development Laboratory Bldg. 830	Fabrication of solid sources, up to Ci amounts, monomer processing (1977)				
Hot Machine Shop Bldg. 530 –1975 Replaced by Bldg. 462	Machining radioactive solids (1977), including uranium and radioactive graphite; repair work on “hot” fuel- handling tools.				
Health Physics & Safety, Instrumentation Bldg. 535	Radioactive solutions up to 100 µCi (1977)				
Chemistry Bldg. 555	Radioactive solutions and irradiated targets, up to 1 mCi (1977)				
CLIF Bldg. 931A	Production of radioactive isotopes. See ”Accelerators & RHIC” above. Dates of operation were not located.				
Reclamation and Hot Laundry Bldg. 650	Radioactive decontamination, up to mCi amounts (1977) 82% of activity released to sewer in 1973 was H-3, rest was gross beta (ERDA 1977, p. 125)				

Facility[a]	Compound[b]	RN	Solubility[c] type	Particle size[d] (µm AMAD)	Activity fraction
HFBR Bldg. 750 (1965–1997)	"Fully" enriched uranium and aluminum alloy, heavy-water-cooled and -moderated reactor that operated up to 40 MW (thermal) (60 MW planned in 1977) Fractions based on activity in heavy water when systems were opened for refueling or maintenance (1977).	H-3			9.998E-01
		Na-24			2.22E-04
		Cr-51			2.22E-06
		Co-59			8.89E-10
		Co-60			6.67E-10
		Zn-69			8.89E-09
		I-131			6.67E-10
		Cs-137			3.33E-10
Tandem Van de Graaff Accelerator Bldg. 901, 901A	Tritium gas and vapor. Fractions based on activity released from facility in 1979 (Naidu 1979)	H-3	Gas		8.95E-01
		H-3	Vapor		1.05E-01
Superconducting Test, Machine Shop, RARAF Bldg. 902	Irradiated target processing, up to 100 µCi. (1977)				
BLIP Facility Bldgs. 930 and 931B	Processing irradiated samples containing short-lived radionuclides (1977) for medical use; targets were sealed during normal operations but radioactive gases (N-13, O-14, O-15, N-16) and other isotopes formed in cooling water and equipment (ERDA 1977, p. 113). Fractions estimated based on activity in cooling and shield tank after one year of operation (ERDA 1977, p. 123).	H-3	HTO		6.35E-01
		Be-7			3.05E-01
		Na-22			2.54E-03
		Na-24			5.08E-02
		Cr-51			4.07E-03
		Co-58			1.52E-03
		Co-60			1.02E-03
Waste Management Incinerator Bldg. 445 (1981–)	BNL granted a permit by New York in March 1981. Fractions based on averages 1981–1991 for isotopes of importance for internal dose.	Fe-59			9.01E-02
		I-131			1.03E-01
		Mn-54			1.02E-02
		Ru-103			2.87E-02
		Ru-106			2.68E-03
		Tc-99			5.01E-02
		Zn-65			7.15E-01

a. Facilities were combined for this analysis if they were similar and had a common list of radionuclides of concern.
b. If chemical compounds were not available, the best description found is listed.
c. Specific information was not located; the solubility that is most favorable to the claimant should be applied.
d. Specific information was not located; the 5-µm default is assumed to apply.

5.11 FACILITY-SPECIFIC RADIONUCLIDE CONVERSIONS

The natural uranium fuel elements for the BGRR were reportedly fabricated by the BNL metallurgy group. The enriched uranium, aluminum-clad elements that replaced the natural fuel were apparently not fabricated at BNL. These data are summarized in Table 5-6.

Table 5-6. Facility-specific radionuclide conversions.

Process description	Activity per unit mass (Bq/g uranium)			
	U-234	U-235	U-236	U-238
BNL metallurgy group, natural U fuel fabrication, late 1940s and possibly up to 1958	1.26E+04	5.59E+02	negligible	1.21E+04

5.12 WORKPLACE MONITORING DATA

If bioassay data are not adequate to evaluate an individual's internal doses, dose reconstructors can use workplace monitoring data (NIOSH 2002). The following types of workplace data might be available for BNL: breathing zone air samples, general area air samples, and surface contamination surveys. However, these data are not likely to be in individual exposure records. Data on respirator use are not likely to be available. Fit testing records are Industrial Hygiene records maintained by the Safety and Health Services Division. In the case of surface contamination data, site/process-specific resuspension factors are not likely to be available. During the operation of the HFBR, the airborne tritium contamination had been between 1×10^{-6} µCi/cm^3 and 1×10^{-5} µCi/cm^3 on the equipment level. Since the shutdown, the concentration has been between 1×10^{-7} µCi/cm^3 and 5×10^{-7} µCi/cm^3 on the equipment level and between 1×10^{-8} µCi/cm^3 and 5×10^{-8} µCi/cm^3 on the operations level. A reasonable estimate of the maximum exposure can be made by assuming that an individual spends 4 hours/day on the operations level and 4 hours/day on the equipment level (BNL 1999).

5.13 SOURCE TERM DATA

Without bioassay or air sample data, the last resort is determination of airborne concentrations using source term evaluations (NIOSH 2002, p. 19). Data on the amount of dispersible material available does not appear to be available for BNL.

5.14 RADON

For dose reconstruction under EEOICPA, occupational radon exposure is exposure to radon emanating from sources other than those naturally occurring in the area. Dose reconstructors must subtract the natural background level of radon exposure from any measured values when assessing occupational exposure (NIOSH 2002, p. 32). BNL was not a processing or storage location for large quantities of ^{226}Ra or ^{222}Rn [15]. On-site environmental monitors occasionally detected low levels of ^{226}Ra between 1987 and 1996 (see Table 4-2). The source was likely the April 26, 1986 accident at the Chernobyl Nuclear Power Plant in Ukraine.

5.15 GUIDANCE FOR DOSE RECONSTRUCTORS

During the ER process NIOSH determined that bioassay data after 1979 was available from the site. Therefore if the energy employee has no bioassay data, it will be assumed that the energy employee didn't need to be monitored for internal exposure and only ambient environmental intakes need to be assigned. The following is some additional guidance for tritium dose assessments. If there is no bioassay and no tritium doses reported with external doses, then no tritium dose is assigned for any given year. If there is no tritium bioassay, but there is a tritium dose with the external report, use the larger of

- the reported dose (lognormal distribution with a GSD of 3) or
- the missed dose (triangular dist) based on the threshold at which BNL recorded bioassay results or calculated H-3 dose. Based on a review of the records, the threshold for calculating dose was 0.3 µCi/L. The annual missed dose based on the application of the 0.3 uCi would be 11 mrem (0, 0.011 and 0.022 would be the IREP input parameters).

6.0 OCCUPATIONAL EXTERNAL DOSIMETRY

6.1 INTRODUCTION

BNL was established to provide facilities for scientific research which, because of size, complexity or mode of operation were beyond the means of most single universities. In providing nuclear reactors and particle accelerators for its own staff and perhaps more importantly visiting scientists, emphasis was placed on a multidisciplinary approach to scientific questions. That same mode of operation is still in practice today.

6.2 PURPOSE

The purpose of this section is to describe the external dosimetry systems and practices at BNL, and to assist in the evaluation of occupational external exposures from processes that occur at BNL. An objective of this section is to provide supporting technical data to evaluate, with assumptions favorable to the claimant, occupational external doses that can reasonably be associated with radiation exposures to both the monitored and unmonitored worker.

6.3 SCOPE

This section presents historical and current practices in relation to the evaluation of external exposure data for monitored and unmonitored workers, and addresses the evaluation of worker exposure, missed dose, and the bias and uncertainty associated with the monitoring of external dose.

6.4 BNL DOSIMETRY PROGRAM

The Oak Ridge dosimeter was used and processed by BNL from start-up through 1984, at which time they switched to a vendor (Lane and Reciniello 2003). The vendor services continued through 1995. It should be noted that the dosimetry data through 1984 is available only as quarterly summaries, even though the badge exchange period was monthly.

In December 1995, BNL was DOELAP-accredited (Loesch 1995) and started its own program using the Harshaw 8814 and 8806 TLD dosimeters. At times, primarily in the accelerator facilities, these dosimeters were complemented with CR-39 as the neutron dosimeter (Sengupta 2000).

6.4.1 Neutron Dosimetry

The neutron doses were measured with NTA film from the beginning of operations through 1995, when it was replaced with TLD in combination with CR-39 and Lexan foils. The CR-39 and Lexan are analyzed by an outside vendor. Spallation products produced stars on the NTA film, and were evaluated by counting the number of prongs on the stars that were produced by those spallation products. The total number of prongs were counted and related to an effective neutron dose with the result added to the total neutron dose. It was found that the dose from these spallation products was very small. A relative biological effectiveness (RBE) and later a quality factor (QF) of 10 was used from the very beginning of operations of the accelerators and cyclotrons for these products (Cowan ca. 1953).

6.4.2 Special Dosimetry

On occasion, special dosimeters were worn to monitor nonroutine work that resulted in “significantly non-uniform doses to various areas of the whole body” (Sengupta 2000). The special dosimeters were worn without the regular dosimeter. The highest dose measured by the special dosimeters was the dose of record. All radiations measured were recorded as WB dose or dose equivalent. The

correct value for the RBE (later the QF) was determined to be conservative; because a value of 10 was always used (Patterson and Thomas 1964; Cowan 1963).

6.4.3 Lost or Destroyed Dosimeters

In the cases of lost or destroyed dosimeters, results were derived from past results of similar work, coworker results, or the product of instrument measurements and time spent in the radiation zone (Reciniello 2006).

6.5 MISSED DOSE

Missed doses for monitored employees at BNL are basically from dosimeter MDLs and exchange periods. In reviewing individual dose records, the exchange period and zeros for that individual can be determined. The review of individual records is necessary because exchange periods varied before 1955 (Cowan ca. 1953). This is applicable for both Hp (0.07) and Hp (10).

Another potential source of missed dose historically is possible error in determining true doses from high-energy particles. However, it has been determined that the values of the RBEs (and later QFs) used historically were conservative resulting in larger than actual true doses being recorded (Cowan ca. 1953, Cowan undated). Apparently all workers were issued dosimeters from startup through 1954 (Cowan ca. 1953).

Table 6-1 lists the period of use, type of dosimeter, exchange period, MDL, and estimated annual missed dose.

Table 6-1. Estimated annual missed photon, beta, and neutron dose (mrem).

Period of use	Dosimeter	MDL[a]	Exchange frequency	Maximum annual missed dose[b]
Startup–1954	Two-element film	30	Weekly Monthly	780 180
1955–1995	Multielement film	30	Monthly	180
1996–present	Harshaw 8814 TLD	10	Monthly	60
Startup–1995	NTA film[c]	<50	Weekly Monthly	1,300 300
1996–present	CR-39[c]	<20	Monthly	120

a. Estimated MDLs for each dosimeter in the workplace even though many doses were reported at less than the MDL.
b. Estimated annual missed dose calculated using MDL/2 from NIOSH (2007b).
c. Processing done by RS Landauer. Not routinely used after 2003.

6.5.1 Unmonitored Worker

Unmonitored workers are those workers who generally did not enter radiation zones or areas where work with radioactive materials was undertaken. These workers were not issued dosimeters based on the expectation that the probability of exceeding 10% of the allowable limit was small (Sengupta 2000). Therefore, these workers can be assigned doses as given in Table 4-1 of this document. All radiation workers were monitored from the startup of operations (Cowan ca. 1953).

Doses for unmonitored employees could be as much as 10% of the relevant standard which was 1500 mrem/yr (i.e., 300 mrem/wk) in the latter 1940s and then 500 mrem/yr from the early 1950s until 1987. In 1987, a 100 mrem/yr guideline was established before monitoring was required [16].

6.6 RADIATION ENERGIES AND PERCENTAGES AT SELECTED BNL FACILITIES

Section 2.0 describes the different types of facilities at BNL, including reactors, accelerators, and support facilities and target areas.

Tables 6-2 and 6-3 list the facilities and related data.

Table 6-2. Selection of beta (electron) and photon energies and percentages.

Process/building	Description	Operations		Radiation type	Energy (keV)	Percentage
		Begin	End			
BGRR	Reactor	1950	1969	Beta Photon	>15 30-250 >250	100 25 75
HFBR/750	Reactor	1965	1999			
BMRR/491	Reactor	1959	2000			
MRC490/490A	Radio-isotopes	1958	Present			
RTF/490	Accelerators	1991	<2006	Electron Photon	>15 >250	100 100
BLIP/931	Accelerator	1973	Present	Electron Photon	>15 30-250 >250	100 a a
PET/490	Accelerator	1977	Present	Electron Photon	>15 >250	100 100
Cosmotron/same	Cyclotron	1952	1966	Photon	30-250 >250	a a
RHIC/same	Accelerator	1999	Present			
AGS/same	Synchrotron	1960	Present	Photon	30-250 > 250	a a
AGS experimental area/912	Accelerator	1960	Present			
AGS ring/913		1960	Present			
AGS booster/942		1992	Present			
200 MeV Linear Accelerator/ 930	Accelerator	1972	Present			
Tandem Van de Graaff/901	Accelerator	1970	Present			
Tandem-to-Booster Beam Line/ Heavy Ion Beam tunnel	Accelerator	1991	Present			
Accelerator Test Facility/ 820	Accelerator	1989	Present	Electron Photon	>15 unknown	100 a
NSLS/725	Electron storage	1982	Present	Electron Photon	>15 30-250	100 100
Chemistry Dept./490A	Accelerator			Electron Photon	>15 unknown	100 a

a. General guidance is to use 100% 30 – 250 keV for overestimates, 100% >250 keV for underestimates, 50% each for best estimate.

Table 6-3. Beta and photon energies and percentages (support facilities).[a]

Process/building	Description	Operations		Radiation type	Energy (keV)	Percentage
		Begin	End			
NSRL	NASA Space Lab	2003	Present	Unknown	Unknown	Unknown
Tritium evaporator/802B	Tritium processing	1995	Present	Beta	<15 avg.	100
WCF/811	Waste processing	1947	1987	Beta Photon	>15 30-250 >250	100 25 75
TPL/801	Hot Laboratory	1951	Present			
HWMF/444	Incinerator	1970s	Early 1990s			
Chemistry Dept/555 & 490A	Chemistry R&D	1966	Present			
LEAF/555	Laser electron accelerator	1998	Present			
Biology/463	Biological R&D					

Process/building	Description	Operations		Radiation type	Energy (keV)	Percentage
		Begin	End			
Oceanographic Sciences/318	Oceanographic R&D					
Rad. Sciences/703, 703W	HP & Env. Support					
Nuclear Waste Mgt./830	Waste Handling					

a. The isotopes involved ranged from H-3 to Au-198 resulting in beta, electron, and photon energies ranging from a few 10s to several 1000s of keVs with wide ranging percentages.

6.7 NEUTRON RADIATIONS AND PERCENTAGES

Table 6-4 lists facilities with neutron radiations. They are reactors, accelerators, general laboratories, and medical facilities. The reactors are no longer in operation, the last being shut down in 2000.

Table 6-4. Facilities, neutron energies, percentages, and correction factors.

Facilities	Source	Neutron Energy (MeV)	Dose Fraction	ICRP 60[a] Correction Factor
BGRR, HFBR, BMRR	Reactors	0.1–2.0	100%	1.91
Cosmotron, AGS, RHIC, NSLS	Accelerators: Particle Interactions[b]	0.1–2.0	75%	1.91
		>2	25%	1.32
Medical, calibration, chemistry sources	^{252}Cf	0.1–2	100%	1.91
	AmBe, PuBe,	2–10	100%	1.32
	Weighted Average[c]	0.1–2	57%	1.66
		>2	43%	

a. ICRP (1991).
b. Select energy appropriate for facility and work activities.
c. Weighted average from alpha-neutron and spontaneous fission neutrons (ORAUT 2009).

Figures 6-1 and 6-2 show the neutron energy information upon which Table 6-4 is based. For Figure 6-1, measurements in the thermal column were normalized such that the flux in the bare thermal column was 7 X 10^8 n/cm^2/sec. The thermal flux in the instrument tunnel was 2 X 10^9 n/cm^2/sec. The converter plate was a U-235 plate used to convert the thermal beam into a fission spectrum.

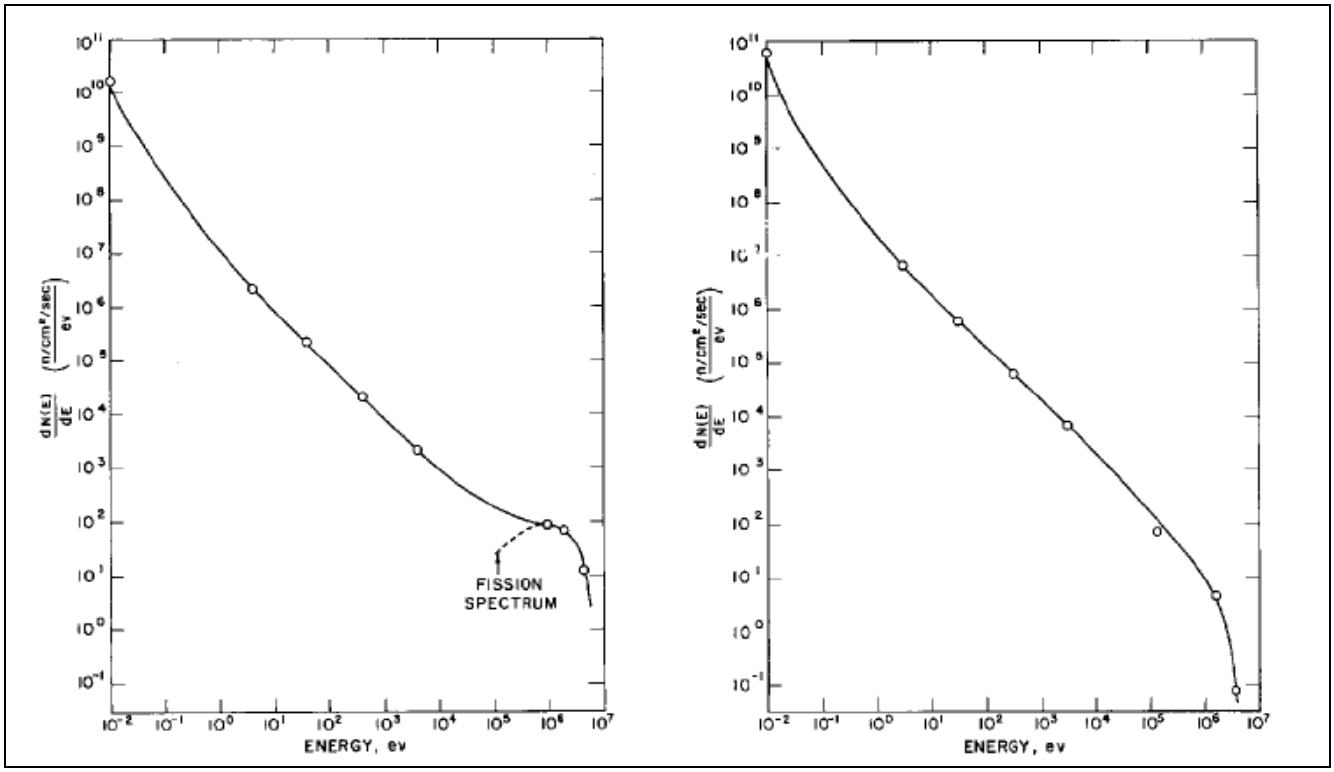

Figure 6-1. Neutron Spectrum in the Thermal Column with the Converter Plate (left) and in the Instrument Tunnel (right).

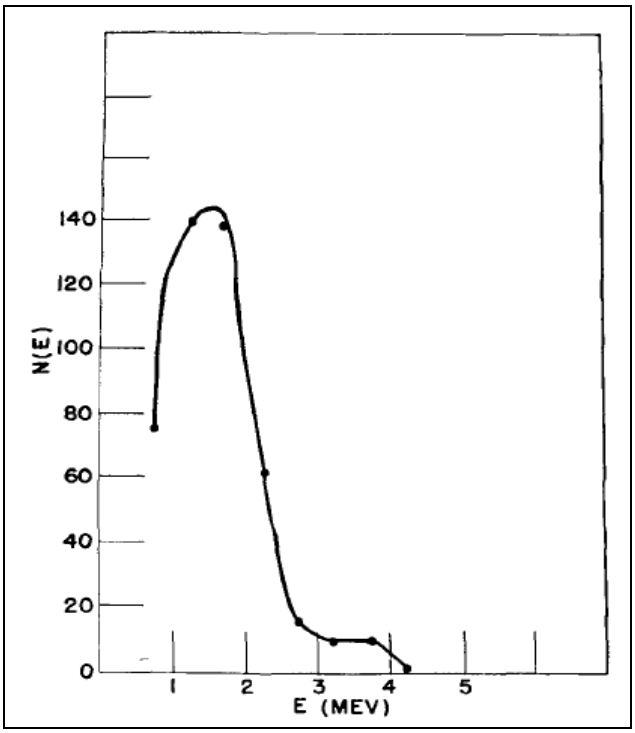

Figure 6-2. Neutron Energy Spectrum at the Cosmotron (Sanna 1963).

All potential neutron exposures of >100 mrem annually used NTA film through 1995. From start up to 1984, the NTA film was only processed if the density or darkening behind the cadmium (Cd) filter was greater than some predetermined value behind a photon equivalent, but neutron insensitive, filter (Faust 2010). This data could also be used to determine thermal neutron doses. Documentation of BNL's method has not been found, but it is thought to be consistent with the practices of other sites (Caruthers 1964, Strom 1982). Caruthers (1964) indicates that a difference in exposure behind the Cd and neutron insensitive filters of 20 mR would be equivalent to about 10 mrem from thermal neutrons. BNL included the dose from thermal and slow neutrons in their fast neutron results. Starting in 1996, the Harshaw 8806 TLD along with CR-39 was used at the accelerators (Lane and Reciniello 2003; Sengupta 2000). Recorded neutron doses include both thermal and fast neutrons generated by the accelerators with energies >100 MeV (Sengupta 2000). The actual "dose of record" always included a QF of 10 starting from the first day of operation (Cowan ca. 1953). DOE is in the process of implementing ICRP Publication 60 (ICRP 1991) neutron weighting factors into the routine determination of the recorded neutron dose. For BNL, the date this is scheduled to begin is July 1, 2010. Once this change is made, no adjustment in the recorded neutron dose (as described in the last column of Table 6-4) will be necessary, thereafter.

6.8 RECORDED DOSE PRACTICES

Recorded dose practices at BNL are given in Table 6-5 and include those provided by both the site and its vendor and any special dosimeter results (Sengupta 2000). Special dosimeters were worn if needed due to abnormal conditions, such as highly directional beams. If more than one dosimeter was required, the highest value was recorded. The regular dosimeter was not worn on these occasions (Sengupta 2000).

Table 6-5. Recorded dose practices.

1949–1984	Beta=Open window, mrem[a] Photon (P), mR Fast Neutron (FN), mrem	Skin = OW+P WB = P+ FN+ tritium
1985–1995	Beta or nonpenetrating, mrem Photon (P), mrem Fast Neutron (FN), mrem	Skin = NP + P WB = NP + P + FN + tritium
1996–present	Beta or nonpenetrating, mrem Photon (P), mrem Fast Neutron (FN), mrem	Skin = NP + WB WB = P + NP + FN + tritium

a. At startup, mrep was used interchangeably with mR, mrad, and later mrem.
b. Attached to either dosimeter when neutrons might be present.

6.9 INTERPRETATION OF REPORTED DOSES

Early personnel doses were reported in units of mrep for both penetrating (photon) and nonpenetrating (beta) if beta or low-energy electrons were present. High-energy beta or electrons were recorded as penetrating dose. The recorded total doses include the results from any special dosimeters worn for that exchange period. If it is necessary to obtain organ doses, dose reconstructors should use *External Dose Reconstruction Implementation Guidelines* (NIOSH 2007b).

Table 6-6 lists the interpretation of the reported data by period. Reported doses have been corrected for background using site controls. The controls are dosimeters kept on site in locations used for the storage of personnel dosimeters. All issued dosimeters were stored on storage racks at positions throughout the site. Dosimeters were not to be taken home at the end of the shift, a practice beginning at the startup of the site and continuing at present (Sengupta 2000).

Table 6-6. Interpretation of reported data.

Period	Reported quantity	Description	Interpretation of zeros	Interpretation of blanks	Rollup of individual and annual data	Monitored/ unmonitored
Startup –1985	Skin = mrad WB =mR Neutrons = mrem	mrep (about startup) mR, mrad, and mrem used interchangeably	MDL/2 times number of zeros	If no dosimeter for that period, treat as unmonitored.	If special dosimeters were used, include results.	Only those >10% of standards were monitored. Those entering controlled areas were issued visitors' dosimeters.
1986–present	Skin=mrem WB= mrem Neutrons=mrem	mrem used for all.	MDL/2 times number of zeros	If no dosimeter for that period, treat as unmonitored.	If special dosimeters were used, include results.	All personnel expected to be exposed to >100 mrem in an exchange period were monitored.

6.10 ADJUSTMENTS TO RECORDED DOSE

Because most but not all penetrating photons are above 30 keV, it is suggested that an adjustment is necessary to account for the contribution to Hp(10) from the lower energy photons. It is estimated that a correction equal to 10% of the <250-keV values be made. Corrections are made for each energy group. Table 6-2 should be consulted for the applicable facility specific energy fractions. The NSLS photons are all considered to be in the lower energy group [measurements indicate a peak at 75 keV (Preisig 1997)]. These adjustments also increase Hp(0.07) because that dose was always the sum of the open-window (OW) and WB doses. Table 6-7 lists the corrections. The fading correction for NTA film is about 9%/week (Meyer 1994), and the angular dependence correction factor is 1.3 (Kathren 1965).

Table 6-7. Adjustments to recorded dose.

Period	Facility	Adjustment to reported dose	
		Photon energy	Multiply by
Startup–1985	Reactors	30-250 keV	1.1
		> 250 keV	1.0
1958–present	MRC 490/490A	30-250 keV	1.1
		> 250 keV	1.0
1982–present	NSLS	30-250 keV	1.1

6.11 BIAS AND UNCERTAINTY

No site-specific data has been found about the bias and uncertainty for 1947 to 1984 when BNL used in-house film badges with NTA film. BNL did participate in some film badge performance tests in the mid-1960s, which can be used as an indication of the performance that was achieved.

In one test, 12 commercial film badges suppliers and two national laboratories were included in a blind intercomparison study of the accuracy and consistency of film badge readings that were exposed in March 1963. BNL was one of the national laboratories according to the acknowledgements. The national laboratories were not tested for consistency (precision), but their performance was consistent with the better-performing group of commercial processors. The study concluded that the accuracy that could be reasonably expected in practice, with a confidence limit of 90%, was in the range of –50% to +200% for groups of badges exposed to X-rays, gamma rays, and

mixtures thereof, over the exposure range of approximately 20 mR to 8,000 mR (Gorson, Suntharalingam, and Thomas 1965).

A 1967 study to determine film dosimeter performance criteria included participants from 15 AEC laboratories (Unruh et al. 1967). Although the results did not identify the laboratories, it is logical that BNL would have participated. Averaged over all radiation categories about 90% of the tests were passed by AEC contractors. The bias performance criterion was 90% to 110% (within 10%).

The uncertainty factors in Table 6-8 are proposed based on judgment of uncertainty of dosimeter performance in the site-specific fields for the period from start-up to 1984.

Table 6-8. Uncertainty factors.

Dosimeter	Uncertainty Factor[a]
Two-element film dosimeter (1947–1963)	1.4
Multi-element Film (1964–1984)	1.3
NTA Film (1954–1984) (2–14 MeV)	1.3
NTA Film (1954–1984) (0.1–2 MeV)	1.5

a Estimated variability of measured dose based on dosimeter technology as used in site radiation fields for long term workers.

In 1985, BNL contracted with R. S. Landauer Company for film badge services. The following table is a summary of the specifications from Landauer in 1988 (Schopfer 1988).

A few reports of quality control checks on Landauer's performance were located. A report from 1986 showed that Landauer was generally able to meet the "mean accuracy" specification (Schopfer 1986). In a 1988 report, the bias (average relative error) over the whole test range (up to 5000 mrem) for beta-gamma, CR-39, NTA and Lexan dosimeters was –0.09, –0.02, –0.17, and –0.03, respectively. It was noted, however, that the precision in this test failed to meet expectations (Schopfer 1988).

Table 6-9. Landauer gamma film, NTA film, and CR-39 specifications.

Radiation Category	Source Used	Range (mrem)	Mean Accuracy[a] (mrem)	Precision (1 σ)
High Energy Photon	Cs-137	50	20	20 mrem
		500	50	10%
		5000	500	10%
High Energy X-ray		50	20	20 mrem
		500	75	15%
		5000	750	15%
Low Energy X-ray	Am-241 15-20 keV 55-65 keV	50	20	20 mrem
		500	75	25%
		5000	750	25%
Fast Neutron NTA	AmBe	50	20	20 mrem
		500	100	20%
		5000	1000	15%
Fast Neutron CR-39	AmBe	50	20	20 mrem
		500	100	20%
		5000	1000	15%

a. Mean accuracy is the limit of the average difference of result of a group of dosimeters from the delivered exposure or dose.

In December 1995, BNL received DOELAP accreditation in external dosimetry (Loesch 1995). In 1996, the Landauer film badge service was replaced by TLD system processing on site. The

Landauer-supplied CR-39 and Lexan dosimeters were discontinued after June 1997. Bias and uncertainty from 1996 on are expected to be consistent with DOELAP standards.

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. Conventional References, which are provided in the next section of this document, link data, quotations, and other information to documents available for review on the Project's Site Research Database (SRDB).

[1] Potter, Eugene. M. H. Chew & Associates. Principal Health Physicist. November 2009. Figure 2-2 was taken from a BNL document that has since been removed from the BNL web site. It was annotated by the section's author with names and arrows that point out the major radioactive material and radiation-producing facilities. This figure is similar to figures that appear in a number of BNL site environmental reports, which may be consulted for comparison.

[2] Elyse Thomas. ORAUT Team. Principal Medical Dosimetrist. December 2009. Review of claim file records from BNL.

[3] Elyse Thomas. ORAUT Team. Principal Medical Dosimetrist. December 2009. Review of claim file records from BNL.

[4] Elyse Thomas. ORAUT Team. Principal Medical Dosimetrist. December 2009. Review of claim file records from BNL.

[5] Robert Morris. ORAUT Team. Principal Health Physicist. August 2006 Review of actual films at BNL.

[6] Robert Morris. ORAUT Team. Principal Health Physicist. August 2006 Review of actual films at BNL.

[7] Potter, Eugene. M. H. Chew & Associates. Principal Health Physicist. November 2009. Conclusions were based on a review of the environmental reports listed in the References at the end of this revision.

[8] Potter, Eugene. M. H. Chew & Associates. Principal Health Physicist. November 2009. The factor of 1.5 is suggested in ORAUT-PROC-0031 and is not accounted for separately in the tool used for dose reconstruction.

[9] Potter, Eugene. M. H. Chew & Associates. Principal Health Physicist. November 2009. A reduction factor of 0.01 was selected as a conservative value after considering a number of different scenarios and typical values as input to atmospheric transport models.

[10] Potter, Eugene. M. H. Chew & Associates. Principal Health Physicist. November 2009. This statement is based on professional judgment after reviewing the available data in a number of references.

[11] Potter, Eugene. M. H. Chew & Associates. Principal Health Physicist. November 2009. The uncertainty range values quoted are based on professional judgment and experience.

[12] Potter, Eugene. M. H. Chew & Associates. Principal Health Physicist. November 2009. These conclusions are based on the review of a number of whole body count results in individual dosimetry files.

[13] Potter, Eugene. M. H. Chew & Associates. Principal Health Physicist. November 2009. These conclusions are based on the review of a number of whole body count results in individual dosimetry files, as well as other records and interviews.

[14] Potter, Eugene. M. H. Chew & Associates. Principal Health Physicist. November 2009. These conclusions are based on the review of a number of bioassay data packages and whole body count records.

[15] Potter, Eugene. M. H. Chew & Associates. Principal Health Physicist. November 2009. Based on a review of records and site interviews.

[16] Potter, Eugene. M. H. Chew & Associates. Principal Health Physicist. November 2009. This statement is based on the historical monitoring thresholds.

REFERENCES

AEC (U.S. Atomic Energy Commission), 1949, *Monthly Status and Progress Report for April 1949*, New York Operations Office, New York, New York, May 10. [SRDB Ref ID: 6291, p. 93]

AEC (U.S. Atomic Energy Commission), 1949a, *Monthly Status and Progress Report for January 1949*, New York Operations Office, New York, New York, February 7. [SRDB Ref ID: 6291, p. 1]

AEC (U.S. Atomic Energy Commission), 1949b, *Monthly Status and Progress Report for February 1949*, New York Operations Office, New York, New York, March 8. [SRDB Ref ID: 6291, p. 25]

AEC (U.S. Atomic Energy Commission), 1949c, *Monthly Status and Progress Report for March 1949*, New York Operations Office, New York, New York, April 7. [SRDB Ref ID: 6291, p. 55]

AEC (U.S. Atomic Energy Commission), 1949e, *Monthly Status and Progress Report for September 1949*, New York Operations Office, New York, New York, October 10. [SRDB Ref ID: 6291, p. 124]

AEC (U.S. Atomic Energy Commission), 1950, *Monthly Status and Progress Report for December 1949*, New York Operations Office, New York, New York, January 5. [SRDB Ref ID: 6291, p. 217]

AEC (U.S. Atomic Energy Commission), 1955, urinalysis report for Sample A8962, Form N.Y. 99, New York Operations Office, New York, New York, July 20. [SRDB Ref ID: 6274]

AEC (U.S. Atomic Energy Commission), 1957, urinalysis report for Sample B1300, Form N.Y. 99, New York Operations Office, New York, New York, December 16. [SRDB Ref ID: 6302, p. 5]

AEC (U.S. Atomic Energy Commission), 1958, urinalysis report for Sample A6352, Form N.Y. 99, New York Operations Office, New York, New York, October 14. [SRDB Ref ID: 6302, p. 8]

AEC (U.S. Atomic Energy Commission), 1961, urinalysis report for Sample D1780, Form N.Y. 99, New York Operations Office, New York, New York, August 28. [SRDB Ref ID: 6302, p. 28]

AEC (U.S. Atomic Energy Commission), 1962, urinalysis report for Sample D607, Form N.Y. 99, New York Operations Office, New York, New York, August 14. [SRDB Ref ID: 6302, p. 32]

AEC (U.S. Atomic Energy Commission), 1963, urinalysis report for Sample D756, Form N.Y. 99, New York Operations Office, New York, New York, April 16. [SRDB Ref ID: 6302, p. 35]

Astarita Associates, 1998–2004, collection of reports on Patient Radiographic Skin Doses, Smithtown, New York. [SRDB Ref ID: 22528]

Bishop, W. H. Jr., 1958, "Progress Report," memorandum to L. Gemmell, Associated Universities, Brookhaven National Laboratory, Upton, New York, April 8. [SRDB Ref ID: 22919, p. 7]

BNL (Brookhaven National Laboratory), undated, excerpt from *HFBR Safety Analysis Report: Radioactive Wastes and Effluents*, Upton, New York. [SRDB Ref ID: 22464]

BNL (Brookhaven National Laboratory), 1951, *Health Physics Summary for August, 1951*, Associated Universities, Upton, New York, August. [SRDB Ref ID: 22848, p. 8]

BNL (Brookhaven National Laboratory), 1952, *Health Physics Summary for May 1952*, Associated Universities, Upton, New York, May. [SRDB Ref ID: 22915, p. 6]

BNL (Brookhaven National Laboratory), 1963, *Heath Physics and Safety Summary for May 1963*, Associated Universities, Upton, New York, Undated. [SRDB Ref ID: 6517, p. 96]

BNL (Brookhaven National Laboratory), 1972, *1971 Environmental Monitoring Report*, Associated Universities, Upton, New York, July. [SRDB Ref ID: 6356]

BNL (Brookhaven National Laboratory), 1973, *Safety Policy Manual*, Brookhaven National Laboratory, Upton, New York, April. [SRDB Ref ID: 22479]

BNL (Brookhaven National Laboratory), 1993, "8.7 Internal Monitoring," RD APM 8.7, Rev. 0, Associated Universities, Upton, New York, August 13. [SRDB Ref ID: 55393]

BNL (Brookhaven National Laboratory), 1995, "Radiological Health Support Operations," Chapter 5, *Radiological Control Manual*, Associated Universities, Brookhaven National Laboratory, Upton, New York, November 20. [SRDB Ref ID: 22455]

BNL (Brookhaven National Laboratory), 1997a, *Review of Potential Environmental Release Points, Draft, Directors Office Building 701/BGRR*, Associated Universities, Upton, New York. [SRDB Ref ID: 77713]

BNL (Brookhaven National Laboratory), 1997b, *Review of Potential Environmental Release Points, Directors Office Buildings 701, 704, 708, 709*, Rev. 1, Associated Universities, Upton, New York. [SRDB Ref ID: 77712]

BNL (Brookhaven National Laboratory), 1997c, *Review of Potential Environmental Release Points, Department/Division -Reactor Building/Facility -750/HFBR, 707A/Pumphouse, 707B/Water Treatment House & Cooling Towers*, Associated Universities, Upton, New York June 2. [SRDB Ref ID: 77716]

BNL (Brookhaven National Laboratory), 1997d, *Review of Potential Environmental Release Points, Medical Department/490*, Rev. 1, Associated Universities, Upton, New York. [SRDB Ref ID: 77702]

BNL (Brookhaven National Laboratory), 1997e, *Review of Potential Environmental Release Points, Reactor Division, Building 491/Brookhaven Medical Research Reactor*, Associated Universities, Upton, New York, July. [SRDB Ref ID: 77703]

BNL (Brookhaven National Laboratory), 1997f, *Review of Potential Environmental Release Points, Chemistry Department, Building 906*, Associated Universities, Upton, New York. [SRDB Ref ID: 77720]

BNL (Brookhaven National Laboratory), 1997g, *Review of Potential Environmental Release Points, RHIC Project, Building 902 Complex*, Associated Universities, Brookhaven National Laboratory, Upton, New York, June 18. [SRDB Ref ID: 77719]

BNL (Brookhaven National Laboratory), 1997h, *Review of Potential Environmental Release Points, AGS Department, Building Forms: Level I, II & III,* Associated Universities, Upton, New York, June. [SRDB Ref ID: 77723]

BNL (Brookhaven National Laboratory), 1997i, *Review of Potential Environmental Release Points, RHIC Project, Building 960 Complex*, Associated Universities, Brookhaven National Laboratory, Upton, New York, June 18. [SRDB Ref ID: 77722]

BNL (Brookhaven National Laboratory), 1997j, *Review of Potential Environmental Release Points, Medical Department, Building 931*, Associated Universities, Upton, New York. [SRDB Ref ID: 77721]

BNL (Brookhaven National Laboratory), 1997k, *Review of Potential Environmental Release Points, Chemistry Department, Building 901*, Associated Universities, Brookhaven National Laboratory, Upton, New York, May. [SRDB Ref ID: 77718]

BNL (Brookhaven National Laboratory), 1997l, *NSLS Building 725 Final Facility Review Report, NSLS,* Associated Universities, Upton, New York. [SRDB Ref ID: 77714]

BNL (Brookhaven National Laboratory), 1997m, *NSLS Building 729 Final Facility Review Report*, NSLS, Associated Universities, Upton, New York, June 17. [SRDB Ref ID: 77715]

BNL (Brookhaven National Laboratory), 1997n, *Review of Potential Environmental Release Points, RHIC Project, RHIC Complex*, Associated Universities, Brookhaven National Laboratory, Upton, New York, June. [SRDB Ref ID: 77724]

BNL (Brookhaven National Laboratory), 1997o, *Review of Potential Environmental Release Points, Medical Department/Division, Building/Facility: Building 801*, Rev. 2, Associated Universities, Upton, New York, July 25. [SRDB Ref ID: 71622]

BNL (Brookhaven National Laboratory), 1997p, *Review of Potential Environmental Release Points, Department of Advanced Technology, Building 830*, Associated Universities, Upton, New York, June. [SRDB Ref ID: 77717]

BNL (Brookhaven National Laboratory), 1997q, *Review of Potential Environmental Release Points, Chemistry Department, Building 555*, Associated Universities, Upton, New York, June. [SRDB Ref ID: 77707]

BNL (Brookhaven National Laboratory), 1997r, *Review of Potential Environmental Release Points, Physics Department, Building 510 Including Trailers*, Associated Universities, Upton, New York, September. [SRDB Ref ID: 77704]

BNL (Brookhaven National Laboratory), 1997s, *Review of Potential Environmental Release Points, RHIC Project Buildings 620, 820, 835, 836*, Associated Universities, Upton, New York, June. [SRDB Ref ID: 77708]

BNL (Brookhaven National Laboratory), 1997t, *Review of Potential Environmental Release Points, Physics Department/Division Central Shops, Division Building/Facility 530*, Associated Universities, Upton, New York, June. [SRDB Ref ID: 77705]

BNL (Brookhaven National Laboratory), 1997u, *Review of Significant Environmental Release Issues, Instrument Division, Building 535*, Associated Universities, Upton, New York, June. [SRDB Ref ID: 77706]

BNL (Brookhaven National Laboratory), 1997v, *Review of Potential Environmental Release Points, Safety & Environmental Protection Division Bldg. 855, 860, 865 and 870*, Associated Universities, Upton, New York, June. [SRDB Ref ID: 77725]

BNL (Brookhaven National Laboratory), 1997w, *Review of Potential Environmental Release Points*, Safety & Environmental Protection/Plant Engineering, Building 650-650T/Radiological Waste Decontamination & Hot Laundry Facility, Associated Universities, Upton, New York, August. [SRDB Ref ID: 77709]

BNL (Brookhaven National Laboratory), 1999, *1998 Site Environmental Report*, BNL-52572, Brookhaven Science Associates, Upton, New York, September. [SRDB Ref ID: 6478]

BNL (Brookhaven National Laboratory), 1999, *Tritium Dose to HFBR Personnel, July-December 1999*, Brookhaven Science Associates, Upton, New York. [SRDB Ref ID: 22425]

BNL (Brookhaven National Laboratory), 2000, *1999 Site Environmental Report*, BNL-52585, Brookhaven Science Associates, Upton, New York, August. [SRDB Ref ID: 6480]

BNL (Brookhaven National Laboratory), 2001a, *2000 Site Environmental Report*, BNL-52626, Brookhaven Science Associates, Upton, New York, September. [SRDB Ref ID: 6484]

BNL (Brookhaven National Laboratory), 2001b, *Technical Basis for the BNL Internal Dosimetry Program*, Rev. 3, Brookhaven Science Associates, Upton, New York, March 29. [SRDB Ref ID: 22519]

BNL (Brookhaven National Laboratory), 2002, *2001 Site Environmental Report*, BNL-52671, Brookhaven Science Associates, Upton, New York, September. [SRDB Ref ID: 33177]

BNL (Brookhaven National Laboratory), 2003, *2002 Site Environmental Report*, BNL-71521-2003, Brookhaven Science Associates, Upton, New York, October. [SRDB Ref ID: 33167]

BNL (Brookhaven National Laboratory), 2004, *2003 Site Environmental Report*, BNL-73160-2004, Brookhaven Science Associates, Upton, New York. [SRDB Ref ID: 33169]

BNL (Brookhaven National Laboratory), 2005, *2004 Site Environmental Report*, BNL-74909-2005, Brookhaven Science Associates, Upton, New York, October. [SRDB Ref ID: 33171]

BNL (Brookhaven National Laboratory), 2009a, "Image Library," Brookhaven Science Associates, Upton, New York, March 9. [SRDB Ref ID: 79734]

BNL (Brookhaven National Laboratory), 2009b, "The Physics of RHIC," Brookhaven Science Associates, Upton, New York, March 9. [SRDB Ref ID: 79735]

Bond, V. P., 1963, "Medical Examinations of Reactor Operators," memorandum to C. Williams, Associated Universities, Brookhaven National Laboratory, Upton, New York, January 29. [SRDB Ref ID: 53887]

Brodksy, A., 1964, minutes of meetings. [SRDB Ref ID: 17344]

Carter, E. N., 1975a, "Progress Report May/June, 1975," memorandum to C. W. Flood, Associated Universities, Brookhaven National Laboratory, Upton, New York, September 24. [SRDB Ref ID: 22832, p. 8]

Carter, E. N., 1975b, "Progress Report January/February, 1975," memorandum to C. W. Flood, Associated Universities, Brookhaven National Laboratory, Upton, New York, April 3. [SRDB Ref ID: 22832, p. 16]

Carter, J., 1978, "Radiation Protection Guidance to Federal Agencies for Diagnostic X Rays," *Federal Register*, volume 43, number 22, February 1. [SRDB Ref ID: 8141]

Carter, N., 1978, "X-Ray Exposures," memorandum to R. Fairchild, Associated Universities, Brookhaven National Laboratory, Upton, New York, October 11. [SRDB Ref ID: 53909]

Caruthers, L. T. and Story, E. J., 1964, "Capture Gammas for Neutron Dosimetry with a Film Badge," *Health Physics*, volume 10, September, pp. 667-672

Conrad, R. D., 1948, "Medical Department X-Ray Exposure Records." [SRDB Ref ID 55355]

Cooley, R. C, 1967, "Personnel Radiation Exposures from Medical X-rays – Savannah River Plant – Part II," memorandum to E. C. Morris, July 11. [SRDB Ref ID: 68124]

Cowan, F. P., 1948, "X-Ray Exposure Records," memorandum to R. D. Conrad, Associated Universities, Brookhaven National Laboratory, Upton, New York, April 28. [SRDB Ref ID: 55356].

Cowan, F. P., 1948, "X-Ray Exposure Records," memorandum to R. D. Conrad, Associated Universities, Brookhaven National Laboratory, Upton, New York, April 26. [SRDB Ref ID: 55356].

Cowan, F. P., 1957a, "Radiation Safety in a Research Laboratory," Associated Universities, Brookhaven National Laboratory, Upton, New York, May. [SRDB Ref ID: 22501]

Cowan, F. P., 1957b, "P^{32} Spill of April 23, 1957," memorandum to J. B. H. Kuper, Associated Universities, Brookhaven National Laboratory, Upton, New York, June 7. [SRDB Ref ID: 6319, p. 85]

Cowan, F. P., 1963, "Personnel Dosimetry of Very-High Energy Radiations," *Symposium On Personnel Dosimetry Techniques For External Radiation, Madrid, 1st - 5th April 1963*, European Nuclear Energy Agency and Junta de Energia Nuclear, p. 273. [SRDB Ref ID: 22498]

Cowan, F. P., ca. 1953, "A Preliminary Report on Health Physics Problems at the Brookhaven Alternating Gradient Synchrotron," *Colloque sur la Protection Aupres des Grands Accelerateurs*, p. 143. [SRDB Ref ID: 22497]

Cowan, F. P., undated, *Health Physics Program for the Brookhaven National Laboratory Synchrotrons*, Associated Universities, Brookhaven National Laboratory, Upton, New York. [SRDB Ref ID: 22490]

Cowan, F. P., L. B. Farabee, and R. A. Love, 1952, "Health Physics and Medical Aspects of a Strontium 90 Inhalation Incident," *The American Journal of Roentgenology and Radium Therapy*, volume 67, number 5. pp. 805–809. [SRDB Ref ID: 22543]

Cowan, F. P., and J. S. Handloser, 1953, *Health Physics Program for the Brookhaven Cosmotron*, BNL-264, Associated Universities, Brookhaven National Laboratory, Upton, New York, November. [SRDB Ref ID: 22516]

Cowan, F. P., L. F. Phillips, and R. J. King, 1963, *Some Dosimetry Problems of the Alternating Gradient Synchrotron (AGS)*, BNL 7151, Associated Universities, Brookhaven National Laboratory, Upton, New York, July 1. [SRDB Ref ID: 22492]

Cowan, F. P., and J. Weiss, 1957, "Bioassay Data and Analysis Relating to the P^{32} Spill of April 23, 1957," memorandum to R. A. Love, Associated Universities, Brookhaven National Laboratory, Upton, New York, June 7. [SRDB Ref ID: 6319, p. 80]

Crease, R. P., 1999, *Making Physics, A Biography of Brookhaven National Laboratory, 1946–1972*, University of Chicago Press, Chicago, Illinois. [SRDB Ref ID: 23541]

Day, L. E., and J. R. Naidu, editors, 1983, *1982 Environmental Monitoring Report*, BNL 51697, Associated Universities, Brookhaven National Laboratory, April. [SRDB Ref ID: 6405]

Day, L. E., and J. R. Naidu, editors, 1984, *1983 Environmental Monitoring Report*, BNL 51827, Associated Universities, Brookhaven National Laboratory, Upton, New York, June. [SRDB Ref ID: 6409]

Day, L. E., R. P. Miltenberger, and J. R. Naidu, editors, 1985, *1984 Environmental Monitoring Report*, BNL 51884, Associated Universities, Brookhaven National Laboratory, Upton, New York, April. [SRDB Ref ID: 6414]

Day, L. E., R. P. Miltenberger, and J. R. Naidu, editors, 1986, *1985 Environmental Monitoring Report*, BNL 51993, Associated Universities, Brookhaven National Laboratory, Upton, New York, April. [SRDB Ref ID: 6426]

DOE (U.S. Department of Energy), 1999, *Draft Environmental Impact Statement for the High Flux Beam Reactor Transition Project at the Brookhaven National Laboratory, Brookhaven National Laboratory, Upton, New York*, Office of Basic Energy Sciences, Germantown, Maryland, April. [SRDB Ref ID: 22517]

Eisenbud, M., 1957, "Explosion at Brookhaven National Laboratory," memorandum to K. E. Fields, U.S. Atomic Energy Commission, New York Operations Office, New York, New York, June 7. [SRDB Ref ID: 6319, p. 31]

ERDA (Energy Research and Development Administration), 1977, *Final Environmental Impact Statement, Brookhaven National Laboratory*, Upton, New York, ERDA-1540, Washington D.C., July. [SRDB Ref ID: 6384]

Faust, L. G., 2010, "NTA Film Usage," documented communication with H. Kahnhauser., Oak Ridge Associated Universities Team, Oak Ridge, Tennessee. March 26. [SRDB Ref ID: 80141]

Flood, C., 1976, "Health Protection and Health Surveillance," memorandum to V. Pai, Associated Universities, Brookhaven National Laboratory, Upton, New York, May 17. [SRDB Ref ID: 55020].

Gorson, R. O., N. Suntharalingam, and J. W. Thomas, 1965, "Results of a Film-Badge Reliability Study," unknown journal, volume 84, February, pp. 333–346. [SRDB Ref ID: 15022]

Handloser, J. S., ca. 1959, *Stray Radiation Dosimetry Around Pulsed Accelerators*, BNL 3519, Associated Universities, Brookhaven National Laboratory, Upton, New York. [SRDB Ref ID: 22500]

Handloser, J. S., and R. A. Love, 1951, "Radiation Doses from Diagnostic X-Ray Studies," *Radiology*, volume 57, pp. 252–254. [SRDB Ref ID: 13354]

Hardy, H.; Hodges, H.; and Wolf, B. S., 1948, "Tentative Program for Control of Beryllium Hazard in AEC Contracts," memorandum with attachment to S. Warren (Washington, D.C.), U.S. Atomic Energy Commission, New York Operations Office, August 4. [SRDB Ref ID: 11318, p. 74]

Haworth, L. J., 1960, untitled letter to E. L. Van Horn (U.S. Atomic Energy Commission, Brookhaven Area Office), Associated Universities, Brookhaven National Laboratory, Upton, New York, September 29. [SRDB Ref ID: 6271]

Holeman, G. R., 1994, *Personnel Monitoring External Dosimetry Quality Assurance Plan*, PM-QAP-001, Rev. 0, Associated Universities, Brookhaven National Laboratory, Upton, New York, December 27. [SRDB Ref ID: 22787]

Holeman, G. R., 1999, "A Document Describing the External and Internal Dosimetry Programs," e-mail with attachment to H. F. Kahnhauser, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, March 24. [SRDB Ref ID: 22477]

Hull, A. P., 1963, *1962 Environmental Radiation Levels at Brookhaven National Laboratory*, BNL 807, Associated Universities, Brookhaven National Laboratory, Upton, New York, May. [SRDB Ref ID: 6330]

Hull, A. P., 1964, *1963 Environmental Radiation Levels at Brookhaven National Laboratory*, BNL 915, Associated Universities, Brookhaven National Laboratory, Upton, New York, November. [SRDB Ref ID: 6333]

Hull, A. P., 1966, *1964 Environmental Radiation Levels at Brookhaven National Laboratory*, BNL 50001, Associated Universities, Brookhaven National Laboratory, Upton, New York, June. [SRDB Ref ID: 6334]

Hull, A. P., editor, 1973, *1972 Environmental Monitoring Report*, BNL 17874, Associated Universities, Brookhaven National Laboratory, Upton, New York, May. [SRDB Ref ID: 6359]

Hull, A. P., and J. A. Ash, editors, 1974, *1973 Environmental Monitoring Report*, BNL 18625, Associated Universities, Brookhaven National Laboratory, Upton, New York, March. [SRDB Ref ID: 6360]

Hull, A. P., and J. A. Ash, editors, 1975, *1974 Environmental Monitoring Report*, BNL-19977, Associated Universities, Brookhaven National Laboratory, Upton, New York, April. [SRDB Ref ID: 6362]

Hull, A. P., and J. A. Ash, editors, 1976, *1975 Environmental Monitoring Report*, BNL-21320, Associated Universities, Brookhaven National Laboratory, Upton, New York, March. [SRDB Ref ID: 6369]

Hull, A. P., and J. T. Gilmartin, 1967, *1965 Environmental Radiation Levels at Brookhaven National Laboratory*, BNL 50093, Associated Universities, Brookhaven National Laboratory, Upton, New York, September. [SRDB Ref ID: 6340]

Hull, A. P., and J. T. Gilmartin, 1969, *1966 Environmental Radiation Levels at Brookhaven National Laboratory*, BNL 50196, Associated Universities, Brookhaven National Laboratory, Upton, New York, September. [SRDB Ref ID: 6353]

ICRP (International Commission on Radiological Protection), 1975, *Reference Man: Anatomical, Physiological and Metabolic Characteristics*, Publication 23, Pergamon Press, Oxford, England.

ICRP (International Commission on Radiological Protection), 1983, *Protection of the Patient in Diagnostic Radiology*, Publication 34, Pergamon Press, Oxford, England.

ICRP (International Commission on Radiological Protection), 1991, *1990 Recommendation of the International Commission on Radiological Protection*, Publication 60, Pergamon Press, Oxford, England.

Kathern R. L., Prevo, C. T., and Block, S., 1965, "Angular Dependence Of Eastman Type A (NTA) Personnel Monitoring Film," *Health Physics*, volume 11, October, pp. 1067–1069.

Lane, G., and R. Reciniello, 2004, "Brookhaven National Laboratory, e-mail - Georgette Lane and Richard Reciniello 12/22/2003 and 3/31/2004." [SRDB Ref ID: 18040]

Lee, R. J., J. R. Naidu, G. L. Schroeder, D. E. Paquette, S. Scarpitta, R. Howe, W. Dorsch, A. Bou, and W. Gunther, 1999, *Brookhaven National Laboratory Site Report for Calendar Year 1997*, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, February. [SRDB Ref ID: 6471]

Lessard, E. T., C. Schaefer, and R. Karol, 2001, *Technical Basis for Bioassay Requirements, Collider-Accelerator Department*, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, January 22. [SRDB Ref ID: 22428, p. 10]

Loesch, R. M., 1995, "Laboratory Accreditation of Brookhaven National Laboratory (BNL) Personnel Dosimetry,", memorandum to C. L. Nealy (Brookhaven Area Office), U.S. Department of Energy, Office of Worker Protection Programs and Hazards Management, Washington, D.C., December 12. [SRDB Ref ID: 22457]

Love, R. A., 1957, untitled letter to B. A. Brundage (Atomics International), Associated Universities, Brookhaven National Laboratory, Upton, New York, November 13. [SRDB Ref ID: 53880]

Love, R. A., 1959, untitled letter to T. M. Fleidner (Universitat Heidelberg), Associated Universities, Brookhaven National Laboratory, Upton, New York, September 25. [SRDB Ref ID: 53618]

Love, R. A., 1963, untitled letter to C. L. Gilbert (Columbia University), Associated Universities, Brookhaven National Laboratory, Upton, New York, November 19. [SRDB Ref ID: 53891]

Love, R. A., 1964, untitled letter to H. J. Thompson (University of Minnesota), Associated Universities, Brookhaven National Laboratory, Upton, New York, June 8. [SRDB Ref ID: 53893]

Meinhold, C. B., and A. P. Hull, 1998, *Radiological Environmental Monitoring Report for Brookhaven National Laboratory, 1967-1970*, BNL 52551, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, October. [SRDB Ref ID: 6497]

Meinhold, C. B., and A. F. Meinhold, 2001, *Radiological Emissions and Environmental Monitoring for Brookhaven National Laboratory, 1947 - 1961*, P. D. Bond, editor, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, May. [SRDB Ref ID: 6495]

Meyer, H. E. (compiler), 1994, *History of Personnel External Dosimetry Program at the Dayton Project and Mound Laboratory 1946-1993*, Mound Laboratory, Miamisburg, Ohio. [SRDB Ref ID: 3276]

Michel, L., 2003, "MDA Determination for the WBC," memorandum to R. Reciniello, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, November 26. [SRDB Ref ID: 17882]

Michel, L., 2004, "MDA Determination for the WBC," memorandum to R. Reciniello, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, July 15. [SRDB Ref ID: 22481, p. 4]

Michel, L., 2005, "MDA Determination for the WBC," memorandum to R. Reciniello, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, May 17. [SRDB Ref ID: 22481, p. 6]

Michel, L., and C. Sun, 2003, "MDA Determination for the WBC," memorandum to R. Reciniello, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, March 28. [SRDB Ref ID: 22481, p. 2]

Miltenberger, R. P., 1978, "I-126 Release of May 16, 1978 from BLIF Facility," memorandum to file, Associated Universities, Brookhaven National Laboratory, Upton, New York, August 18. [SRDB Ref ID: 58853]

Miltenberger, R. P., 1981a, "Whole Body Counting Results for Building 750," memorandum to A. Humm, Associated Universities, Brookhaven National Laboratory, Upton, New York, January 8. [SRDB Ref ID: 50910]

Miltenberger, R. P., 1981b, "Whole-Body Counting Results," memorandum to A. Lukas, Associated Universities, Brookhaven National Laboratory, Upton, New York, December 21. [SRDB Ref ID: 58848]

Miltenberger, R. P., 1989, "Radiological Results of Thyroid Counting Performed for Medical Department Personnel on June 1, 1989," memorandum to N. Carter, Associated Universities, Brookhaven National Laboratory, Upton, New York, June 7. [SRDB Ref ID: 22420, p. 9]

Miltenberger, R. P., N. A. Greenhouse, and E. T. Lessard, 1980, "Whole Body Counting Results from 1974 to 1979 for Bikini Island Residents," *Health Physics*, volume 39, September, pp. 395–407.

Miltenberger, R. P., and E. T. Lessard, 1987, "Suspected Uptake of Xenon and Iodine by [Privacy Act Information]," memorandum to file, Associated Universities, Brookhaven National Laboratory, Upton, New York, January 14. [SRDB Ref ID: 58996]

Miltenberger, R. P., B. A. Royce, and J. R. Naidu, 1992, *Brookhaven National Laboratory Site Report for Calendar Year 1990*, BNL 52322, Associated Universities, Brookhaven National Laboratory, Upton, New York, January. [SRDB Ref ID: 6445]

Miltenberger, R. P., B. A. Royce, and J. R. Naidu, editors, 1987, *1986 Environmental Monitoring Report*, BNL 52088, Associated Universities, Brookhaven National Laboratory, Upton, New York, June. [SRDB Ref ID: 6429]

Miltenberger, R. P., B. A. Royce, and J. R. Naidu, editors, 1988, *1987 Environmental Monitoring Report*, BNL 52152, Associated Universities, Brookhaven National Laboratory, Upton, New York, April. [SRDB Ref ID: 6433]

Miltenberger, R. P., B. A. Royce, and J. R. Naidu, editors, 1989, *Brookhaven National Laboratory Site Report for Calendar Year 1988*, BNL-52207, Associated Universities, Brookhaven National Laboratory, Upton, New York, April. [SRDB Ref ID: 6437]

Miltenberger, R. P., B. A. Royce, S. S. Chalasani, D. Morganelli, and J. R. Naidu, 1990, *Brookhaven National Laboratory Site Report for Calendar Year 1989*, BNL 52264, Associated Universities, Brookhaven National Laboratory, Upton, New York, December. [SRDB Ref ID: 6441]

Miltenberger, R. P., and J. Steimers, 1984, "Bioassay Results," memorandum to A. Lukas, Associated Universities, Brookhaven National Laboratory, Upton, New York, June 11. [SRDB Ref ID: 22817]

Morris, R. L., 2006a, "BNL Occupational X-Ray: Interview with [Name Redacted], RT, X-Ray Technician (retired), Brookhaven National Laboratory," documented communication, Oak Ridge Associated Universities Team, Oak Ridge, Tennessee, March 3. [SRDB Ref ID: 22720]

Morris, R. L., 2006b, "BNL Occupational X-Ray: Interview with [Name Redacted], RT, X-Ray Technician, Brookhaven National Laboratory," documented communication, Oak Ridge Associated Universities Team, Oak Ridge, Tennessee, March 2. [SRDB Ref ID: 22453]

Morris, R. L., 2006c, "BNL Occupational X-Ray: Interview with [Name Redacted], RT, X-Ray Technician (retired), Brookhaven National Laboratory," documented communication, Oak Ridge Associated Universities Team, Oak Ridge, Tennessee, March 28. [SRDB Ref ID: 22722]

Morris, R. L., 2006d, "Historical Info on OMC X-Ray Policies," documented communication, Oak Ridge Associated Universities Team, Oak Ridge, Tennessee, March 28. [SRDB Ref ID: 22721]

Murray, B., 1993, "Results of Annual Routine Whole Body Counts Performed of HFBR Personnel from 7/16 through 9/16/1993," memorandum to R. Reciniello, Associated Universities, Brookhaven National Laboratory, Upton, New York, October 19. [SRDB Ref ID: 22792, p. 21]

Murray, B., 1999, "*A priori* Minimum Detectable Activities of Representative Nuclides for the Accuscan II *In Vivo* Counters Using the Total Body Geometry: (MDA Workaround)," memorandum to G. Holeman, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, August 25. [SRDB Ref ID: 22423, p. 4]

Musolino, S. V., 2000, *Technical Basis for Bioassay Requirements, BGRR Decommissioning Project*, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, September 27. [SRDB Ref ID: 22428, p. 2]

Naidu, J. R., editor, 1977, *1976 Environmental Monitoring Report*, BNL-22627, Associated Universities, Brookhaven National Laboratory, Upton, New York, April. [SRDB Ref ID: 6379]

Naidu, J. R., editor, 1979, *1978 Environmental Monitoring Report*, BNL 51031, Associated Universities, Brookhaven National Laboratory, Upton, New York, April. [SRDB Ref ID: 6387]

Naidu, J. R., editor, 1980, *1979 Environmental Monitoring Report*, BNL 51252, Associated Universities, Brookhaven National Laboratory, Upton, New York, April. [SRDB Ref ID: 6390]

Naidu, J. R., and L. L. Olmer, editors, 1981, *1980 Environmental Monitoring Report*, BNL 51417, Associated Universities, Brookhaven National Laboratory, Upton, New York, April. [SRDB Ref ID: 6396]

Naidu, J. R., and L. L. Olmer, editors, 1982, *1981 Environmental Monitoring Report*, BNL 51724, Associated Universities, Brookhaven National Laboratory, Upton, New York, April. [SRDB Ref ID: 6399]

Naidu, J. R., D. E. Paquette, G. L. Schroeder, and R. J. Lee, editors, 1996, *Brookhaven National Laboratory Site Report for Calendar Year 1995*, BNL-52522, Associated Universities, Brookhaven National Laboratory, Upton, New York, December. [SRDB Ref ID: 6466]

Naidu, J. R., and B. A. Royce, editors, 1994, *Brookhaven National Laboratory Site 1976 Environmental Monitoring Report for Calendar Year 1993*, BNL-52432, Associated Universities, Brookhaven National Laboratory, Upton, New York, May. [SRDB Ref ID: 6459]

Naidu, J. R., and B. A. Royce, editors, 1995, *Brookhaven National Laboratory Site Report for Calendar Year 1994*, BNL-52490, Associated Universities, Brookhaven National Laboratory, Upton, New York, May. [SRDB Ref ID: 6461]

Naidu, J. R., B. A. Royce, and R. P. Miltenberger, 1992, *Brookhaven National Laboratory Site Environmental Report for Calendar Year 1991*, BNL 52347, Associated Universities, Brookhaven National Laboratory, Upton, New York, September. [SRDB Ref ID: 6451]

Naidu, J. R., B. A. Royce, and R. P. Miltenberger, 1993, *Site Environmental Report for Calendar Year 1992*, BNL-52411, Associated Universities, Brookhaven National Laboratory, Upton, New York, May. [SRDB Ref ID: 6455]

NCRP (National Council on Radiation Protection and Measurements), 1976, *Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies up to 10 MeV*, Report 49, Bethesda, Maryland.

NCRP (National Council on Radiation Protection and Measurements), 1989, *Medical X-Ray, Electron Beam and Gamma-Ray Protection for Energies up to 50 MeV*, 102, Bethesda, Maryland.

Nelson, R., 1973, "Calibration of Doses from the Diagnostic X-Ray Machines," memorandum to C. W. Flood, Associated Universities, Brookhaven National Laboratory, Upton, New York, August 13. [SRDB Ref ID: 55059]

NIOSH (National Institute for Occupational Safety and Health), 2007a, *Radiation Exposures Covered for Dose Reconstructions Under Part B of the Energy Employees Occupational Illness Compensation Program Act*, OCAS-IG-003, Rev. 0, Office of Compensation Analysis and Support, Cincinnati, Ohio, November 5.

NIOSH (National Institute for Occupational Safety and Health), 2007b, *External Dose Reconstruction Implementation Guideline*, OCAS-IG-001, Rev. 3, Office of Compensation Analysis and Support, Cincinnati, Ohio, November 21.

NIOSH (National Institute for Occupational Safety and Health), 2002, *Internal Dose Reconstruction Implementation Guideline*, OCAS-IG-002, Rev. 0, Office of Compensation Analysis and Support, Cincinnati, Ohio, August 1.

O'Connell, E. J. III, 1975, "Progress Report - January, 1975," memorandum to C. W. Flood, Associated Universities, Brookhaven National Laboratory, Upton, New York, February 20. [SRDB Ref ID: 22831, p. 31]

ORAUT (Oak Ridge Associated Universities Team), 2004, *Technical Basis Document for the Oak Ridge National Laboratory -- Occupational Environmental Dose*, ORAUT-TKBS-0012-4, Rev. 00, Oak Ridge, Tennessee, May 7.

ORAUT (Oak Ridge Associated Universities Team), 2005, *Dose Reconstruction from Occupationally Related Diagnostic X-Ray Procedures,* ORAUT-OTIB-0006, Rev. 03 PC-1, Oak Ridge Tennessee, December 21.

ORAUT (Oak Ridge Associated Universities Team), 2006, *Atomics International – Occupational External Dose*, ORAUT-TKBS-0038-6, Rev. 01, Oak Ridge Tennessee, November 16.

ORAUT (Oak Ridge Associated Universities Team), 2006, *Estimating the Maximum Plausible Dose to Workers at Atomic Weapons Employer Facilities*, ORAUT-OTIB-0004, Rev. 03 PC-2, Oak Ridge, Tennessee, December 6.

ORAUT (Oak Ridge Associated Universities Team), 2007, *Site Profile and Technical Basis Document Development*, ORAUT-PROC-0031, Rev. 02, Oak Ridge, Tennessee, August 17.

ORAUT (Oak Ridge Associated Universities Team), 2009, *Y-12 National Security Complex – Occupational External Dosimetry*, ORAUT-TKBS-0014-6, Rev. 02, Oak Ridge, Tennessee, December 18.

ORAUT (Oak Ridge Associated Universities Team), 2010, *Hanford Site – Occupational External Dose*, ORAUT-TKBS-0006-6, Rev. 04, Oak Ridge, Tennessee, January 7.

Patterson, H. W., and R. H. Thomas, editors, 1994, *The History of Accelerator Radiological Protection, Personal and Professional Memoirs*, Nuclear Technology Publishing, Kent, England. [SRDB Ref ID: 33209]

Preisig, J. R., 1995, "Alternating Gradient Synchrotron (AGS) Bonner Multisphere Spectrometry and Carbon-11 Detector Results," memorandum to E. Lessard and H. Kahnhauser, Associated Universities, Upton, New York, July 24. [SRDB Ref ID: 22845]

Preisig, J. R., 1997, "1997 Bonner Multisphere Spectrometer Measurements at the NSLS (April/May, 1997), Associated Universities, Upton, New York, May 21. [SRDB Ref ID: 22843]

Reciniello, R. N., 2006, "Un-Monitored Workers," e-mail to L. Faust, Brookhaven Science Associates, Brookhaven National Laboratory, April 4. [SRDB Ref ID: 33175]

Sanna, R. and O'Brien, K., 1963, "The Use of Nuclear Emulsions to Estimate Stray Neutron Spectra near Particle Accelerators," *Health Physics*, volume 9, January, pp. 25-29.

Scarpitta, S. C., 2001, *Statement of Work for In-Vitro Radiobioassay Tritium Analyses Performed at Brookhaven National Laboratory*, BNL RCD/ASL 2001-Rev 0, Brookhaven Science

Associates, Brookhaven National Laboratory, Upton, New York, January. [SRDB Ref ID: 22482, p. 3]

Schroeder, G. L., D. E. Paquette, J. R. Naidu, R. J. Lee, and S. L. K. Briggs, 1998, *Site Environmental Report for Calendar Year 1996*, BNL-52543, Associated Universities, Brookhaven National Laboratory, Upton, New York, January. [SRDB Ref ID: 6467]

Sebelius, K., 2009, 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 Brookhaven National Laboratory, Upton, New York," U.S. Department of Health and Human Services, Office of the Secretary, Washington, D.C., December 10. [SRDB Ref ID: 79736]

Sengupta, S., 2000, *External Dosimetry Technical Basis Document*, PM-PD-003, Rev. 1, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, March 31. [SRDB Ref ID: 33173]

Schopfer, C., 1986, "FY87 Film Badge Exchange Schedule," memorandum to Distribution, Associated Universities, Brookhaven National Laboratory, Upton, New York, December 29. [SRDB Ref ID: 53335]

Schopfer, C., 1988, "Quality Control (QC) Test Badge Response to Calibration Sources," memorandum to A. Kuehner, Associated Universities, Brookhaven National Laboratory, Upton, New York, May 24. [SRDB Ref ID: 55069]

Steimers, J., 1965, untitled letter to G. Welford (U.S. Atomic Energy Commission, New York Operations Office), Associated Universities, Brookhaven National Laboratory, Upton New York, September 24. [SRDB Ref ID: 6276, p. 6]

Strom, D. J., 1982, Trip Report: Argonne National Laboratory, 11/14-11/17/82, with attachments, University of North Carolina at Chapel Hill. North Carolina, November. [SRDB Ref ID: 12632]

Stubbings, G. 1962, "Monthly BNL Surveys – March 28 and 29, and May 2 and 3, 1962," memorandum with attachment to A. J. Breslin, U.S. Atomic Energy Commission, New York Operations Office, New York, New York, June 1. [SRDB Ref ID: 6517, p. 74]

Sun, C., R. Reciniello, and S. Sengupta, 2004, *Technical Basis Document of Brookhaven National Laboratory's Internal Dosimetry Program*, Rev. 4, Brookhaven Science Associates, Brookhaven National Laboratory, Upton, New York, March 1. [SRDB Ref ID: 22518]

Sunderman, F. W., 1947a, "Clinical X-ray Equipment," memorandum to P. M. Morse, Associated Universities, Brookhaven National Laboratory, Upton, New York, September 30. [SRDB Ref ID: 55278]

Sunderman, F. W., 1947b, "Health Program for Employees at the Brookhaven National Laboratory," memorandum to P. M. Morse, Associated Universities, Brookhaven National Laboratory, Upton, New York, . [SRDB Ref ID: 55277]

Sunderman, F. W., 1947c "Chest X-Rays of Laboratory Employees," [SRDB Ref ID 55276]

Unruh, C. M., H. V. Larson, T. M. Beetle, and A. R. Keene, 1967, *The Establishment and Utilization of Film Dosimeter Performance Criteria*, BNWL-542, Pacific Northwest Laboratory, Battelle Memorial Institute, Richland, Washington, September. [SRDB Ref ID: 14914]

Wilson, R. H., 1958, "The Hanford Uranium Bio-Assay Program," p. 87, *Symposium on Occupational Health Experience and Practices in the Uranium Industry, Held in New York City, October 15 – 17, 1958*, HASL-58, U.S. Atomic Energy Commission, New York Operations Office, New York, New York, September. [SRDB Ref ID: 7886]

Yoder, R. C., 2005, "Landauer Film Info," email to L. Faust, Glenwood, Illinois, December 7. [SRDB Ref ID: 77874]

Zukas, G., 1983, "X-ray Entrance Doses," memorandum to W. Lehman, Associated Universities, Brookhaven National Laboratory, Upton, New York, October 21. [SRDB Ref ID: 55042]

Zukas, G., 1987, "X-ray Entrance Doses," memorandum to W. Lehman, Associated Universities, Brookhaven National Laboratory, Upton, New York, April 21. [SRDB Ref ID: 50500]

GLOSSARY

absorbed dose
Amount of energy (ergs or joules) deposited in a substance by ionizing radiation per unit mass (grams or kilograms) of the substance and measured in units of rads or grays See *dose*.

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

accelerator
See *particle accelerator*.

accreditation
For external dosimetry, the assessment of whether or not a personnel dosimetry system meets specific criteria. The assessment includes dosimeter performance and the associated quality assurance and calibration programs.

accuracy
The characteristics of an analysis or determination that ensures that both the bias and precision of the resultant quantity will remain within the specified limits.

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

alpha particle (α)
See *alpha radiation*.

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

ampere (A)
International System unit of electrical current equal to 1 coulomb per second.

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

backscatter
Reflection or refraction of radiation at angles over 90 degrees from its original direction.

beam quality
Empirical measure of the ability of a polyenergetic X-ray beam to penetrate matter affected by the kilovoltage, anode material, voltage waveform, and filtration of an X-ray tube. The half-

value layer in millimeters of aluminum is a typical measure of X-ray beam quality for the energy range used in radiography. Also called beam hardness. See *filtration*.

becquerel (Bq)
International System unit of radioactivity equal to 1 disintegration per second; 1 curie equals 37 billion (3.7×10^{10}) Bq.

beta particle (β)
See *beta radiation*.

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.

cladding
The outer layer of metal that encases a reactor fuel element or fissile material of the pit of a nuclear weapon, often made with aluminum or zirconium. In a reactor, cladding promotes the transfer of heat from the fuel to the coolant, and it builds up fission and activation products over time from the fission of the fuel.

Columbia Resin Number 39 (CR-39)
Radiosensitive material used in track-etch neutron dosimeters.

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

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

Cosmotron (Synchrotron)
Accelerator in which charged particles (electrons, protons, ions, etc.) are accelerated in a circular path achieving very high energies.

criticality
State of a radioactive mass (e.g. the core of a nuclear reactor) when the fission reaction becomes self-sustaining. Nuclear reactors *go critical* when started.

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.

cyclotron
Particle accelerator capable of large beam currents where the beam is injected in the center of a circular magnet. A fixed radio frequency signal applied to two D-shaped electrodes

accelerates the beam as it passes from one electrode to the other as the potential alternates. The radius of the beam increases as the energy increases.

decommissioning

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

decontamination

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

deep dose equivalent [Hp(10)]

Dose equivalent in units of rem or sievert for a 1-centimeter depth in tissue (1,000 milligrams per square centimeter). See *dose*.

disintegrations per minute (dpm, d/m)

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

DOE Laboratory Accreditation Program (DOELAP)

Program for accreditation by DOE of DOE site personnel dosimetry and radiobioassay programs based on performance testing and the evaluation of associated quality assurance, records, and calibration programs.

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.

dose equivalent (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.

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.

electron

Basic atomic particle with negative charge and a mass 1/1,837 that of a proton. Electrons surround the positively charged nucleus of the atom.

electron-volt (eV)

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

element

One of the known chemical substances in which the atoms have the same number of protons. Elements cannot be broken down further without changing their chemical properties. Chemical symbols for the elements consist of either a single letter or a combination of letters, some of which descend from the Latin names [e.g., Au from *aurum* (gold), Fe from *ferrum* (iron)]. This glossary indicates *elements* by their names. Specific *isotopes* appear as their standard chemical symbols with the number of protons and neutrons in the nucleus.

Energy Employees Occupational Illness Compensation Program Act of 2000, as amended (EEOICPA; 42 U.S.C. § 7384 *et seq.*)

Law that provides for evaluation of cause and potential compensation for energy employees who have certain types of cancer.

entrance skin exposure (ESE)

Air kerma without backscatter at the point of entry into the body. Also called entrance kerma. See *kerma*.

exchange period (frequency)

Period (weekly, biweekly, monthly, quarterly, etc.) for routine exchange of dosimeters.

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.

exposure geometry

Orientation (physical positioning) of a person or object in relation to a radiation source. This geometry is a factor in the radiation dose to various parts of the body. See *anterior–posterior*, *posterior–anterior*, and *lateral* in relation to radiology.

favorable to claimants

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

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.

filter

Material used in a dosimeter to adjust radiation response to provide an improved tissue equivalent or dose response.

filtration

The process of filtering an X-ray beam, usually with millimeter thicknesses of aluminum material between the X-ray source and the film that preferentially absorbs photons from the beam. Usually measured in equivalent millimeters of aluminum. See *beam quality* and *half-value layer*.

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

Radionuclides produced by fission or by the subsequent radioactive decay of radionuclides.

gamma radiation

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

gamma ray

See *gamma radiation*.

gray (Gy)

International System unit of absorbed radiation dose, which is the amount of energy from any type of ionizing radiation deposited in any medium; 1 Gy equals 1 joule per kilogram or 100 rads.

half-value layer (HVL)

Thickness of a specified substance, usually specified in equivalent millimeters of aluminum, that filters an X-ray beam to reduce the kerma rate by one-half. See *filtration*.

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.

***in vitro* bioassay**

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

***in vivo* bioassay**

The measurements of radioactive material in the human body utilizing instrumentation that detects radiation emitted from the radioactive material in the body.

inhalation class

Former respiratory tract inhalation classification scheme developed by the International Council on Radiological Protection for inhaled material according to its rate of clearance from the pulmonary region of the lung. Materials were classified as D (days, half-life less than 10

days), W (weeks, 10 to 100 days), or Y (years, more than 100 days). See *absorption type*, which superseded this concept.

internal dose
Dose received from radioactive material in the body.

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 *alpha radiation*, *beta radiation*, *gamma radiation*, *photon radiation*, and *X-ray 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. See *element*.

kerma
Measure in units of absorbed dose (usually grays but sometimes rads) of the energy released by radiation from a given amount of a substance. Kerma is the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles (neutrons and photons) per unit mass of a specified material. Free-in-air kerma refers to the amount of radiation at a location before adjustment for any external shielding from structures or terrain. The word derives from kinetic energy released per unit mass.

lateral (LAT)
Orientation of the body during an X-ray procedure in which the X-rays pass from one side of the body to the other. See *exposure geometry*.

linear accelerator (LINAC)
Straight single-pass particle accelerator in which radio frequencies accelerate the beam over the length of the accelerator.

lumbar spine
Region of the spine including the five lumbar vertebrae (lower back).

megaelectron-volt (MeV)
Unit of particle energy equal to 1 million (1×10^6) electron-volts.

milliampere-second (mAs)
In relation to radiography, product of the average X-ray beam current in milliamperes and the time of the exposure in seconds. These factors are selectable on the control panel of most medical X-ray equipment.

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 picocuries 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.

neutron film dosimeter

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

neutron radiation

Radiation that consists of free neutrons unattached to other subatomic particles emitted from a decaying radionuclide. Neutron radiation can cause further fission in fissionable material such as the chain reactions in nuclear reactors, and nonradioactive nuclides can become radioactive by absorbing free neutrons. See *neutron*.

nonpenetrating dose (NP, NPEN)

Dose from beta and lower energy photon (X-ray and gamma) radiation which does not penetrate the skin. It is often determined from the open window dose minus the shielded window dose. See *dose*.

nuclear emulsion

Thick photographic coating in which the tracks of various fundamental particles show as black traces after development. The number of tracks in a given area is a measure of the dose from that radiation. See *nuclear track emulsion, type A*.

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). Also called atomic energy.

nuclear track emulsion, type A (NTA)

Film sensitive to fast neutrons made by the Eastman Kodak. The developed image has tracks caused by neutrons that become visible under oil immersion with about 1,000-power magnification.

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.

occupational dose

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

occupational environmental dose

Dose received while on the grounds of a site but not inside a building or other facility.

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 EEOICPA.

open window (OW)

Area of a film dosimeter that has little to no radiation shielding (e.g., only a holder and visible light protection). See *film dosimeter*.

particle accelerator

Device that accelerates ions using magnetic and/or electrostatic fields for focusing and redirecting ion beams. The main purposes of accelerators are the investigation of high-energy particle behavior and production of synthetic isotopes.

penetrating dose (PEN)

Dose from higher energy photon (gamma and X-ray) radiation that penetrates the outer layers of the skin. See *dose*.

personal dose equivalent [$H_p(d)$]

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 $H_p(0.07)$ and $H_p(10)$, respectively. The International Commission on Radiological Measurement and Units recommended $H_p(d)$ in 1993 as dose quantity for radiological protection.

phantom

Any structure that contains one or more tissue substitutes (any material that simulates a body of tissue in its interaction with ionizing radiation) and is used to simulate radiation interactions in the human body. Phantoms are primarily used in the calibration of *in vivo* counters and dosimeters.

photofluorography (PFG)

Historical radiographic technique used for chest images for screening a large number of people in a short period of time. The X-ray image produced on a fluorescent screen was photographed on 4- by 5-inch film. PFG was the primary method of screening large populations for tuberculosis before the advent of nonradiographic screening methods. Also called fluorography or mass miniature radiography. Not to be confused with *fluoroscopy*.

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.

PM

A procedure detailing specific actions or directions and usually limited to one service or activity.

posterior-anterior (PA)

Physical orientation of the body relative to a penetrating directional radiation field such that the radiation passes through the body from the back to the front. See *exposure geometry*.

probability of causation

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

proton

Basic nuclear 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. See *element*.

quality factor (QF)

Principal modifying factor (which depends on the collision stopping power for charged particles) that is employed to derive dose equivalent from absorbed dose. The quality factor multiplied by the absorbed dose yields the dose equivalent. See *dose*, *relative biological effectiveness*, and *weighting factor*.

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. 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. See *radionuclide*.

radiograph

Image produced on film by gamma rays or X-rays. See *radiology*.

radiography

The process of producing images on film (or other media) with radiation.

radiology

Medical science and specialty of producing images on radiographic film or other media, which are used to identify, diagnose, and or treat diseases, injuries, or other conditions.

radionuclide

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

reactor

Device in which a fission chain reaction occurs under controlled conditions to produce heat or useful radiation for experimental purposes or to generate electrical power or nuclear fuel.

reactor elements

Fabricated fuel and target components inserted into reactors.

relative biological effectiveness (RBE)

Ratio of the absorbed dose of a reference radiation to the absorbed dose of a test radiation that produces the same biological effects, other conditions being equal. A factor applied to account for differences between the amount of cancer effect produced by different forms of radiation.

rem

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

rep

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

roentgen (R)

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

shallow dose equivalent [SDE, H_s, $H_p(0.07)$]

Dose equivalent in units of rem or sievert at a depth of 0.07 millimeters (7 milligrams per square centimeter) in tissue equal to the sum of the penetrating and nonpenetrating doses.

sievert (Sv)

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 Sv equals 100 rem.

skin dose

See *shallow dose equivalent*.

technique

Combination of X-ray machine settings used to produce radiographs, which consists of the kilovoltage, tube current (milliamperes), and exposure time (seconds). The last two parameters are often multiplied to yield the electric charge that has crossed the X-ray tube during the exposure in units of milliampere-seconds. Any combination of time and tube current that produces a given product in milliampere-seconds produces the same exposure for a fixed peak kilovoltage.

source-to-image distance (SID)

Distance from the X-ray machine target (anode) to the plane of the image receptor (film). This distance is standardized for typical radiographic procedures. Chest X-rays, for example, are performed at a 72-inch SID.

tandem Van de Graaff accelerator
Accelerator in which charge exchange (negative to positive) occurs in the terminal on either a thin foil or in a gas stripper tube.

thermoluminescent dosimeter (TLD)
Device for measuring radiation dose that consists of a holder containing solid chips of material that, when heated by radiation, release the stored energy as light. The measurement of this light provides a measurement of absorbed dose.

tissue equivalent
Substance with response to radiation equivalent to tissue. A tissue-equivalent response is an important consideration in the design and fabrication of radiation measuring instruments and dosimeters.

type
See *absorption type*.

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

weighting factor
The ratio of the stochastic risk arising from tissue *T* to the total risk when the whole body is irradiated uniformly. (ICRP 1978)

whole-body counter (WBC)
Equipment used to perform *in vivo* bioassay. Radiation emitted from radioactive material deposited throughout the body is measured.

whole-body (WB) 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
(1) See *X-ray radiation*. (2) See *radiograph*.

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.

zirconium
Metallic element with atomic number 40. Zirconium is highly resistant to corrosion, and it is alloyed with aluminum to make cladding for nuclear fuel and sometimes in small amounts with the fuel itself.