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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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
AP	anterior-posterior
ATR	AGS-To-RHIC transfer line
BF	Backscatter factor
BGRR	Brookhaven Graphite Research Reactor
BIRC	Brookhaven Isotope Research Center
BLAF	Brookhaven Lab Animal Facility
BLIP	Brookhaven Linac Isotope Producer
BMRR	Brookhaven Medical Research Reactor
BNCT	Boron Neutron Capture Therapy
BNL	Brookhaven National Laboratory
Bq	Becquerel
CBA	Colliding Beam Accelerator
cGy	centigray
CLIF	Chemistry Linac Irradiation Facility (also CLIP in some documents)
cm	centimeter
CNF	Cold Neutron Facility
CR-39	Columbia resin, number -39
D&D	Decontamination and Decommissioning
DAS	Department of Applied Science
DAT	Department of Applied Technology
DCF	dose conversion factor
DE	Dose Equivalent
DOE	U.S. Department of Energy
DOELAP	Department of Energy Laboratory Accreditation Program
Dpm	disintegration per minute
DR	dose rate
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
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)
FDA	Food and Drug Administration
G	Gram
GIF	Gamma Irradiation Facility
Gy	gray

HASL	Health and Safety Laboratory
HEBT	High Energy Beam Transport
HFBR	High Flux Beam Reactor
HIRDL	High Intensity Radiation Development Laboratory
HITL	Heavy Ion Transfer Line
HPI	Health Physics Instruction
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)
kVp	kilovolts-peak
L	liter
LAF	Laser Electron Accelerator Facility
LAT	lateral
LEAF	Low Energy Accelerator Facility
LINAC	linear accelerator
LMFR	Liquid Metal Fuel Reactor
M	moderate (solubility rate)
mA	milliampere
MDA	minimum detectable activity, or amount
MDL	minimum detectable level
MEL	Metallurgical Evaluation Laboratory
MeV	million electron volt
MFP	mixed fission products
mg	milligram
mGy	milligray
min	minute
mL	milliliter
mm	millimeter
mR	milliroentgen
mrad	milliard
MRC	Medical Research Center
mrem	millirem
ms	millisecond
MW	megawatts
NaI (TL)	Sodium-iodide, thallium-activated scintillation detector
NBTF	Neutral Beam Test Facility
nCi	nanocurie
NCRP	National Council on Radiation Protection
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 of the AEC

ORAU	Oak Ridge Associated Universities
OW	open window
PA	posterior-anterior
pCi	picocurie
PET	Positron Emission Tomography
QF	quality factor
R	roentgen
RARAF	Radiological Research Accelerator Facility
RBE	relative biological effectiveness
REF	Radiation Effects Facility
RHIC	Relativistic Heavy Ion Collider
RSD	Remote Skin Dose
RTF	Radiation Therapy Facility
S	slow (solubility rate)
SD	standard deviation
sec	second
SF	spontaneous fission
SID	source-to-image distance
SSD	source-to-skin distance
ST	Severn-Trent
TBD	technical basis document
TPL	Target Processing Laboratory
U.S.C.	United States Code
VUV	Vacuum Ultraviolet
WBC	whole-body counter
WBNIF	Whole Body Neutron Irradiation Facility
WMF	Waste Management Facility
yr	year
µCi	microcurie
µg	microgram

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 the NIOSH staff in the completion of the individual work required for each dose reconstruction.

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

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

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

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

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

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.

1.2 SCOPE

This site profile consists of six sections: Introduction, Site Description, Occupational Medical Dose, Occupational Environmental Dose, Occupational Internal Dose, and Occupational External Dosimetry.

1.2.1 Site Description

Section 2, Site Description, of this site profile describes the features and the history of the Brookhaven National Laboratory (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 various facilities that operated, or are operating at the BNL. These include the Brookhaven Graphite Research Reactor and its replacement, the High Flux Beam Reactor; the operations of the Medical Research Center, the positron emission tomography facility and the medical research reactor; the operation of the various 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, Occupational Medical Dose, of this site profile provides information regarding the historical BNL occupational x-ray program. Much of this information was obtained through personal interviews with the clinicians and x-ray technicians. Beginning in 1947 and continuing through at least 1964, reactor operators and possibly hospital medical staff were subjected to an entry and annual physical examination including a PA chest x-ray. All other workers, including visiting scientists employed for more than three months received an entry physical and re-examination, including a PA chest x-ray on a frequency averaging about one exam every 2.5 years. The section presents organ doses for both PA and LAT chest films using collimated and uncollimated exposures. Skin doses both inside and outside the primary beam are determined for PA and LAT chest projections.

1.2.3 Occupational Environmental Dose

Section 4, Occupational Environmental Dose, discusses the radiation doses received by workers at the BNL but outside the facilities. From 1967 to 1984 ambient gamma radiation dose rates are available from four perimeter stations surrounding the site at NW, SW, SE, and NE 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 Ar-41 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 (Bq/yr) listed. Neither potable groundwater nor soil ingestion have been found to be pathways of exposure. No ingestion dose is indicated.

1.2.4 Occupational Internal Dose

Section 5, Occupational Internal Dose, discusses the internal dosimetry systems and practices employed at the BNL. The section provides supporting technical data to evaluate internal occupational doses that can reasonably be associated with worker radiation exposures covered by the EEOICPA legislation. These doses include occupational internal exposures in BNL facilities and onsite exposures to BNL environmental releases. 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, Occupational External Dosimetry, discusses the external dosimetry systems and practices at the 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 the 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 and exchange periods, as well as the inability to determine true doses from high energy particles generated by the various accelerators. Neutron doses were measured with NTA film. Spallation products, that produced stars on the NTA film, were related to an effective neutron dose that was added to the total neutron dose.

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, under a contract between the U.S. Atomic energy Commission (AEC) (which has now been assumed by the Department of Energy) and Associated Universities Inc. (AUI). 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. The BNL was established to provide facilities for scientific research and was organized into Departments that provide research nuclear reactors, various particle accelerators, and engineering facilities, and support the disciplines of Biology, Chemistry, Physics, Medicine, Applied Science, Accelerator and Applied Mathematics Departments.

2.2 PURPOSE

The purpose of this section is to describe the facilities of the Brookhaven National Laboratory (BNL), 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 the 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.

Figure 2-1. Aerial view of Brookhaven National Laboratory.

Research Reactors

The Laboratory's scientific history began in 1950 with the operation of the *Brookhaven Graphite Research Reactor (BGRR)*, a research reactor used for peaceful scientific exploration in the fields of medicine, biology, chemistry, physics, and nuclear engineering. The BGRR operated until 1969. In 1965 its capacity was replaced and surpassed by the *High Flux Beam Reactor (HFBR)*, which provide neutrons to researchers of all disciplines, from solid state physics to art history.

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 *Medical Research Center (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), operated jointly by the BNL Medical Department and State University of New York at Stony Brook, is a high-energy dual x-ray mode linear accelerator (LINAC) for radiation therapy of cancer patients. This accelerator was designed to deliver therapeutically beams of x-rays and electrons for conventional and advanced radiotherapy techniques.

Chemists and physicians teamed up 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 all currently operating.

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 also 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 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 meters 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 via an underground beam tunnel to the BLIP facility where they strike various target metals. These metals, which become activated by the proton beam, are then processed at *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 between 1994 in support of the Brookhaven Isotope Research Center (BIRC) program. The *200 MeV Proton Linear Accelerator* serves as a proton injector for the AGS and also 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 give off 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 linear accelerator and booster synchrotron as an injection system for two electron storage rings which 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 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 1971-1972, the *High Intensity Radiation Development Laboratory (HIRDL)*, which contains million-curie range Co-60 and Cs-137 sources, is used for source development and experimental process irradiations.

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 within 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 are intended to 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. The BGRR operated until 1969. At the present time, the BGRR facility is used as a visitor's center, museum, and office area for other projects.

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 foot, 700-ton graphite cube was built in two halves separated by a narrow vertical 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 which discharged into a 100 meter high stack.

The BGRR achieved criticality on August 22, 1950 and operated at power levels up to 28 MW with natural uranium fuel. In April of 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 was terminated and initial decommissioning operations began. The last fuel shipped to the Savannah River processing plant in June 1972 and the canal was pumped dry.

Building 709 –
Building 709 is the fuel transfer and storage canal of the BGRR. During the 1950's, prior to 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.

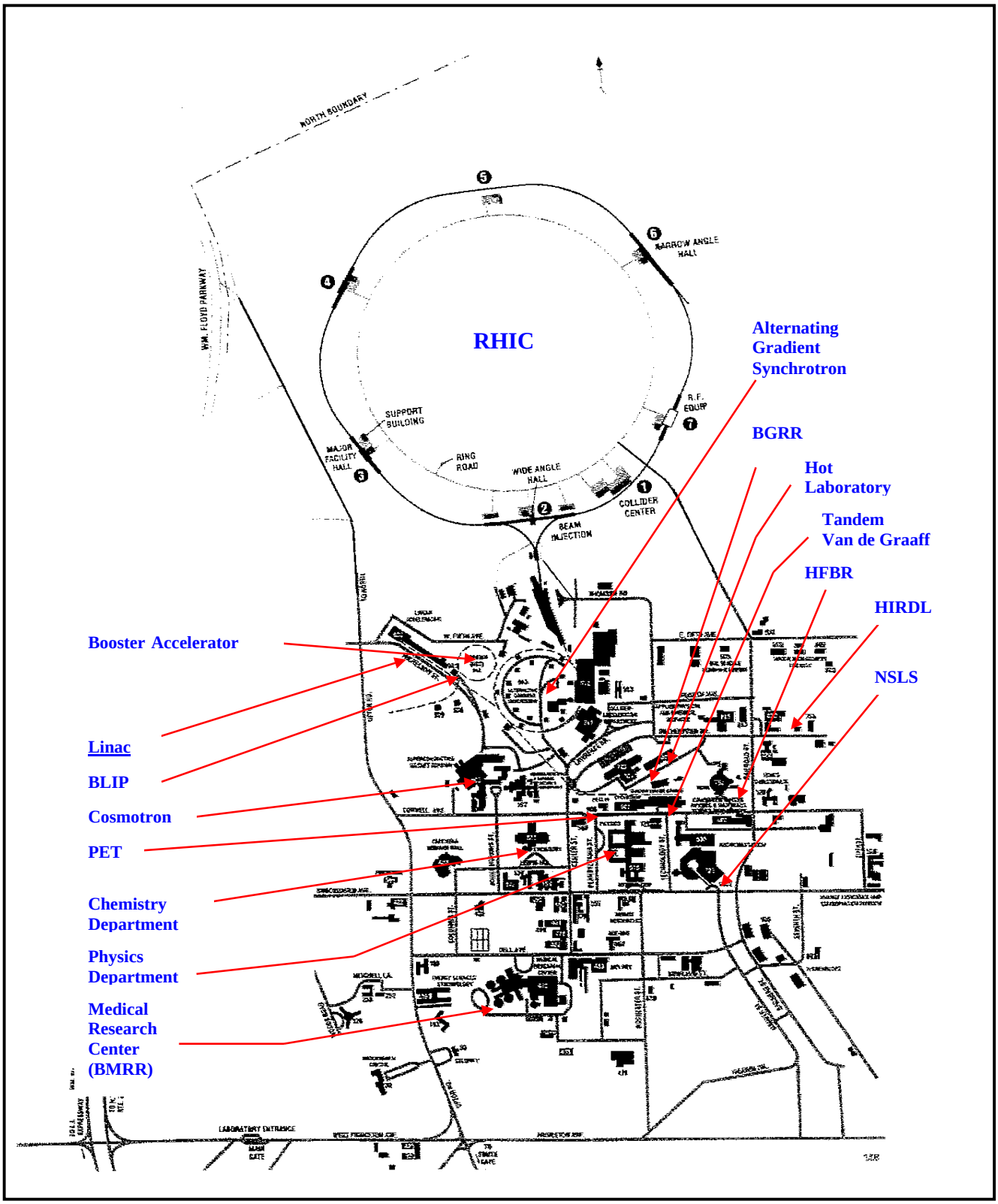

Figure 2-2. Nuclear and radioactivity sites at BNL.

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

Section	Name	Description	Period	Building No.	Note
2.4.1	Brookhaven Graphite Research Reactor (BGRR)	Uranium fueled Graphite moderated and reflected Reactor 28 MW	1950-1969	701	
2.4.1	BGRR fuel canal	BGRR fuel storage	1950-1972	709	
2.4.1	BGRR exhaust fan house	Highly contaminated ducting and fans	1950-1972	704	
	BGRR exhaust filter house	Contaminated HEPA filter elements	1950-unknown	708	filter elements are still in place in 1997
2.4.2	High Flux Beam Reactor (HFBR)	30-60 MW thermal heavy water moderated research reactor	1965-1999	750	Building cease 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	Cold Neutron Facility (CNF)	Produce extremely low energy neutron by moderate neutron with liquid hydrogen	1980-unknown	751	
2.4.3	Medical Research Center (MRC)	Medical Department	1959-present	490	Dispersible radioisotopes PuBe sources
2.4.4	Brookhaven Medical Research Reactor (BMRR)	Enriched U fueled, light water moderated and cooled reactor	1959-2000	491	
2.4.5	PET Imaging Laboratory	Positron Emission Tomographic 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	Alternating Gradient Synchrotron (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	Pre-accelerator and linear accelerator providing proton source	1967-present	930	
2.4.7	LINAC cooling support service	Provides 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 fan houses	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	
2.4.7	E10 Power Supply Building	Houses an assortment of power supply	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 80” 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’ 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	Brookhaven LINAC Isotope Producer (BLIP)	Production of radioisotopes via irradiation in the LINAC beam (200 Mev Protons)	1961-1962	931B	Bldgs 931A and C have no nuclear hazard
2.4.9	Tandem Van de Graaff	Van de Graaff accelerators 60” proton Cyclotron producing 10 MeV protons, 20 MeV deuterons and 40 MeV alpha particles for medical radionuclide research	1970 - present	901	Dynamitron (positron accelerator)

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

Section	Name	Description	Period	Building No.	Note
2.4.10	National Synchrotron Light Source (NSLS)	Produce intense sources of x-rays, ultraviolet and infra-red radiation	1981-present	725	
2.4.10	NSLS Development Laboratory	Houses a linear accelerator	1981-present	729	
2.4.11	Relativistic Heavy Ion Collider (RHIC) Complex	High-energy particle accelerator and collider BRAHMS experimental hall RHIC service building Open area (future experimental area) RHIC support building Beam tunnel Offices and tech shops STAR Detector Service building Beam tunnel PHENIX experiment Experimental support building PHOBOS experiment Future experimental hall	1999-present 1981-present 1981-present 1996-present 1994-present 1981-present 1981-present 1985-present 1981-present 1981-present 1988-present 1985-present 1994-present 1994-present	 1002 1004A 1004 1004B 1005 1005S 1006 1006A 1007 1008 1008A 1010 1012	 Has prior radioactive works Uranium plate machining Has prior radioactive works
2.4.12	Hot Laboratory	Target Processing Laboratory	1951-present	801	There was an explosion of UF_6/BrF_3 on 5/15/1957. Few people injured.
2.4.13	High Intensity Radiation Development Laboratory (HIRDL)	Radioactive sources fabrication, irradiation cells and since 1970, the Gamma Irradiation Facility (GIF)	1951-present GIF 1970-present	830	The GIF contains approximately 35,000 Ci of Co-60 and million Ci Co-60 and Cs-173 source
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	Radioactive material storage, counting labs
2.4.16.1	LMFR Support Facility	Research and development work for the Liquid Metal Fuel Reactor	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 within the Waste Management facility (WMF) for processing of radwaste	1997-present	865	
2.4.17	Tritium Evaporator Facility	Reduce tritium release by evaporation	1995-present	802B	
2.4.17	Waste Management Incinerator	Low-level Waste incinerator	1995-present	444	
2.4.18	Radiological Waste Decontamination Facility	Decontamination of radiological waste	1959-1996	650	

During the early years of operation of the BGRR, fuel failures occurred which 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 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 argon-41, iodine-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 iodine-133 were released in somewhat larger concentrations.

Over 2414 fuel elements, generated in a 12-year period, were shipped from the canal. The contaminated water, filter media, and back flushing 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.

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.

Building 708 –
Radioactive hot air was filtered and discharged from the reactor through underground concrete ducts located between the reactor building 701, the instrument house building 708, and the fan house, 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 cesium-137 and strontium-90. 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 are still in place.

2.4.2 High Flux Beam Reactor (HFBR), Building 750

The BGRR capacity was replaced and surpassed in 1965 by the High Flux Beam Reactor (HFBR). 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 wide variety of neutron scattering research projects and to allow for the radiating of materials close to the reactor core by insertion through special tubes positioned 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 which 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 which 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 which contains the reactor and almost all associated process systems. The reactor, its beam lines and laboratories are located on the second main level

known as the Experimental Level. The top most 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 installed in building 751.

Building 705 –
Building 705 is a 100 meter stack that provides the path for ventilation exhaust from the HFBR. A 30 inch 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.

2.4.3 Medical Research Center (MRC), Building 490

The Medical Department (Building 490) was opened in 1956 and currently conducts research in body composition and imaging, and Boron Neutron Capture Therapy (BNCT) 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 Lab Animal Facility (BLAF). Bench top 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 housed within 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 for the Whole Body Neutron Irradiation Facility (WBNIF) are stored in a vault below the facility and raised into the facility when in use. In addition, there are many fume hoods and other apparatus typically found in research labs.

2.4.4 Brookhaven Medical Research Reactor, Building 491

The Medical Research Reactor (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 Medical Research Center and is housed in a 60 foot diameter steel and concrete structure adjacent to the Medical Research Center (Building 490). It is fueled with enriched uranium, moderated and cooled by light water, and is operated intermittently at power levels up to 3 MW (thermal). The reactor is capable of operating for short periods of time 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 reactor vessel. When air is drawn through the reflector, it is exposed to a neutron field which causes the natural argon gas in the air to become radioactive (as argon-41). 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 (BNCT) research and patient treatment. Testing of neutron capture compounds and techniques was ongoing.

2.4.5 Positron Emission Tomography, Building 906

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

Radiopharmaceuticals labeled with short-lived positron emitters (carbon-II, fluorine-18, nitrogen-13 and oxygen-15) 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.

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.

The balance of the high bay area of 902 was used for research and development of superconducting magnets. Eventually the Medical Department moved their equipment out and the high bay was devoted entirely to the development and fabrication of 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

2.4.7 Alternating Gradient Synchrotron, 900 Series Buildings

The Alternating Gradient Synchrotron (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 Relativistic Heavy Ion Collider (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 meter circumference rapid cycling Booster synchrotron located in Buildings 914 and 942, and the 800 meter 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 via a beam transfer line. The particles which are accelerated by the AGS facility are extracted into and stopped in various experimental areas located around the ring, or sent via a transfer line to the RHIC. Building 912 was the original experimental target area. The asphalt pad on the inside of the AGS ring adjacent to Building 912 was an experimental area in the 1960's 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.

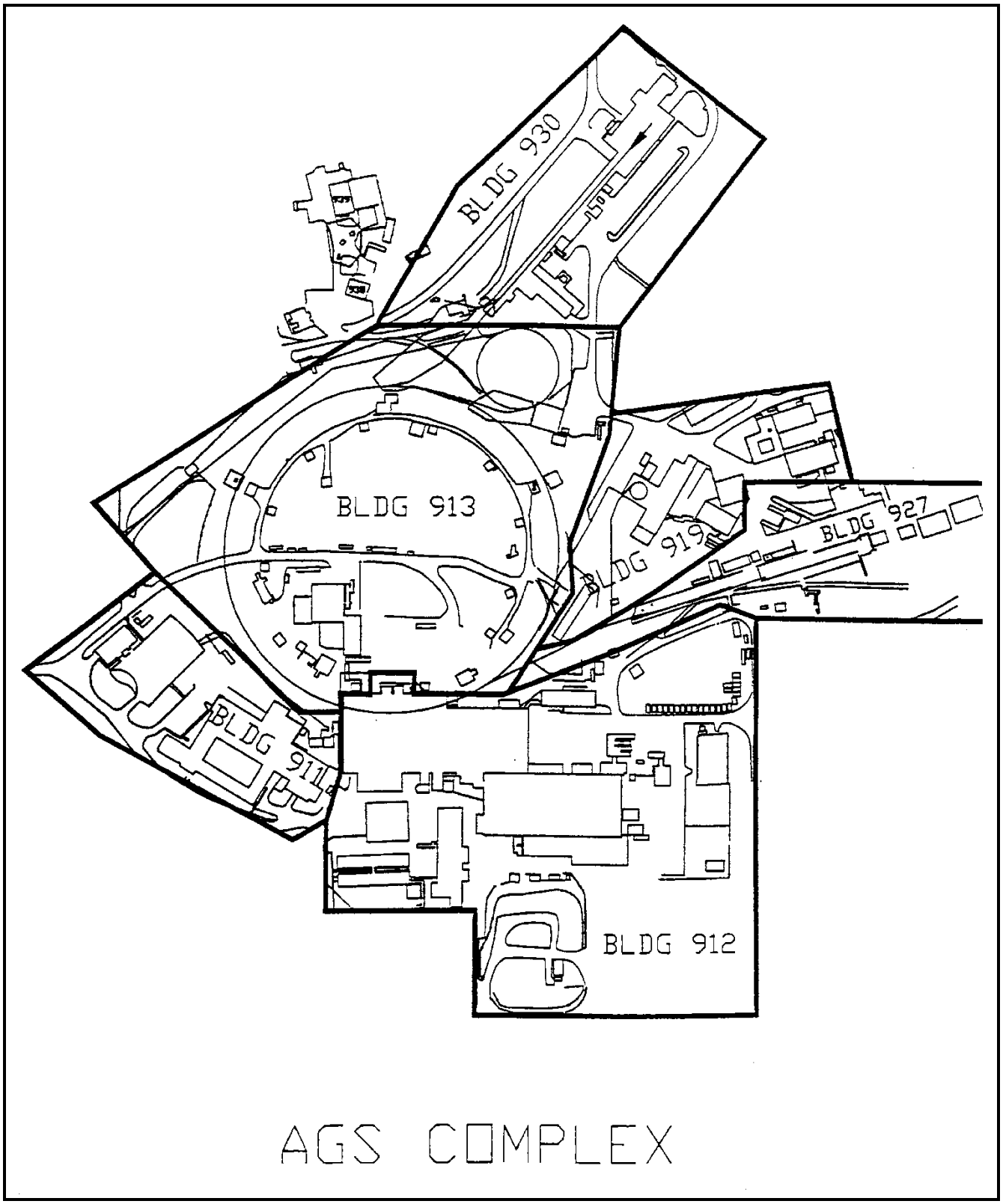

Figure 2-3. The AGS Complex.

The AGS Linear Accelerator (LINAC), Building 930 and Associated Facilities:
The LINAC was designed and built in the late 1960's as part of a major upgrade to the AGS facility. The Linear accelerator tunnel is 140 m long and consists of nine large accelerators. From the end of the LINAC a 17 meter long spur tunnel injects the beam into the Booster accelerator. Another high-energy beam transport (HEBT) line extends 95 meters to connect with the AGS. Another spur tunnel provides beam to the Brookhaven Linac Isotopes Producer (BLIP) facility, the Chemistry Linac Isotopes Facility (CLIF), the Radiation Effects Facility, and 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 1970's and contains shops and storage areas. 930A was added on in the late 1980's as a service building for the Booster project. It contains power supplies and computer control equipment for the Booster.

The AGS Accelerator Rings, Buildings 913 and 914 and Associated Facilities:
The AGS tunnel, Building 913 has a circumference of 800 meters and is buried under a 7 meter thick berm of earth and concrete. There are 240 large alternating gradient dipole electromagnets, over one hundred supporting focus and beam tuning magnets as well as RF accelerating components, vacuum systems, water cooling systems, etc., located in the tunnel. Supporting the tunnel operation are the ventilation system fan houses 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 meters. 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 via the HEBT transfer tunnel. The original connecting tunnel is now used to transfer beam from the Booster to the AGS. The Booster tunnel is 200 meters in circumference and is buried under a 5 meter thick berm.

The new section of the Booster tunnel was built in 1988. Some radioactive gases were created by activation of the ventilating air within the tunnel and experimental areas of the AGS. But, since they are short-lived (carbon-11, half-life 20.5 min; nitrogen-13, half-life 10.0 min; oxygen-15, 2.1 min), they did not create a measurable radiation level beyond the immediately adjacent on-site area. All of the cooling water systems in the AGS and Booster tunnels are activated. This includes systems which use the AGS ring as a utility tunnel for piping which 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.

Other Related Buildings:
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 back-up 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 which 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 cooling system to cool water from the AGS ring, it does contain activated water.

Building 912 - Building 912 is the designation of the approximately 5 indoor acres of AGS experimental floor. It is not one building, but 5 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 within 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 both inside and outside of building 912. Depleted Uranium was used in experimental areas in the past, but its use and disposition was tightly controlled. Small radioactive sources (nCi) are used. They are inventoried and stored in locked shielding boxes.

Building 913A-E - AGS ventilation system fan houses 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 fan house. Air handled in the fan houses is from the AGS tunnel air and can also be activated.

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 1970's and 1980's, 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.

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 919 housed the 80 inch bubble chamber which 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 1980's 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.

Building 920 - Building 920 is the EI0 Power Supply building, and is located 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.

Buildings 928 (Siemens motor generator house) - Building 928 is directly adjacent to and at one corner connected to Building 929. Both buildings share a common 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 928 and 929 and for systems in the AGS ring. There were potential radiation hazards from activated cooling water.

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 919 contains water-cooled magnets and vacuum pumps. The cooling water is shared with the target so it is activated.

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 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 abandonment. 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.

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 in 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 cool down period the component is repaired and stored until needed.

Building 918 (Warehouse) - This building is located adjacent to Building 912. It was built in 1957/58. 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.

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 1991/92. The building housed depleted uranium, lead, activated copper magnet coils, vacuum pumps with oil, and other activated components.

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

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

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

2.4.8 Brookhaven LINAC Isotope Producer, Building 931

In 1972 the Brookhaven LINAC Isotope Producer (BLIP -Bldg. 931B) and the CLIF (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 via irradiation in the LINAC beam. It consists of a main building which houses a "hot cell" over a shaft which descends approximately thirty feet. The shaft allows targets containing various substances to be lowered along a track down 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 (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 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 placed around the main BLIP containment tank. This leads to some activation of the shielding soil.

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.

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 that 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 wide variety of materials. Areas inside the building include the cyclotron area, the RFQ-DTL area, laboratory space associated with the Department of Applied Science (DAS), and a mechanical shop area which 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 I -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 108-112). 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" lab. The "hot" lab contains preparation and purification equipment as well as shielded hoods for the processing of the radioisotopes from the cyclotrons into radiopharmaceuticals.

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.

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.

Area 4 - 901W Dynamitron and Robot Room - The 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 901W is occupied by the Dynamitron.

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" cyclotron which, in 1959, was moved from the test shack in the rear of the Cosmotron and reassembled in the new building. The 18" cyclotron was capable of accelerating protons to energies of about 3 MeV. During the years 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)3He reaction on a target of zirconium tritide. The accelerator was capable of consistent beam currents of 100 uA and occasionally reached beam currents of 200 uA.

The 60" cyclotron was installed in 1950 and became operational in 1951. The 60" 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” 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 He-3 and 46 MeV alpha particles. During the late 1950's and early 1960's, a number of radioisotopes were in development and/or production at what was known then as LEAF (Low Energy Accelerator Facility) which included the cyclotrons, and the Van de Graaff accelerator. The isotopes were: 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 generator, and Mo-99-Tc-99m generator. The major purpose of these isotopes was medical research.

In 1965 the Dynamitron was installed in 901W. It was essentially an electron or positron accelerator designed for physics research. In the early years, it was used exclusively for the study of solid state physics. It was used as a positron accelerator during the late 1980's into the 1990's to study positron reactions. During this time it used a large Na-22 source as the generator of positrons. This source was removed when the facility was shut down 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 He-3 beam were begun. The first test of the triton beam was carried out in June of 1968. During 1968 and for a few years after, Mg-28 was being produced routinely on the Van de Graaff using the

26 Mg(t,p)28 Mg nuclear reaction. During the period of 1968 through the late 1970's 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 shut down of the Van de Graaff in 1991.

2.4.10 National Synchrotron Light Source, Building 725

Building 725 is the National Synchrotron Light Source (NSLS). It is one of the most intense sources of x-rays, ultraviolet and infra-red 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 wide variety of experiments. There are also wet labs 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 set-up 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.

Building 729 is the National Synchrotron Light Source, Source Development Laboratory. The building houses a linear accelerator coupled to a magnetic "wiggler" which produces an intense x-ray beam.

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 beam lines. 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:

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 prior to 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

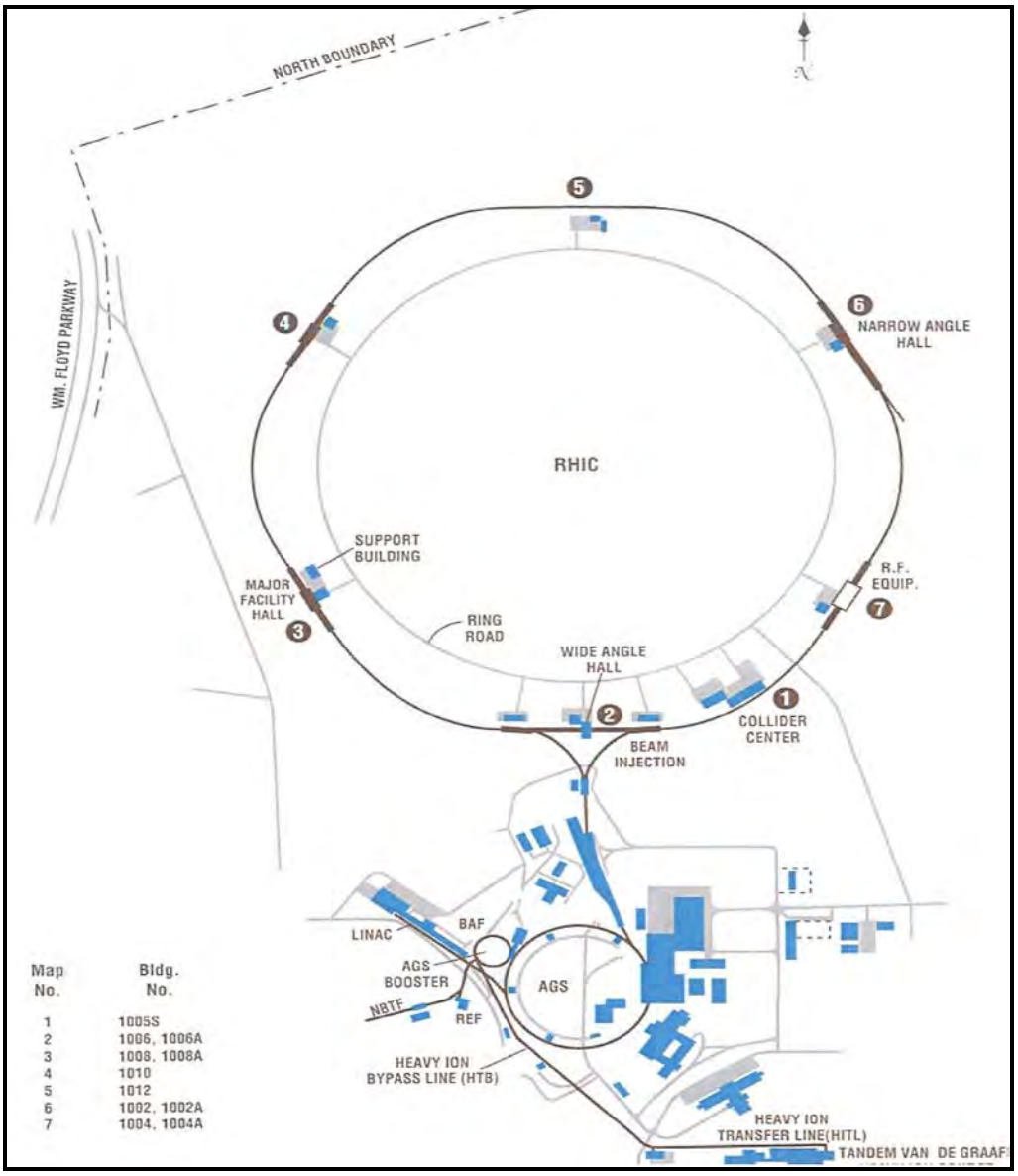

Figure 2-4. The Relativistic Heavy Ion Collider (RHIC) Complex.

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

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

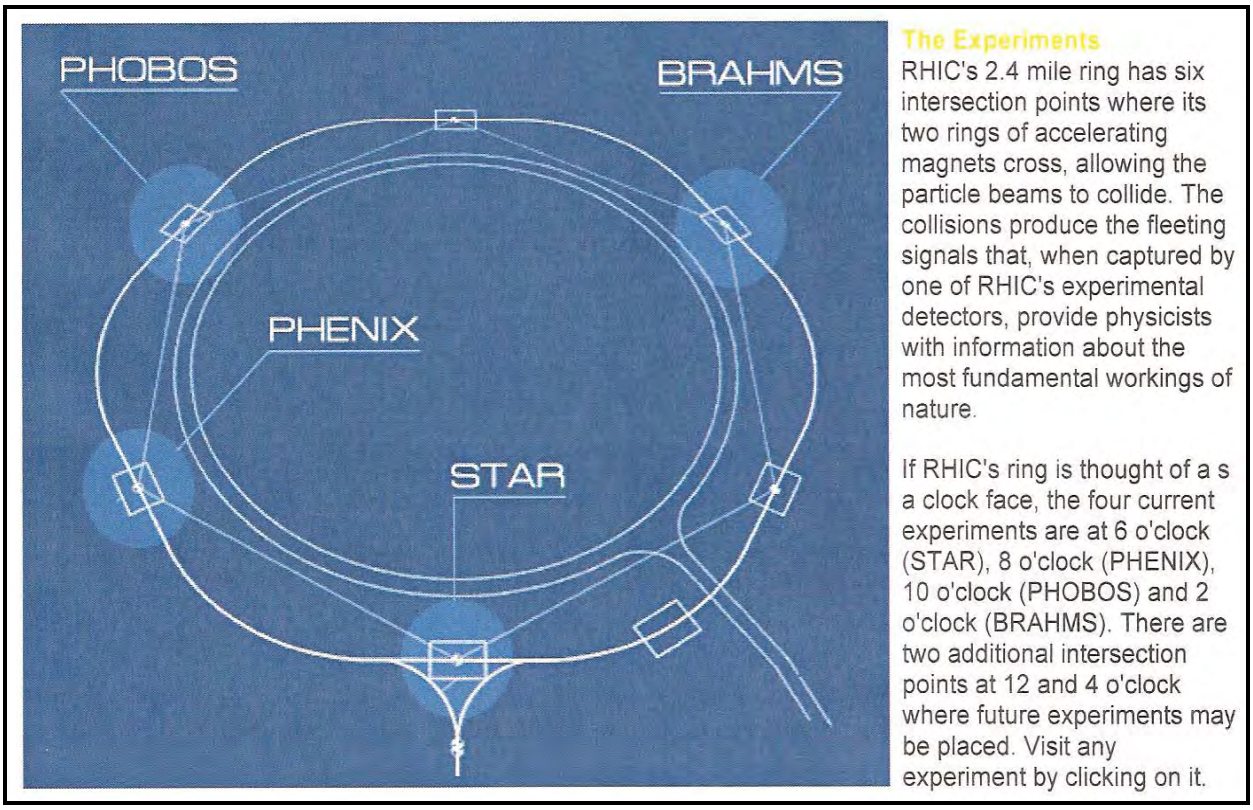

Figure 2-5. RHIC ring intersection points.

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 lab for Survey Group

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, the TPL, was renamed the Hot Laboratory in 1993. The Hot Laboratory officially opened January 15, 1951. It consisted of a central laboratory, a fan house, 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 labs 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) located in the Semi Works Area (Area 56) that were constructed in1958. Metallurgical studies on highly radioactive reactor components are performed in this facility by Department of Applied Technology (DAT) personnel.

There are "D" & "F" waste systems (storage tanks and piping) housed in the building basement. The "D" waste system holds radioactive non-hazardous liquid waste. The "F" waste system holds non-radioactive, non- hazardous 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.

There was a Co-60 irradiation pool in what is now the TPL (Lab 66). The pool, which was constructed of concrete, had depths of 4', 10', 14' where large amounts of sealed Co-60 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 Co-60 pool was moved, water drained and concrete decontaminated and backfilled with sand.

From March of 1952 to June of 1960 there was a program at the Hot Laboratory to produce iodine-131 by acid-dissolution of irradiated uranium samples. A separate exhaust system, that included NaOH scrubbers and backup charcoal filters, was installed in the hot cell and ducted to a stainless steel pipe within 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 5/15/57 a very 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 lbs of un-irradiated uranium to the local environment. Damaged occurred to nearby trees,

automobiles and building equipment. Environmental sampling of the appropriate areas may identify residual uranium contamination.

In August of 1960 some highly radioactive waste (reactor fuel elements) were 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 house 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 contained in the concrete floor and is labeled as a radioactive area.

2.4.13 High Intensity Radiation Development Laboratory (HIRDL), 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), 2 inactive hot cells, analytical laboratories, electron microscopy, and associated offices.

In 1963 Building 830 commenced operations as the HIRDL. At this time it consisted of the high bay area (which houses the 2 hot cells), laboratories, and offices. Cell #1 (preparation Cell) was used to fabricate high intensity Cobalt-60 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 within the cell until needed. Items to be irradiated were moved in and out of the Irradiation Cell by means of 2 transfer tunnels under the cell. Sources were also kept in the 2 bays for storage and irradiation purposes.

In 1970 the Low Dosimetry Facility (currently known as the Gamma Irradiation Facility or 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 down via 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 various radioactive materials and contaminated equipment.

Currently, the two hot cells in Building 830 have very little mission essential work. The Laboratory spaces are being used for various experiments, and the GIF currently contains approximately 35,000 curies of cobalt-60. The GIF is used sporadically for various experiments.

2.4.14 Chemistry Department, Building 555

Building 555 is the home of BNL's Chemistry Department. It was built between 1963-1966. 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 lab. There are pipe chases between rows of labs to deliver all services to the labs. Transparent glass piping in the basement carries waste water from the sinks in the labs 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 wide variety of specialized equipment and instrumentation is in use in different labs; 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 suffice it to say that virtually every chemical element in the Periodic Table has been used at one time or another in the building.

Some radiological problems associated with the building are:

Disposition of sealed Co-60 irradiation sources in labs 171-173. These sources are contained in stainless-steel containers that penetrate the lab floors and are in the ground below. See diagram in Appendix 5. There is evidence that one source (40-Curie source strength) is leaking small amounts of Co-60 into the water that surrounds the source to provide radiological shielding. Some of this contaminated water has gotten into the soil surrounding the buried containment vessel. The amount of Co-60 in the water and in the soil is small. (The estimated Co-60 activity remaining in this soil is less than 35 nCi.)

Radioactive materials and counting samples are used and/or stored in many rooms: Labs 225, 227, 229, 233, 235, 236, 253, 367, 369, 374; and counting rooms 103, 203, 204, 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 P-32 and the other, U-238, were confined to the chemistry labs in which they occurred. The third involved a Kimwipe contaminated with I-124 that was inadvertently thrown into the trash, and was subsequently detected in the garbage truck before it left the BNL site.

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 located 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/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.

The northeast corner of the building houses in the Health Physics Section (Rm 1-136) where there are 35 vaults for storage of radioactive materials. There are 9 Type A vaults that are 12" in diameter and penetrate 10' into the ground, 6 Type B vaults which are 8" in diameter and penetrate 10' into the ground, and 20 Type C vaults which are 8" in diameter and penetrate 3' into the ground. Vault #17 is contaminated because it contained a radium source. The source has been placed in a sealed PVC pipe and is now stored in Vault #4.

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.

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 its equipment and function relocated to building 462. The building was then utilized as a storage area by Plant Engineering until 1988 at which time it was demolished.

Operational Chronology:

1947-1975 - Hot Machine Shop for the Central Shops Division

1975-1988 - Storage Area for Plant Engineering

2.4.16.3 Health Physics & Safety Instrumentation, Building 535

Building 535 was constructed between 1962-1963 and was operational in 1964. The building is a multi-tenant, multi-functional 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 High Flux Beam Reactor (HFBR), the Alternating Gradient Synchrotron (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.

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.

2.4.17 Waste Management Facility (WMF), Radwaste Reclamation Building, Building 865

The Waste Management Facility (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 feet high around the perimeter of the radwaste portion of the facility ensures that incidental exposures meet the BNL design criteria of 25 mrem/year to non-radiation workers.

The WMF includes an Operations Building (Bldg. 860), a RCRA Waste Building (Bldg. 855), a Radwaste Reclamation Building (Bldg. 865), and a Mixed Waste Building (Bldg. 870).

Radwaste Reclamation Building, Building 865 - The Reclamation Building is the primary facility for radioactive waste handling, size reduction, and repackaging for subsequent off-site disposal for BNL. The goal is to size reduce the radwaste 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 prior to shipment off-site. To achieve the goal of waste reduction, Bldg. 865 will house a 500 pound per day lead smelter, a trash compactor, and a shredder.

Additional radwaste treatment facilities include:

Wastewater processing began in 1995. The Tritium Evaporator Facility (BLDG. 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.

Bldg. 811 was designed in the late 1940's 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 which is not removed during this process is tritium. The tritiated water which 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 previously done at Building 446. Decontamination of large pieces continues 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 walk through). Already removed were two wet decontamination tanks (a 20' × 4' × 4' top tank used for acid/base/detergent wash).

Associated with the Waste Decon Facility is an outside decontamination pad. From 1957 to 1981 the 20' × 20' pad was used for washing off surface contamination of 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 has been laid by OER to contain the radiological materials. Soil in the vicinity of the pad has been characterized by OER and is in their remedial plan (1993 Survey, Cs-137, Eu-152, Eu-154, depth of 0.5 feet, exceeding OER clean up 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 both contaminated and clean laundry. In 1996, laundry services were subcontracted and the facility is

now being used for storage of custodial supplies. 650T has always been used as offices since they were first acquired in 1994.

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 within 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 2 of the BNL site profile, that is, to provide background information only.

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

Table 2-2. Area information and parameters.

Section	Name	Description	Period	Building No.	Radionuclide
2.4.1	Brookhaven Graphite Research Reactor (BGRR)	Uranium 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
					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 fan house	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	High Flux Beam Reactor (HFBR)	30-60 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

Table 2-2 (Continued). Area information and parameters.

Section	Name	Description	Period	Building No.	Radionuclide
2.4.2	Cold Neutron Facility (CNF)	Produce extremely low energy neutron by moderate neutron with liquid hydrogen	1980-unknown	751	
2.4.3	Medical Research	Medical Department	1959-present	490	

	Center (MRC)				
2.4.4	Brookhaven Medical Research Reactor (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
					Zn-65
					Zn-69m
2.4.5	PET Imaging Laboratory	Positron Emission Tomographic Scanners for nuclear medicine and neurosciences researches	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	Alternating Gradient Synchrotron (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

Table 2-2 (Continued). Area information and parameters.

Section	Name	Description	Period	Building No.	Radionuclide
2.4.7	200 MeV LINAC	Pre-accelerator 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 fan houses	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	Radiation sources and activated targets

2.4.7	g-2/Bubble Chamber	Contains the 80" 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	H-3
2.4.7	AGS Warehouses	Warehouses	1960-present	975,918,196,209,424,178	
2.4.8	Brookhaven LINAC Isotope Producer (BLIP)	Production of radioisotopes via irradiation in the LINAC beam (200 Mev Protons) Carbon-11, Fluorine-18, nitrogen-13 and oxygen-18	1961-1962	931B	As-72
					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" 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	National Synchrotron Light Source (NSLS)	Produce intense sources of x-rays, ultraviolet and infra-red radiation	1981-present	725	
2.4.10	NSLS Development Laboratory	Houses a linear accelerator	1981-present	729	

Table 2-2 (Continued). Area information and parameters.

Section	Name	Description	Period	Building No.	Radionuclide
2.2.11	Relativistic Heavy Ion Collider (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	
			1988-present	1008	
			1985-present	1008A	

		PHENIX experiment Experimental support building PHOBOS experiment Future experimental hall	1994-present 1994-present	1010 1012	
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
2.4.13	High Intensity Radiation Development Laboratory (HIRDL)	Radioactive sources fabrication, irradiation cells and since 1970, the Gamma Irradiation Facility (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
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 Liquid Metal Fuel Reactor	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 within the Waste Management facility (WMF) for processing of radwaste.	1997-present	865	

Table 2-2 (Continued). Area information and parameters.

Section	Name	Description	Period	Building No.	Radionuclide
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
					H-3
					Mn-54
					Na-22

					Se-75
					Zn-65
2.4.17	Waste Management Incinerator	Low-level Waste incinerator	1995-present	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	1959-1996	650	

2.6 MAGNITUDE OF SITE ACTIVITY

Table 2-3 intends to provide a perspective of the magnitude of the nuclear operations at BNL. The Site Profile preparation guide (ORAU 2005) 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*. Hence, 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 is 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.	Radioactivity	
					Radionuclide	Activity Fraction
2.4.1	Brookhaven Graphite Research Reactor (BGRR)	Uranium fueled Graphite moderated and reflected Reactor 28 MW	1950-1969	701	Ba-140	1.70E-01
					Ce-144	1.08E-01
					Cs-137	7.19E-03

Table 2-3 (Continued). Magnitude Site Activity.

Section	Name	Description	Period	Building No.	Radioactivity	
					Radionuclide	Activity Fraction
					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
2.4.1	BGRR fuel canal	BGRR fuel storage	1950-1972	709	Same as above	Same as above
2.4.1	BGRR exhaust fan house	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	High Flux Beam Reactor (HFBR)	30-60 MW thermal heavy water moderated research reactor	1965-1999	750	Be-7	3.41E-08
					Br-77	3.14E-05
					Br-82	7.31E-06
					Cs-137	2.5E-08
					H-3	1.00E+00
					I-126	4.79E-09
					Mn-54	1.46E-09
					Xe-133	4.06E-07
					Xe-135	4.77E-06
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	Cold Neutron Facility (CNF)	Produce extremely low energy neutron by moderate neutron with liquid hydrogen	1980-unknown	751		
2.4.3	Medical Research Center (MRC)	Medical Department	1959-present	490		
2.4.4	Brookhaven Medical Research Reactor (BMRR)	Enriched U fueled, light water moderated and cooled reactor	1959-2000	491	Ar-41	1.00E+00
					Al-26	5.45E-12
					As-76	2.12E-07
					Ba-128	8.38E-08
					Ba-140	7.03E-08
					Br-82	3.88E-06
					Ce-141	8.20E-11
					Ce-144	6.40E-10
					Co-60	1.19E-09
					Fe-59	1.73E-08
					Hg-203	2.66E-08
					I-124	8.51E-09
					I-131	1.50E-08

Table 2-3 (Continued). Magnitude of Site Activity.

					Radioactivity	
Section	**Name**	**Description**	**Period**	**Building No.**	**Radionuclide**	**Activity Fraction**
					I-133	1.64E-07
					La-140	3.72E-07
					Mo-99	6.94E-11
					Na-24	1.04E-07
					Sb-122	2.17E-10
					Sc-46	9.68E-09
					Se-75	9.19E-11
					Sr-91	1.50E-07
					Tc-99m	2.64E-08
					Ti-44	5.81E-08
					Xe-133	4.59E-08
					Xe-135	4.82E-07
					Zn-65	8.78E-09
					Zn-69m	6.49E-10
2.4.5	PET Imaging Laboratory	Positron Emission Tomographic 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	Alternating Gradient Synchrotron (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	

Table 2-3 (Continued). Magnitude of Site Activity.

Section	Name	Description	Period	Building No.	Radioactivity	
					Radionuclide	Activity Fraction
2.4.7	200 MeV LINAC	Pre-accelerator 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 fan houses	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” 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	Brookhaven LINAC Isotope Producer (BLIP)	Production of radioisotopes via irradiation in the LINAC beam (200 Mev Protons) Carbon-11, Fluorine-18, nitrogen-13 and oxygen-18	1961-1962	931B	As-72	1.33E-07
					As-74	7.24E-10
					Be-7	1.60E-06
					Co-57	3.56E-08
					Co-58	1.44E-07
					Co-60	1.40E-08
					Cs-132	1.43E-09
					Cs-137	2.09E-09
					H-3	1.16E-04
					Mn-54	1.66E-07
					Na-22	6.54E-09
					O-15	1.00E+00
					Sc-46	2.88E-09
					Co-56	1.86E-07
					Ga-68	1.38E-08
					Ge-69	2.01E-09
					I-126	4.17E-08
					Xe-127	4.17E-08
					Zn-65	5.49E-08
2.4.9	Tandem Van de Graaff	Van de Graaff accelerators 60” proton Cyclotron producing 10-MeV protons, 20-MeV	1970 - present	901	Yt-90	
					Ca-47	
					Cu-67	
					Ar-38	
					Mg-28	

		deuterons and 40-MeV alpha particles for medical radionuclide research			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	National Synchrotron Light Source (NSLS)	Produce intense sources of x-rays, ultraviolet and infra-red radiation	1981-present	725		

Table 2-3 (Continued). Magnitude of Site Activity

					Radioactivity	
Section	**Name**	**Description**	**Period**	**Building No.**	**Radionuclide**	**Activity Fraction**
2.4.10	NSLS Development Laboratory	Houses a linear accelerator	1981-present	729		
2.4.11	Relativistic Heavy Ion Collider (RHIC) Complex	High-energy particle accelerator and collider BRAHMS experimental hall RHIC service building Open area (future experimental area) RHIC support building Beam tunnel Offices and tech shops STAR Detector Service building Beam tunnel PHENIX experiment Experimental support building PHOBOS experiment Future experimental hall	1999-present 1981-present 1981-present 1996-present 1994-present 1981-present 1981-present 1985-present 1981-present 1981-present 1988-present 1985-present 1994-present 1994-present	 1002 1004A 1004 1004B 1005 1005S 1006 1006A 1007 1008 1008A 1010 1012		
2.4.12	Hot Laboratory	Target Processing Laboratory	1951-present	801	As-72	2.29E-04
					As-74	9.8E-04
					Be-7	5.23E-04
					Co-57	2.11E-04
					Co-58	1.79E-03
					Co-60	2.39E-04
					Cs-132	9.73E-05
					Cs-137	2.06E-04
					H-3	8.74E-05
					Mn-54	5.80E-05
					Na-22	5.33E-06
					Au-199	4.79E-03
					Bi-213	2.14E-02
					Br-77	8.97E-01
					Br-82	1.54E-02
					Se-75	4.94E-02
					V-48	6.72E-04
					I-126	2.84E-03
					Se-75	6.76E-10
					Ge-69	4.56E-03
2.4.13	High Intensity Radiation Development Laboratory (HIRDL)	Radioactive sources fabrication, irradiation cells and since 1970, the Gamma Irradiation Facility (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 Liquid Metal Fuel Reactor	1957-1975	820		
2.4.16.2	Hot Machine Shop	Hot Machine Shop	1947-1975	530		

Table 2-3 (Continued). Magnitude of Site Activity.

					Radioactivity	
Section	**Name**	**Description**	**Period**	**Building No.**	**Radionuclide**	**Activity Fraction**
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 within the Waste Management facility (WMF) for processing of radwaste	1997-present	865		
2.4.17	Tritium Evaporator Facility	Reduce tritium release by evaporation	1995-present	802B	I-133	1.48E-05
					Rb-83	1.08E-05
					Rb-86	4.43E-05
					Be-7	2.40E-04
					Co-56	1.51E-06
					Co-57	1.52E-05
					Co-58	9.13E-06
					Co-60	1.21E-05
					Cs-137	2.68E-05
					H-3	9.99E-01
					Mn-54	9.62E-06
					Na-22	6.8E-07
					Se-75	1.07E-06
					Zn-65	2.24E-04
2.4.17	Waste Management Incinerator	Low-level Waste incinerator	1995-present	444	H-3	2.66E-02
					Sr-85	4.83E-05
					I-125	3.14E-02
					Co-57	4.83E-06
					Sc-47	1.21E-05
					Zn-65	1.69E-02
					C-14	7.00E-01
					P-32	1.93E-02
					S-35	1.06E-01
					Fe-59	2.41E-03
					Sn-117m	2.41E-03
					Sn-113	6.35E-03
					Cr-51	2.66E-02
					Be-7	6.16E-02
2.4.18	Radiological Waste Decontamination Facility	Decontamination of radiological waste	1959-1996	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 which 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 the natural uranium. There was one rupture of a uranium oxide (U3O8) sample that was being irradiated for the radioiodine-production program. Aside from argon-41, iodine-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 iodine-133 were released in some what larger concentrations.
Hot Laboratory, Building 801	5/15/1957	There was a very serious incident involving the Volatility Project where uranium reprocessing was the objective. There was an explosion of UF6/BrF3 and a few people were injured, one hospitalized. There was a release of about 13 lbs of un-irradiated uranium to the local environment. Apparently, the UF6 combines with moisture readily to form an oxide. The BrF3 is very corrosive and damaged nearby trees and automobiles and equipment in the Building.
	8/1960	There was 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 to the house vacuum system. The house 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 contained in the concrete floor and is labeled as a radioactive area.
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.

2.8 RADIOLOGICAL ACCESS CONTROLS

Radiological access controls are 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).

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3.0 OCCUPATIONAL MEDICAL DOSE

3.1 INTRODUCTION

U.S. Atomic Energy Commission-funded work at Brookhaven National Laboratory (BNL) began in 1948. BNL clinicians prescribed chest X-rays as part of the pre-employment and routine physical examination. These radiographs caused exposure of the lungs and other tissues of the body. Exposure came from the primary X-ray beam and from scattered and leakage radiation.

Substantial information regarding the historical BNL occupational X-ray program has been located. The current medical director and two BNL X-ray technicians were interviewed and a few older X-ray films were reviewed to gain insight into the occupational medical program and collimation practices (Morris 2006a, b, c, and d). A peer-reviewed publication (Handloser and Love 1951) provided exposure rate data specific to the BNL radiographic equipment and techniques in use for diagnosis of radioactive material workers in 1950. A transcript of interviews conducted in preparation for an epidemiology study (Brodsky 1960) included discussions with BNL's first medical director regarding the early radiographic examination practices, equipment and exposure rates.

3.2 PURPOSE

The purpose of this section is to determine the radiation dose associated with the occupational medical X-ray program conducted at the BNL.

3.3 SCOPE

The scope of this effort involved reviewing records, interviewing current and previous X-ray technicians and reviewing X-ray films selected at random and dating back to 1948. Peer-reviewed publications provided exposure-rate data specific to the BNL radiographic equipment and practices in use for diagnosis of radioactive-material workers in 1950. Review of transcripts of interviews with BNL's first medical director revealed the early radiographic examination practices, equipment and exposure rate.

3.4 EXAMINATION FREQUENCY

The energy employee medical chart provided by DOE may provide information on the number and kind of X-rays administered to the energy employee.

Beginning in 1947 and continuing until at least 1964, pile (reactor) operators and possibly the hospital medical staff were subjected to an entry and an annual physical examination, including a PA chest X-ray. All other workers, including visiting scientists employed for more than three months, were on a less frequent schedule. This group received an entry physical and a re-examination, including a PA chest X-ray, on a frequency averaging about one exam every 2.5 years (Brodsky 1964 pp. 38 – 39 and p.72). It is assumed this examination frequency pattern continued through 1978.

In 1978 a Presidential Recommendation to federal agencies advised to not perform routine or screening radiographic examinations, including chest X-rays, on patients for whom no prior clinical evaluation of the patient is made (Carter, 1978). This recommendation, at least in part, was incorporated into BNL practice and the average time between radiographic examinations increased. Starting with 1979 the re-examination cycle is assumed for all employees to be once every 7 years (Morris 2006b). Pre-employment radiographic examination is assumed to continue as a condition of employment.

At some date in the 1980s (the exact year is unknown) 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 re-examination frequency.

Current (as of 2006) pre-employment 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, pre-employment PA and LAT chest X-ray are required. No lumbar spine films are done as a pre-employment requirement. The time between routine chest X-rays has been extended over the years and now occurs on a 7 to 10 year cycle (Morris 2006b and c).

3.5 EQUIPMENT AND TECHNIQUES

The first BNL occupational X-ray was taken in October 1947 using a machine known as the "Powers unit" which may have been a portable machine designed for tuberculosis screening using photosensitive paper as the image receptor. No specific data are available about the technique, filtration or collimation. However, in a retrospective interview, the medical director stated each film caused a 4,000 mR exposure (Brodsky 1964, p. 36). It is assumed that the primary beam was not collimated. Medical radiographic tubes used in the 1940s typically had inherent filtration of 0.5 mm Al (ORAUT 2005, p. 9). Assuming the unit operated at a nominal tube potential of 70 kV, this corresponds to an HVL of approximately 0.8 mm Al (NCRP 1989, Table B.2).

By 1948 or 1949 the hospital facilities at BNL were built and a "photocross pocket unit" was installed. No specific data are available about the technique, filtration or collimation. However, the medical director stated some of the techniques used created a 1,000 mR exposure. It is assumed that the primary beam was not collimated.

The "photocross pocket unit" was soon replaced with another unit, not otherwise described. This new unit reduced the exposure associated with a 14 × 17 inch film to between 50 and 75 mR. It is assumed that the primary beam was not collimated.

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 photofluoroscopic unit, a fluoroscopic unit and a diagnostic film unit. However, it is concluded that only the diagnostic unit was used routinely for examinations required as a condition of employment (Brodsky). The 14 × 17 inch PA chest film technique used for employee screening was done using a Dynamax 25 tube head, style number 981625, serial number 12173, with 0.5 mm Al filtration operating at 200 mA and 1/10 second at 72 inches. The nominal tube potential used in this technique was 72 kV and only the tube potential was adjusted to compensate for patient size (Handloser and Love 1951). The HVL of the X-ray beam is expected to be 0.8 mm Al (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, collimated General Electric machine capable of fluoroscopy was in use for chest exposures in 1960. The unit was set up in Room 2 and used almost exclusively for chest X-ray (Morris 2006c). The equipment was equivalent to the new X-ray machines in service at nearby Smithtown General Hospital. Although no specific information is available regarding filtration, it is assumed that the unit contained 2.5 mm Al filtration as recommended by the NCRP at that time (ORAU 2005, p. 9). The technique used for chest film remained consistent from 1960 to 1993 (Morris 2006a). For a PA chest film the nominal technique was 100 kVp, 200 mA, 1/60 s at 72 inches and the exposure was about 5 mR. The LAT chest film nominal technique was 100 kVp, 200 mA, 1/30 s at 72

inches. The GE machine was in service until 1991 when it was replaced by a Picker unit that is currently in service in room 1.

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 half value layer (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, 2004). For a PA chest film the nominal technique in current use is 110 kVp and 3.2 mAs at 72. 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 the years 1949 through 1971 were reviewed to determine past beam collimation practices. The equipment in use appears to have allowed the technician to manually set the collimation. In some films prior to the early 1970's 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 may indicate that collimation was established just at the edges of the film cassette and where 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 since 1960 were collimated.

3.6 ENTRANCE SKIN EXPOSURE (ESE)

In 1951 the BNL medical staff adopted the unusual (possibly unique) practice of recording the ESE for some examinations. Such information is found on the radiologist's interpretation form "Report of X-ray Examination" which 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 (Brodsky 1964, p 67). These contemporary data reflect the exposure for a specific machine and a nominal, not patient-specific, technique. It is not known if this exposure included backscatter, and it does not appear to adjust for the patient's chest thickness. So though it may 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

The first BNL medical director stated in a retrospective interview that each X-ray exposures made in 1947 using the "Power[s] unit" caused a 4 R exposure (Brodsky 1964, p 36).

1948 to 1949

In 1948 or 1949 the "photocross pocket unit" was in use creating a 1 R exposure. By 1950, the exposure associated with a 14 × 17 inch film was reduced to 50 to 75 mR (Brodsky 1964, p 36). This is consistent with the specific information published in Handloser and Love (1951).

1950 to 1960

Precisely measured exposure for diagnostic procedures was reported in a peer-reviewed journal (Handloser and Love 1951). PA chest films (14 × 17 inches) produced an exposure at the skin location, including backscatter, of approximately 54 mR. Exposure was measured with and without a paraffin phantom adjacent to the detector. The results were tabulated only for the measurements with the phantom, but they were displayed graphically for measurements with and without the phantom. Visual interpretation of the data shows the skin exposure was approximately 22% higher when the

phantom was in place. This is equivalent to a backscatter factor (BF) of 1.22. To determine ESE, which is exclusive of backscatter, the measured value with a phantom is divided by the BF resulting in an ESE for PA chest films of 44 mR.

Although it seems unlikely that the following techniques were routinely used for examinations performed as a condition of employment, the following ESEs were also reported:

- PA chest photofluoroscopy ranged from 700 to 1,200 mR, proportional to patient size,
- AP lumbar spine 1,500 mR,
- LAT lumbar spine 5,700 mR.

1960 to 1990
By 1960 the GE equipment in Room 2 was in routine service for chest radiography (Morris 2006c). In 1985 a measurement of the GE unit in Room 2 was performed at 100 kVp and 200 mA (Zukas 1987), the chest technique in use at the time (Morris 2006a). The exposure rate at the film for a 1/40 s exposure was 1.60 mR/mAs. When this is scaled to the 1/60 s exposure time used in the PA chest view and corrected based on the inverse squared relationship for a SSD of 154 cm the entrance skin exposure for that view is calculated as 7.5 mR. When LAT view is scaled for exposure time, 1/30 s, and corrected for SSD the calculated entrance skin exposure is 15 mR. It is possible that higher tube potentials were used for the LAT chest view. For consistency with a rule of thumb (ORAU 2005, p 20) and to ensure this exposure is not underestimated it is rounded up to 20 mR.

1991 to present
Between 1996 and 2004 the PA chest ESE from the Picker unit in Room 1 was measured at least five times by ABR / ABMP 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 inch SID and 23 cm phantom. The ESE ranged from 6.7 to 8.1 mR. For years 1991 to the present (2006) 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 (ORAU 2005, p 20).

3.7 ORGAN DOSE CALCULATIONS

ICRP Publication 34 Method for collimated exposures
The methodology of ICRP Publication 34 (1982) is used to estimate the organ doses when the tabulated dose conversion factors (DCF) for collimated X-ray beams are applicable. The method is described in section 3.7.1, Organ Dose from Collimated Exposure. Modifications to this method to account for poorly collimated X-ray beams are described in section 3.7.2, Organ Dose from Uncollimated Exposure. Calculation of skin dose is described in section 3.7.3, Skin Dose.

Tables 3-1 and 3.2 are summaries of parameters, organ doses and skin doses for 14-in. by 17-in. PA and LAT chest radiographs respectively, for the periods during which each X-ray system was in use. In these tables the remainder organs are assigned the same dose as the female lung which is the organ with the highest DCF.

Tables 3-3 and 3-4 list, by year, certain organ doses useful in a dose reconstruction for PA chest and LAT chest, respectively. When the organ dose differs between male and female, the larger of the two is listed. In these tables both the maximum additional organs and the maximum remainder organs are

assigned the same dose as the female lung which, for chest projections, is the organ with the highest DCF.

3.7.1 Organ Dose from Collimated Exposure

In ICRP 34 (1982) methodology, organ dose (OD) is the product of entrance kerma (EK) and a dose conversion factor (DCF). Entrance kerma is defined in ICRP 34 (1982) as "air kerma in air without backscatter." For practical application it is numerically the same as, and can be used interchangeable with, entrance skin exposure (ESE) (ORAUT 2005, p. 16). For organs other than skin, organ dose is calculated as shown in Eq. 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 appropriately collimated.

DCFs for some organs are not tabulated in ICRP 34 (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 34 (1982) lists gender-based DCFs and in that situation the larger of the two values is assigned as the DCF to the IREP organ analogues.

3.7.2 Organ Dose from Uncollimated Exposure

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

For exposures prior to 1960 the HVL is known or assumed to be less than 1 mm Al. ICRP 34 DCF values are reported only for beam quality in which the HVLs range from 1.5 to 4 mm Al. To address these data shortfalls, DCFs tabulated for HVLs of 1.5 mm Al are used. If the DCFs for an HVL of 0.8 mm Al are derived from a power function fitted to the ICRP 34 data, they would, on average, be lower by about 50%.

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 may 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 Tables 3.1 and 3.3.

3.7.3 Skin dose

Skin doses from AP and LAT chest projections are calculated differently depending on proximity 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 Eq. 3.2. The BF is from Table B-8 of NCRP 102 (NCRP 1989) or from empirical data (Handloser and Love 1971). The ENSD

applies to all skin surfaces in the beam on the *entrance side* of the body. For collimated chest projections this includes the skin of the back, back of the neck, back of the shoulders, and upper lower back. For poorly collimated chest projections this includes the skin of all of the above, plus skin of the upper arms, elbows, and ears.

$$ENSD = ESE \times BF \tag{3.2}$$

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 No. 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. For collimated chest projections this includes the skin of the front of the neck, the front of the shoulders, and upper abdomen. For poorly collimated chest projections this includes the skin of the all of the above, plus the face below the eyebrows, upper arms, elbows, and ears.

$$EXSD = {ENSD}/{AFF} \tag{3.3}$$

$$AFF = AF \times 0.9 \tag{3.4}$$

ENSDNPB is 10% of the ENSD as shown in equation 3.5. This equation is based on the tabulated values in ICRP 34 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 No. 49 (NCRP 1976),
- average depth dose (ADD) at 12 cm (mid chest depth) for the technique tabulated in NCRP 102 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.

$$RSD = ENSD \times 0.0005 \times ADD \times 1.1 \times \left(\frac{1}{R}\right)^2 \tag{3.7}$$

3.8 DOSE RECONSTRUCTION

Tables 3-1 through 3-4 may be used for screening calculations to estimate the number and type of X-rays a worker may have received and the organ dose from each one. The medical records provided by DOE may 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 pre-employment 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 that the exposures were made, for example pre-employment 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 envelop 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.

3.9 UNCERTAINTY

ORAU (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. ORAU (2005) assesses the relative error in an individual ESE or organ dose to be ±30% at 1 standard deviation. For adjustment that is favorable to the claimant, the actual doses could have been as much as 30% larger than those listed in Tables 3-1 through 3-4.

Table 3-1. Parameters and organ doses in rem for 14-in. by 17-in. PA chest radiography.

Period	Frequency	Applicability	PA chest ESE (mR)	Organ doses (rem) from 14-in by 17-in PA chest radiography								
				Thyroid[a,c]	Ovaries[a,d]	Testes[a,d]	Lungs[a]	Breast[a]	Uterus (embryo)[a,d]	Bone marrow[a]	WB[a]	Remainder[b]
1947	Entrance: yes Routine reexamination: annual Exit: no	Pile (reactor) operators and medical staff	4000 Assumed to be uncollimated	4.8E-01	2.8E-01	1.2E-02	Male 9.7E-01 Female 1.0E+00	7.2E-02	2.6E-01	Male 2.0E-01 Female 1.7E-01	Male 3.3E-01 Female 2.6E-01	1.0E+00
1947	Entrance: yes Routine reexamination: approximately 2.5 year interval Exit: no	All other workers										
1948 to 1949	Entrance: yes Routine reexamination: annual Exit: no	Pile (reactor) operators and medical staff	1000 Assumed to be uncollimated	1.2E-01	6.9E-02	3.1E-03	Male 2.4E-01 Female 2.5E-01	1.8E-02	6.45E-02	Male 4.9E-02 Female 4.3E-02	Male 8.3E-02 Female 6.6E-02	2.5E-01
	Entrance: yes Routine reexamination: approximately 2.5 year interval Exit: no	All other workers										
1950-1960	Entrance: yes Routine: annual Exit: no	Pile (reactor) operators and medical staff	44 Assumed to be uncollimated	5.3E-03	3.0E-03	1.4E-04	Male 1.1E-02 Female 1.1E-02	7.9E-04	2.8E-03	Male 2.2E-03 Female 1.9E-03	Male 3.7E-03 Female 2.9E-03	1.1E-02
	Entrance: yes Routine reexamination: approximately 2.5 year intervals Exit: no	All other workers										
1960 to 1978	Entrance: yes Routine: annual Exit: no	Pile (reactor) operators and medical staff	7.5	2.4E-04	7.5E-06	7.5E-08	Male 3.1E-03 Female 3.4E-03	3.7E-04	9.8E-06	Male 6.9E-04 Female 6.5E-04	Male 9.8E-04 Female 8.9E-04	3.4E-03
	Entrance: yes Routine reexamination: approximately 2.5 year intervals Exit: no	All other workers										
1979 to 1991	Entrance: yes Routine: assumed to be at 7-yr intervals Exit: no	All workers										
1991 to present	Entrance: yes Routine: assumed to be at 7-yr intervals Exit: no	All workers	10	6.2E-04	3.2E-05	1.0E-07	Male 5.7E-03 Female 6.1E-03	9.1E-04	3.0E-05	Male 1.5E-03 Female 1.4E-03	Male 1.7E-03 Female 1.6E-03	6.1E-03

a. Organs identified in ICRP (1982) for dose determination from ESE associated with chest radiography.
b. Female lung is the reference organ for "Remainder".
c. For uncollimated projections the DCF for thyroid is based on the AP cervical spine projection as showm in ORAUT (2005) Table 9-11.
d. For uncollimated projections the DCF for ovaries, testes, and uterus is based on the PA abdominal projection as shown in ORAUT (2005) Table 9-11.

Table 3-1 (Continued). Parameters and organ doses in rem for 14-in. by 17-in. PA chest radiography.

Period	Frequency	Applicability	Skin doses (rem) from 14-in by 17-in PA chest radiography						
			Entrance skin dose in primary beam	Exit skin dose in primary beam	Entrance skin dose near but outside primary beam	Exit skin dose near but outside primary beam	Remote skin dose – thighs to knees[e]	Remote Skin dose – knees to ankles[f]	Remote skin dose – ankles[g]
1947	Entrance: yes Routine reexamination: annual Exit: no	Pile (reactor) operators and medical staff	4.9E+00[h]	3.3E-02[j]	4.9E-01	3.3E-03	7.3E-04	2.7E-04	1.2E-04
1947	Entrance: yes Routine reexamination: approximately 2.5 year interval Exit: no	All other workers							
1948 to 1949	Entrance: yes Routine reexamination: annual Exit: no	Pile (reactor) operators and medical staff	1.2E+00[h]	8.1E-03[j]	1.2E-01	8.1E-04	1.8E-04	6.5E-05	2.9E-05
	Entrance: yes Routine reexamination: approximately 2.5 year interval Exit: no	All other workers							
1950-1960	Entrance: yes Routine: annual Exit: no	Pile (reactor) operators and medical staff	5.4E-02[h]	3.6E-04[j]	5.4E-03	3.6E-05	8.0E-06	2.9E-06	1.3E-06
	Entrance: yes Routine reexamination: approximately 2.5 year intervals Exit: no	All other workers							
1960 to 1978	Entrance: yes Routine: annual Exit: no	Pile (reactor) operators and medical staff	1.0E-02[i]	2.3E-04[k]	1.0E-03	2.3E-05	3.3E-06	1.2E-06	5.4E-07
	Entrance: yes Routine reexamination: approximately 2.5 year intervals Exit: no	All other workers							
1979 to 1991	Entrance: yes Routine: assumed to be at 7-yr intervals Exit: no	All workers							
1991 to present	Entrance: yes Routine: assumed to be at 7-yr intervals Exit: no	All workers	1.4E-02[i]	4.3E-04[l]	1.4E-03	4.3E-05	5.4E-06	2.0E-06	9.1E-07

e. Remote Skin Dose – Thighs to Knees is calculated at 0.52 m from the beam center line.
f. Remote Skin Dose - Knees to Ankles calculated at 0.86 m from the beam center line.
g. Remote Skin Dose – Ankles calculated at 1.28 m from the beam centerline.
h. EK times BSF of 1.22 from Handloser and Love, 1951.
i. Ek times BSF of 1.35 from NCRP 102.
j. 1.5 mm Al HVL and chest thickness of 25 cm.
k. 3.0 mm Al HVL and chest thickness of 25 cm.
l. 4.0 mm Al HVL and chest thickness of 25 cm.

Table 3-2. Parameters and organ doses for 14-in. by 17-in. LAT chest radiography.

Period	Frequency	Applicability	LAT chest ESE (mR)	Thyroid[a]	Ovaries[a]	Testes[a]	Lungs[a]	Breast[a]	Uterus (embryo)[a]	Bone marrow[a]	WB[a]	Remainder[b]
Pre-1979	Entrance: none Routine annual: none Exit: none	All workers	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1979 to 1990	Entrance: likely Routine assumed to be at 7 year intervals Exit: none	All workers	20	2.3E-03	1.2E-05	2.0E-06	Male 3.9E-03 Female 4.4E-03	5.1E-03	1.2E-05	Male 7.4E-04 Female 5.8E-04	Male 1.2E-03 Female 1.3E-03	4.4E-03
1991 to present	Entrance: likely Routine assumed to be at 7 year intervals Exit: none	All workers	25	3.8E-03	4.0E-05	2.5E-06	Male 6.9E-03 Female 7.8E-03	7.9E-03	3.5E-05	Male 1.5E-03 Female 1.2E-03	Male 2.4E-03 Female 2.2E-03	7.8E-03

a. Organs identified in ICRP (1982) for dose determination from ESE associated with chest radiography.
b. Female lung is the reference organ for “Remainder”.

Table 3-2 (Continued). Parameters and organ doses in rem for 14-in. by 17-in. LAT chest radiography.

Period	Frequency	Applicability	Skin dose in rem from 14-in × 17-in LAT chest radiography						
			Entrance skin dose in primary beam[c]	Exit skin dose in primary beam[d]	Entrance skin dose near but outside primary beam	Exit skin dose near but outside primary beam	Remote skin dose – thighs to knees[c]	Remote skin dose – knees to ankles[d]	Remote skin dose – ankles[e]
Pre-1979	Entrance: none Routine annual: none Exit: none	All workers	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1979 to 1990	Entrance: likely Routine assumed to be at 7 year intervals Exit: none	All Workers	2.7E-02	1.3E-04	2.7E-03	1.3E-05	4.7E-06	1.7E-06	7.7E-07
1991 to present	Entrance: likely Routine assumed to be at 7 year intervals Exit: none	All workers	3.5E-02	2.3E-04	3.5E-03	2.3E-05	7.4E-06	2.7E-06	1.2E-06

c. Remote Skin Dose – Thighs to Knees is calculated at 0.52 m from the beam center ling.
d. Remote Skin Dose – Knees to Ankles calculated at 0.86 m from the beam centerline.
e. Remote Skin Dose – Ankles calculated at 1.28 m from the beam centerline.

Table 3-3. Maximum organ doses (rem) for 14-in. by 17-in. PA chest radiography.

Year	Maximum thyroid	Maximum ovaries	Maximum additional organs[a]	Maximum remainder[b]
1947	4.8E-01	2.8E-01	1.0E+00	1.0E+00
1948 to 1949	1.2E-01	6.9E-02	2.5E-01	2.5E-01
1950 to 1960	5.3E-03	3.0E-03	1.1E-02	1.1E-02
1961 to 1990	2.4E-04	7.5E-06	3.4E-03	3.4E-03
1991 to 2006	6.2E-04	3.2E-05	6.1E-03	6.1E-03

a. Not including skin.
b. Female lung is the reference organ for "Maximum additional organs" and "Maximum remainder".

Table 3-4. Maximum organ doses (rem) for LAT chest radiography.

Year	Maximum thyroid	Maximum ovaries	Maximum additional organs[a]	Maximum remainder[b]
1947	N/A	N/A	N/A	N/A
1948 to 1949	N/A	N/A	N/A	N/A
1950 to 1960	N/A	N/A	N/A	N/A
1979 to 1990	2.3E-03	1.2E-05	4.4E-03	4.4E-03
1991 to 2006	3.8E-03	4.0E-05	7.8E-03	7.8E-03

a. Not including skin.
b. Female lung is the reference organ for "Maximum additional organs" and "Maximum remainder".

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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. 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 2001).

Monitoring results from up to four onsite stations are available for some years between 1967 and 1984. When 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 has steadily increased to over 50 onsite stations as of 2004.

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 Off-Site Monitoring

Prior to 1962, average and maximum environmental external gamma doses are derived from summary data published in retrospect (Meinhold and Meinhold 2001). During the period 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. After 1966, on-site monitoring results were no longer reported and the only data available are fenceline measurements which in general are remote from areas occupied by employees. Consequently, after 1966 we conservatively assume that both the average and maximum annual doses are 100 mrem, the public dose limit. This assumed average value was exceeded only once in the prior years. The results, presented in Table 4-1, have been adjusted to reflect 2000 hour per year occupancy.

4.4.2 Applicability For Dose Reconstruction

For purposes of dose reconstruction the ambient external dose should be applied to all unmonitored workers.

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

Year	Monitoring location P-9	Monitoring location S-10	Monitoring location S-11	Monitoring location S-12	Site average	Error 1 standard deviation	Maximum
1947					0		0
1948					0		0
1949					0		0
1950					0.18		0.27
1951					6.4		9.2
1952					8.0		11
1953					8.5		12
1954					8.9		13
1955					8.9		13
1956					8.5		12
1957					7.3		11
1958					21		30
1959					27		39
1960					32		50
1961					27		39
1962	44	35	59	74	53	17	74
1963	135	141	125	127	132	8	141
1964	42		64	41	49	13	64
1965	40		97	38	58	34	97
1966	40		128	28	65	54	128
1967 to present					100		100

Notes:
Monitoring locations P-9 was originally known as E-9.
Monitoring locations S-10, S-11 and S-12 were originally known as E-10, E-11 and E-12.
Data prior to 1950 are assumed based on site activities in those years.
Data from 1950 to 1961 are from Meinhold and Meinhold (2001).
Data from 1962 to 1965 are extracted from annual environmental monitoring reports
Data after 1965 are assumed, based on personnel dosimetry program criteria.
Error term includes only counting uncertainty and does not include sampling uncertainty.

4.5 INHALATION OF ONSITE AIRBORNE RADIONUCLIDES

BNL has monitored releases to the environment since 1950 when the first stack became operational (Meinhold &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

Except for 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 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

In Table 4-2 the intake of each radionuclide that substantially contributes to personnel dose is tabulated by year. As stated previously, except for 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 then increased by a factor of 1.5 to account for direct absorption through the skin.

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.

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 the internal dose section of this document. If no data are available default solubility classes and particle size values from the International Commission on Radiological Protection should be used (NIOSH 2002, pp. 15–16).

Table 4-2. Annual environmental occupational radionuclide inhalation (Bq/yr).

Year	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
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	4.88E+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
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	2.59E+03	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

Table 4-2 (Continued). Annual environmental occupational radionuclide inhalation (Bq/yr).

Year	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
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

Table 4-2 (Continued). Annual environmental occupational radionuclide inhalation (Bq/yr).

	Radionuclide												
Year	Tc-99m	Ru-103	Rh-106 Ru-106	Cs-134	Cs-137	Ba-140	La-140	Ce-141	Ce-144	Eu-152	Eu-155	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	0.00E+00	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
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

Table 4-2 (Continued). Annual environmental occupational radionuclide inhalation (Bq/yr).

	Radionuclide												
Year	Tc-99m	Ru-103	Rh-106 Ru-106	Cs-134	Cs-137	Ba-140	La-140	Ce-141	Ce-144	Eu-152	Eu-155	Ra-226	Th-228
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

NOTES:
Highlighted values are bounded by available data. Missing years filled in w/ nearest results (highest value if uneven interval).
Values not highlighted are from closest available result.
Tc-99 reported for incinerator only which operated from 1981-1996.
Tc-99m and Eu-155 are reported for BMRR which began operating in 1959; Tc-99m also reported for incinerator.
Cs-134 reported for BLIP which began operating in 1973; also reported for evaporator.

4.6 INGESTION

Potable water, supplied from on-site 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.

Neither potable groundwater nor soil ingestion have been found to be pathways of exposure. No ingestion dose is indicated.

4.7 UNCERTAINTY

A high degree of uncertainty is associated with environmental monitoring. Uncertainty is the result of many factors listed here in approximately 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 adequately represent the unmonitored worker; efficiency of radioactive iodine sampling media prior to 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 , but can be reasonably expected to range from more than a factor of 10 for atmospheric dilution, to about 20% for accuracy of measurement.

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. The largest annualized concentration or measurement result is used for intake or exposure, and other assumptions 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.

The data presented provide an upper bound for annual external dose and radionuclide intake. The claimant-favorable biases incorporated into the analysis make a quantitative expression of uncertainty unnecessary.

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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 the Brookhaven National Laboratory (BNL). This Section provides supporting technical data to evaluate internal occupational doses that can reasonably be associated with worker radiation exposures covered by the EEOICPA legislation.

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 worker.

The Section presents the technical basis of methods used to prepare dose information for input to the NIOSH IREP (Interactive RadioEpidemiological Program) computer code, and evaluates the uncertainty for BNL exposure and dose records.

5.4 THE BIOASSAY RECORDS IN THE INDIVIDUAL FILES

5.4.1 Brookhaven National Laboratory Bioassay Record (Form 1720)

The BNL bioassay record, Form 1720, contains one line (record) per sample. The record includes 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 mL 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 MFP (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 only appeared with MFP results, indicating a sequential analysis. This form appears

to have been used from 1967 until at least 1986. Data from as far back as 1952 appears to have been transferred to these forms in 1967.

5.4.2 Brookhaven National Laboratory Tritium Exposure Evaluation

This form was used to calculate the whole body dose from tritium bioassay results. Results 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 was less than some threshold (probably about 0.5 µCi/L). The form was used from the 4th 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 Brookhaven National Laboratory 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.

5.4.3 Summary of Whole-body Counting Results

Summaries of the whole-body counting results may 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.

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 at single detector and were 15-minutes in length. 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 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 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.

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 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 (NYOO 1949d). 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. For convenience, this organization will be referred to as *EML* throughout this document.

5.5.2 History of *In Vitro* Urine Analysis

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 (EML 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 utilized 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 AEC's New York Operations Office 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 1956 to 1964, the reporting level for uranium in urine by fluorometric analysis by EML appears to have been 1.0 µg/L (see for example EML 1957). Determination of ^{233}U and ^{235}U in urine was by fluorometry and alpha counting (EML 1956, 1961, 1962). It is uncertain whether the analyses by EML were for direct support, verification, or only for specific analyses needed. In May of 1963, 112 urine samples were processed by the in-house bioassay lab. 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 (Bond 1973). In 1977, the Health Physics and Safety Division housed an analytical chemistry and bioassay laboratory (Liverman 1977). At least by 1999, Eberline was contacted for bioassay analyses, except for H-3 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 the DOE Laboratory Accreditation Program.

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 as fission products from fuel uranium surface contamination, such as ^{24}Na, were present at less than 100 times tolerance.

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 (WBCs and/or urinalysis) using guidance provided by Personnel Monitoring. This could also have included the frequency of monitoring (BNL 1995, Holeman 1999). Therefore, it may 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 clean-up 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 may 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		No comprehensive documentation was located. It appeared to vary from weekly to monthly over time.
24-hour 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 ^{109}Cd, ^{85}Sr, ^{68}Ga, ^{22}Na, and ^{58}Co[a]

a. 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, whole body 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 whole body counting started. Afterwards, all new pile operators received a whole body count before they started working and, starting in about 1962, annually thereafter. Other groups were apparently counted in the whole body counter as time permitted.

Background counts were taken on unexposed individuals as a check on fallout radionuclides (e.g., cesium) in the general population (Love 1964). 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" whole body counter 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 over 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 et al., 1980). In between these measurement trips, the counter was used at BNL as a 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 whole body counting facility to localize the contamination (Miltenberger 1981a). The minimum detection level (MDL) for the shadow shield arrangement was calculated in µCi by:

$$MDL = \frac{4.65\sqrt{Ct_b}}{900 * 37 * K}$$

Where:

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

By 1981, Cs-137 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 I-131 using a NaI counting system was "on the order of 10 nanocuries" (Miltenberger 1989).

The shadow shield replaced by stand up 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 whole body counter. The MDA for each radionuclide was calculated by:

$$MDA = \frac{3.29 * S_b + 3}{KT}$$

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 (Reciniello 2003).

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
Pre-employment and annual WBC[a]	1962-unknown	Annual for pile operators
Urine samples for H-3[b]	1993-unknown	Weekly for reactor operators, supervisors, maintenance technicians, and S&EP building safety services technicians
WBC[b]	1993-unknown	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.

a. Love (1964)
b. Reciniello (1993)

5.7 UNCERTAINTY

At BNL the uncertainty for a single bioassay measurement was not reported consistently. Uncertainties associated with the analysis of MFP, ^{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. Currently, the Severn-Trent (ST) contract laboratory reports results with both a 1 sigma counting error and a 1 sigma total error.

5.8 DETECTION LIMITS

Table 5-3 lists the MDAs and reporting levels for periods corresponding to the bioassay methods discussed in Sections 5.3 and 5.4. 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.

Table 5-3. Detection limits.

Radionuclide	Method/ description	Period	MDA[a]	Reporting level[b]
Na-22 (1274.54 keV)	WBC	1999	3 nCi	
Mn-54 (834.83 keV)	WBC	1999	3 nCi	
Co-57 (122.06 keV)	WBC	1999	7 nCi	
Co-58 (810.76 keV)	WBC	1999	4 nCi	
Fe-59 (1099.22 keV)	WBC	1999	4 nCi	
Co-60 (1332.49 keV)	WBC	1999	5 nCi	
Zn-65 (1115.52 keV)	WBC	1999	5 nCi	
Cs-134 (604.7 keV)	WBC	1999	3 nCi	
Cs-137 (661.65 keV)	WBC	1999	4 nCi	

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

Table 5-3. Detection limits (continued)

Radionuclide	Method/ description	Period	MDA[a]	Reporting level
Be-7 (477.59 keV)	WBC	2003	21.96, 22.2 nCi	
Na-22 (1274.54 keV)	WBC	2003	2.58, 3.21 nCi	
K-40 (1460.81 keV)	WBC	2003	36.50, 131.54 nCi	
Mn-54 (834.83 keV)	WBC	2003	2.22, 3.74 nCi	
Co-57 (122.06 keV)	WBC	2003	3.37, 2.44 nCi	
Co-58 (810.76 keV)	WBC	2003	2.49, 3.23 nCi	
Fe-59 (1099.22 keV)	WBC	2003	4.04, 6.07 nCi	
Co-60 (1332.49 keV)	WBC	2003	1.83, 3.65 nCi	
Zn-65 (1115.52 keV)	WBC	2003	5.18, 6.45 nCi	
Sr-85 (513.99 keV)	WBC	2003	2.38, 5.14 nCi	
I-129 (29.62 keV)	WBC	2003	7.97, 3.01 nCi	
I-131 (364.48 keV)	WBC	2003	2.51, 3.47 nCi	
Cs-134 (604.7 keV)	WBC	2003	2.09, 3.08 nCi	
Cs-137 (661.65 keV)	WBC	2003	2.64, 4.77 nCi	
Ce-139 (165.85 keV)	WBC	2003	3.48, 2.93 nCi	
Ce-144 (133.54 keV)	WBC	2003	27.12, 22.11 nCi	
Bi-214 (609.31 keV)	WBC	2003	7.00, 9.65 nCi	
Pb-214 (351.92 keV)	WBC	2003	7.02, 8.5 nCi	
Am-241 (59.54 keV)	WBC	2003	9.06, 4.94 nCi	

a. Values for 2003 from Michel (2003b, 2003b) published for each calibration.

Table 5-3. Detection limits (continued)

Radionuclide	Method/ description	Period	MDA[a]	Reporting level
Be-7 (477.59 keV)	WBC	2004	23.35 nCi	
Na-22 (1274.54 keV)	WBC	2004	3.97 nCi	
K-40 (1460.81 keV)	WBC	2004	147.04 nCi	
Mn-54 (834.83 keV)	WBC	2004	2.50 nCi	
Co-57 (122.06 keV)	WBC	2004	1.40 nCi	
Co-58 (810.76 keV)	WBC	2004	2.39 nCi	
Fe-59 (1099.22 keV)	WBC	2004	6.10 nCi	
Co-60 (1332.49 keV)	WBC	2004	4.12 nCi	
Zn-65 (1115.52 keV)	WBC	2004	5.09 nCi	
Sr-85 (513.99 keV)	WBC	2004	2.21 nCi	
I-129 (29.62 keV)	WBC	2004	78.83 nCi	
I-131 (364.48 keV)	WBC	2004	2.20 nCi	
Cs-134 (604.7 keV)	WBC	2004	2.29 nCi	
Cs-137 (661.65 keV)	WBC	2004	3.62 nCi	
Ce-139 (165.85 keV)	WBC	2004	1.94 nCi	
Ce-144 (133.54 keV)	WBC	2004	13.59 nCi	
Bi-214 (609.31 keV)	WBC	2004	11.69 nCi	
Pb-214 (351.92 keV)	WBC	2004	8.32 nCi	
Am-241 (59.54 keV)	WBC	2004	5.73 nCi	

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

Table 5-3. Detection limits (continued)

Radionuclide	Method/ description	Period	MDA[a]	Reporting level
Be-7 (477.59 keV)	WBC	2005	20.13 nCi	
Na-22 (1274.54 keV)	WBC	2005	2.76 nCi	
K-40 (1460.81 keV)	WBC	2005	42.99 nCi	
Mn-54 (834.83 keV)	WBC	2005	2.79 nCi	
Co-57 (122.06 keV)	WBC	2005	1.91 nCi	
Co-58 (810.76 keV)	WBC	2005	2.91 nCi	
Fe-59 (1099.22 keV)	WBC	2005	4.92 nCi	
Co-60 (1332.49 keV)	WBC	2005	2.90 nCi	
Zn-65 (1115.52 keV)	WBC	2005	5.54 nCi	
Sr-85 (513.99 keV)	WBC	2005	3.41 nCi	
I-129 (29.62 keV)	WBC	2005	81.99 nCi	
I-131 (364.48 keV)	WBC	2005	1.92 nCi	
Cs-134 (604.7 keV)	WBC	2005	2.89 nCi	
Cs-137 (661.65 keV)	WBC	2005	3.12 nCi	
Ce-139 (165.85 keV)	WBC	2005	1.76 nCi	
Ce-144 (133.54 keV)	WBC	2005	14.63 nCi	
Bi-214 (609.31 keV)	WBC	2005	7.72 nCi	
Pb-214 (351.92 keV)	WBC	2005	7.60 nCi	
Am-241 (59.54 keV)	WBC	2005	4.42 nCi	

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

Table 5-3. Detection limits (continued)

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 hours	No threshold
Br-77	Urinalysis	1975		5 µCi/L[e]
H-3 (in house lab)[c]	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)[d]	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[c]	Urinalysis	1952-1969		5.0 dpm/24 hours
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 hours	No threshold
Pu-239	Urinalysis	2001-2006	8.4×10^{-8} µCi/24 hours	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 hours
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 hours	No threshold
Uranium (fluorometric)	Urinalysis	Up to 1955		10 µg/liter
Uranium (fluorometric)	Urinalysis	1956-1965		1 µg/liter
U-238	Urinalysis	2001-2006	8.4×10^{-8} µCi/24 hours	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 hours	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 Recinello et al. (2001) and Sun et al. (2004), except as noted. Values could be applicable earlier, but documentation was not located.
b. Reporting levels shown could have been the MDA, but were not documented as such.
c. Values from a reactor employee's bioassay data.
d. Value from Scarpitta (2001).
e. Value below which "no exposure was assigned" from O'Connell (1975).

5.9 EXCRETA SAMPLE KIT CODES

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

Table 5-4. Excreta sample kit codes.

Kit code[a]			
D/R	P/U	Media	Sample description
NA	NA	Urine	Routine samples for H-3 were collected as grab samples (1993) to be collected weekly or within 4 hours of completion of a task which 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. Reciniello (1993)
b. Miltenberger and Steimers (1984)
c. Holeman (1999)

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

In the absence of any measurements or studies, NIOSH guidance requires the use of default solubility classes and particle size values from the International Commission on Radiological Protection (NIOSH 2002, pp. 15, 16). Facility-specific solubility and particle size data for BNL has 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] (µ AMAD)	Activity fraction
Sewage Treatment Plant (1962)	Unknown. Measured at the outfall from the Imhoff tank (Loysen 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 (Liverman 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
Brookhaven Graphite Research Reactor (BGRR) Bldgs. 701-703, 704 (fan house), 708 (instrument house), 709 (canal house), 709A (canal water treatment facility) (1950-1957)	Natural uranium metal fuel, 1 by 4 inch 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

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

Facility[a]	Compound[b]	RN	Solubility[c] type	Particle size[d] (µ AMAD)	Activity fraction
Brookhaven Graphite Research Reactor (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 aluminum. Routine releases of fission products occurred due to uranium 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
Brookhaven Graphite Research Reactor (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
Brookhaven Medical Research Reactor (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 (Table 5, p 57, Meinhold and Meinhold, 2001) 99.9% of activity release to sewer from labs was H-3 (Liverman 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
Cosmotron Bldg. (1953-1966)	Activation of short-lived isotopes in the ventilating air within the tunnel and experimental areas. See "Accelerators & RHIC" below.	C-11			
		N-13			
		O-15			
Alternating Gradient Synchrotron (AGS) Bldgs. 905-912 (1960-2006)	Activation of short-lived isotopes in the ventilating air within the tunnel and experimental areas. Processing of irradiated targets (Meinhold and Meinhold, 2001, p. 58; Liverman 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 & RHIC 1953-2006	Posted contamination areas primarily in the vicinity of fixed targets (Lessard et al. 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, fan house, liquid waste tank farm, liquid waste concen-tration plant) Bldg. 801, 802 (1951-	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 H-3 fabricated into accelerator targets (1977). 87% of the liquid waste in 1973 was H-3 (Liverman 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
Physics Bldg. 510	Processing irradiated targets, up to 1 mCi; 5000 Ci Co-60 in the gamma irradiation facility (1977)				

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

Facility[a]	Compound[b]	RN	Solubility[c] type	Particle size[d] (µ AMAD)	Activity fraction
Radiation and Chemical Technology Bldgs. 526-527	Unknown uranium of various enrichments. Originally housed a criticality facility for reactor physics (Liverman 1977, p 48). Monomer processing (Liverman 1977). Concrete dried and impregnated with various monomers.				
High Intensity Radiation Development Laboratory Bldg. 528 (1963-1972)	Contained million-curie 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)				
Chemistry Linac Irradiation Facility (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 (Liverman 1977, p. 125)				
High Flux Beam Reactor Bldg. 750 (1965-1997)	“Fully” enriched uranium and aluminum alloy, heavy water cooled and moderated reactor that operated up to 40 megawatts (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
Superconduct-ing Test, Machine Shop, RARAF Bldg. 902	Irradiated target processing, up to 100 µCi. (1977)				

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

Facility[a]	Compound[b]	RN	Solubility[c] type	Particle size[d] (µ AMAD)	Activity fraction
Brookhaven Linac Isotopes Production Facility (BLIP) Bldgs. 930 & 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 (Liverman 1977, p. 113). Fractions estimated based on activity in cooling and shield tank after one year of operation (Liverman 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 NY 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 which 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 uranium 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. Quantitative fit testing information was not located. 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 1999a).

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.

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6.0 OCCUPATIONAL EXTERNAL DOSIMETRY

6.1 INTRODUCTION

Brookhaven National Laboratory (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 various 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 of the BNL site profile 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 (Landauer, Lane 2003). The vendor services continued through 1995.

In December 1995, BNL was DOELAP accredited (Loesch 1995) and BNL 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 very beginning through 1995 when it was replaced with TLD. In addition, CR-39 and Lexan are also used in neutron dosimetry. 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 RBE and later a QF of ten was used from the very beginning of operations of the various accelerators and cyclotrons for these products (Cowan 1953).

6.4.2 Special Dosimetry

On occasion special dosimeters were worn to monitor non-routine 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. In cases of lost or destroyed dosimeters, results were derived from past results of similar work, co-worker results or instrument measurements and time spent in the radiation zone. 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; since a value of 10 was always used (Patterson 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, co-worker results or the product of instrument measurements and time spent in the radiation zone.

6.5 MISSED DOSE

The missed doses at BNL are basically those resulting from dosimeter minimum detectable levels (MDLs), exchange frequencies, and the possible error in determining the true doses due to the interaction of high energy particles. In the later case it was determined that the values of the RBEs and later QFs were always conservative resulting in larger than true doses recorded (Cowan 1953, Cowan unknown). It also appears that all workers were issued dosimeters from startup through 1954.

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 prior to 1955 (Cowan 1953). This is applicable for both Hp (0.07) and Hp (10).

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 (mrem)[a]	Exchange frequency	Maximum annual missed dose (mrem)[b]
Startup through 1954	Multi-element film + NTA	30	Weekly Monthly	780 180
1955 through 1995	Multi-element film +NTA	30	Monthly	180
1996 to present	Harshaw 8814 TLD+ CR-39	10	Monthly	60
Startup through 1995	NTA film[c]	<50	Weekly Monthly	1,300 300
1996 to 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 (2002).
c. Processing done by RS Landauer.

6.5.1 Unmonitored Worker

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

Missed doses for unmonitored employees could be as much as 500 mrem or 10% of whatever standard was in effect at the time of employment. Workers who did not enter radiation zones or areas where work with radioactive materials was undertaken did not receive dosimeters if the probability of exceeding 10% of the allowable limit was small (Sengupta 2000).

6.6 RADIATION ENERGIES AND PERCENTAGES AT SELECTED BNL FACILITIES

Section 2, describes the different types of facilities at BNL including reactors, accelerators and various support facilities and target areas.

Tables 6-2 and 6-2a 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			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					
AGS ring/913						
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			Unknown		
Accelerator Test Facility/ 820	Accelerator			Electron Photon	>15 unknown	 a
Nat'l. Synchrotron Light Source/725	Electron storage	1982	Present	Electron Photon	>15 30-250	100% 100%
Chemistry Dept./490A	Accelerator			Electron Photon	>15 unknown	100% a

a. Unknown, dependent on target material and isotope produced. Most likely 100% >250

Table 6-2a. 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		Unknown	Unknown	Unknown
Tritium evaporator/802B	Tritium processing	1995		Beta	<15 avg.	100%
WCF/811	Waste processing			Beta Photon	>15 30-250 >250	100% 25% 75%
TPL/801	Hot Laboratory					
HWMF/444	Incinerator					
Chemistry Dept/555 & 490A	Chemistry R&D					
LEAF/555	Laser electron accelerator					
Biology/463	Biological R&D					
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 6.3 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 6-3. Facilities, neutron energies, percentages, and correction factors.

Facility	Source	Neutron energy (MeV)	Default dose % and correction factor
Reactors- BGRR, HFBR, BMRR	Reactors	0.1 to 2.0, W_r=20	100% correction factor = 1.91
Accelerators-Cosmotron, AGS, RHIC, NSLS, Medical	Particle reactions	0.1 to 2, W_r= 20 2 to 14+	100% correction factor = 2.0[b] 100% correction factor = 1.32
Sources- Medical, Calibration, Chemistry	Sources-AmBe, PuBe, Cf-252	0.1 to 2.0(0.57)[a] 2 to 14 (.43)[a]	100% Cf-252, correction factor=1.91 100% Am or Pu Be or accelerator > 2 MeV, correction factor =1.32 Avg. correction if both Cf-252 or either AmBe or PuBE sources are present = 1.66

a. Weighted average dose from alpha-neutron and SF (spontaneous fission) neutrons (Y-12 Section 6 TBD, ORAU-TKBS-0014-6,10/11/05).

b. Correction factor for those exposures resulting from accelerator operations was always 10 be it either RBE or QF.

All potential neutron exposures of >100 mrem annually used NTA film through 1995. Starting in 1996 the Harshaw 8806 TLD along with CR-39 was used at the accelerators (Lane 2003, Sengupta 2000). Recorded neutron doses include both thermal and fast neutrons generated by the various 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.

6.8 RECORDED DOSE PRACTICES

Recorded dose practices at BNL are given in Table 6-4 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.

Table 6-4. Recorded dose practices.

1949 through 1984 Oak Ridge film dosimeter + NTA	Beta=Open window, mrem Photon (P), mR Fast Neutron (FN), mrem	Skin= OW+P WB= P+ FN+ tritium
1985 through 1995 Landauer + NTA film	Beta or nonpenetrating, mrem Photon (P), mrem Fast Neutron (FN), mrem	Skin= NP + P WB= NP + P + FN + tritium
1996 to present – Harshaw 8814 & Harshaw 8806[a] TLD + CR-39[b] for neutrons	Beta or nonpenetrating, mrem Photon (P), mrem Fast Neutron (FN), mrem	Skin= NP + WB WB= P + NP + FN + tritium

a. Issued only when higher energy neutrons might be present.
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 dosimeter worn for that exchange period. If it is necessary to obtain organ doses, dose reconstructors should use External Dose Reconstruction Implementation Guidelines (NIOSH 2002).

Table 6-5 lists the interpretation of the reported data by time 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 dosimeter. All issued dosimeters were stored on storage racks located at various positions through-out the site. Dosimeters were not to be taken home at the end of the shift, a practice beginning at the start-up of the site and continues at present (Sengupta 2000).

Table 6-5. Interpretation of reported data.

Period	Reported quantity	Description	Interpretation of zeros	Interpretation of blanks	Rollup of individual and annual data	Monitored/unmonitored
Startup to 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.	All personnel expected to be exposed to >100 mrem in an exchange period were monitored.
1986 to 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.	Only those>10% of current standards were monitored. Those entering controlled areas were issued visitors dosimeter.

6.10 ADJUSTMENTS TO RECORDED DOSE

Since 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, where required, can be made to the WB dose using the product of 10% times the percentage <250 keV. This adjustment equals 2.5% for those facilities having photons in the 30 to 250 keV range except the NSLS which is 10% since most all of it's photons are estimated to be below 250 keV (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 OW and WB doses. Table 6-6 lists the corrections.

Table 6-6. Adjustments to recorded dose.

Period	Dosimeter	Facility	Adjustment to reported dose
Startup to 1985	Oak Ridge	Reactors	Multiply reported dose by 1.025 to estimate Hp(10)
1958 to present	Oak Ridge, Landauer and Site	MRC 490/490A	Multiply reported dose by 1.025 to estimate Hp(10)
1982 to present	Oak Ridge, Landauer, Site	NSLS	Multiply reported dose by 1.10 to estimate Hp(10)

6.11 BIAS AND UNCERTAINTY

Bias and uncertainty values were not found in any site data. Values given in Table 6-7 are those found in the Hanford TBD (ORAU-2004) and should be similar to those at BNL since both used the multi-element film dosimeter and the TLD dosimeter.

The Landauer dosimeter values were taken from the Atomics International (AI) TBD* (ORAU -2006). The NTA film values were also taken from the AI TBD because the adjusted neutron energy values are similar and are based on Y-12 data (ORAU-2005).

* The Atomics International TBD was originally the ETEC TBD

Table 6-7. Bias and uncertainty.

Site specific dosimetry system	Bias magnitude and range		Uncertainty factors	
	Overall bias[b]	Range in bias	Systematic[c]	Random[d]
Multi element Start-up thru 1995[a]	1.02	0.86-10	1.1	1.4
Site TLD	1.01	0.95-1.05	1.05	1.2
NTA film				
0.1 to 2 MeV	1.35	0.5 –1.5	1.5	
2.0 to 14 MeV	1.35	0.65-1.35	1.35	
CR-39	Unknown	Unknown	Unknown	

a. These values agree with Landauer since NVLAP certification (Yoder 2005).
b. Based on most likely distribution of energy levels and geometries. Divide recorded dose by table's bias value to determine deep dose.
c. Systematic uncertainty due to lack of knowledge of actual distributions of energies and geometries.
d. Random uncertainty due to variations among workers in energy levels and geometry.

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GLOSSARY

absorbed dose
Amount of energy in rads or grays deposited in a substance by ionizing radiation per unit mass of the substance. See *dose*.

absorption type
Categories for materials according to their speed of absorption in the body, which replaced the earlier inhalation clearance classes. Defined by the International Commission on Radiological Protection, the absorption types are F for fast absorption (formerly inhalation class D), M for moderate absorption (formerly inhalation class W), and S for slow absorption (formerly inhalation class Y).

accelerator
See *particle accelerator*.

accreditation
Recognition that a dosimeter system has passed the applicable performance criteria of a program such as the U.S. Department of Energy Laboratory Accreditation Program or the former National Voluntary Laboratory Accreditation Program.

accuracy
Extent to which a given value agrees with the standard value for that measurement. If a series of measurements has small systematic (nonrandom) errors, they are said to have high accuracy. The standard deviation of a series of values is a measure of the accuracy of those values.

Atomic Energy Commission (AEC)
An agency established by the U.S. Government for oversight of nuclear weapons and power production; a predecessor to the U.S. Department of Energy.

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

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

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.

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

Cosmotron (Synchrotron)
Accelerators 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.

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.

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.

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*.

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)
Product of absorbed dose in units of rem or sievert 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.

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.

favorable to the claimant
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. See *probability of causation*.

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

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.

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 rays are very penetrating, but dense materials such as lead or uranium or thick structures can stop them. Gamma photons are identical to X-ray photons of high energy; the difference is that X-rays do not originate in the nucleus.

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.

in vitro

Of or relating to a process that takes place under artificial conditions or outside a living organism (e.g., in the laboratory). From Latin meaning *in glass*.

in vivo

Of or relating to a process that takes place in a living organism. From Latin meaning *in life*.

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 but often have different physical properties.

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.

lumbar spine

The vertebrae of the lower back.

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.

nonpenetrating dose (NP, NPEN)

Dose from beta and lower energy photon radiation, often determined from the open-window dose minus the shielded window dose. See *dose*.

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.

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 (imparts energy to) ions and magnetic or electrostatic fields for focusing and redirecting ion beams. The main purposes of accelerators are the investigation of high-energy particle behavior and 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.

photon

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

photon radiation

Electromagnetic radiation of light energy (photons) from microwaves to gamma rays. Gamma rays and X-rays are examples of ionizing photon radiation, which have enough energy to penetrate matter, including the body, and deposit energy in that matter.

PM

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

probability of causation

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

rad

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

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

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

radiograph

Photographic image produced on film by gamma rays or X-rays. Some of the rays (photons) can pass through parts of an item, while more opaque parts partially or completely absorb them and thus cast a shadow on the film. See *radiology*.

radiology

Science of using X-rays to produce images on photographic film, especially for medical purposes.

radionuclide

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

rem

Traditional unit of radiation dose equivalent that indicates the biological damage caused by radiation equivalent to that caused by 1 rad of high-penetration X-rays multiplied by a quality factor. The average American receives 360 millirem a year from background radiation. The sievert is the International System unit; 1 rem equals 0.01 sievert. The word derives from roentgen equivalent in man; rem is also the plural.

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).

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

Absorbed dose at a tissue depth of 7 mg per square centimeter.

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*.

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

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

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

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.