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National Institute for Occupational Safety and Health

REVIEW OF THE NIOSH SITE PROFILE FOR BROOKHAVEN NATIONAL LABORATORY

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Disclaimer

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ACRONYMS AND ABBREVIATIONS

Advisory Board or ABRWH	Advisory Board on Radiation and Worker Health
AF	Absorption Factor
AGS	Alternating Gradient Accelerator
AP	anteroposterior
BGRR	Brookhaven Graphite Research Reactor
BLIP	Brookhaven Linac Isotope Producer
BMRR	Brookhaven Medical Research Reactor
BNL	Brookhaven National Laboratory
CBA	Colliding Beam Accelerator
CFR	*Code of Federal Regulations*
CR-39	Columbia Resin, type 39
D&D	Decontamination and Decommissioning
DOE	Department of Energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
FN	Fast neutron
GeV	Giga (thousand million) electron volts
HFBR	High Flux Beam Reactor
HHS	Health and Human Services
HP	Health Physics
HPRS	Health Physics Record System
ICRP	International Commission on Radiological Protection
IR	Infrared
keV	kilo electron volt; 1,000 electron volts
LAT	lateral
LET	Linear energy transfer
LFMR	Liquid Fuel Metal Reactor
LINAC	Linear Accelerator
LLD	Lower Limit of Detection
LOD	Limit of Detection
µg	Microgram

MDA	Minimum Detectable Activity
MDL	Minimum Detectable Level
MeV	Million electron volts
MFP	Mixed fission products
mR	milliroentgen
mrem	Millirem
NIOSH	National Institute for Occupational Safety and Health
NP	Non-penetrating
NSLS	National Synchrotron Light Source
NTA	Eastman Kodak Nuclear Track Film Type A
OCAS	Office of Compensation Analysis and Support
ORAU	Oak Ridge Associated Universities
ORAUT	Oak Ridge Associated Universities Team
OTIB	ORAU Technical Information Bulletin
P	Photon
PA	posteroanterior
PFG	Photofluorography
pCi	picocurie
POC	Probability of Causation
PM	Personnel monitoring
QA	Quality Assurance
QF	Quality Factor
R	Roentgen
RBE	Relative Biological Effective
RH	Relative humidity
RHIC	Relativistic Heavy Ion Collider
R&D	Research and Development
rem	Roentgen equivalent man
SC&A	S. Cohen and Associates
S&EP	Safety and Environmental Protection
SEB	Slow Extracted Beam
SRDB	Site Research Database
TBD	Technical Basis Document

TIB/OTIB	NIOSH Technical Information Bulletin
TLD	Thermoluminescent Dosimeter
TP	Tetra Protons
UV	Ultraviolet
WB	Whole body
WBC	Whole-body counting/counter

1.0 EXECUTIVE SUMMARY

This draft report presents the S. Cohen and Associates (SC&A, Inc.) evaluation of the National Institute for Occupational Safety and Health (NIOSH) Summary Site Profile document for the Brookhaven National Laboratory (BNL), ORAUT-TKBS-0048 (ORAUT 2006). This review was conducted during the period February through August 2009, in support of the Advisory Board on Radiation and Worker Health (Advisory Board) in the latter's statutory responsibility under the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA) to conduct such reviews and advise the Secretary of Health and Human Services (HHS) on the "completeness and adequacy" of the EEOICPA program. It was conducted in accordance with the Board's "Data Access and Interview Procedures" (ABRWH-PROC-010), as well as Board-approved SC&A procedures for the conduct of site profile reviews.

The BNL is a multi-program national laboratory operated by Brookhaven Science Associates for the U.S. Department of Energy (DOE). The laboratory was established in 1947 on Long Island in Upton, New York, and has supported a diverse scope of radiological facilities over its long history, including research reactors, high-energy accelerators, medical isotope facilities, medical research facilities, and waste management operations. Early accelerator facilities included the 3 GeV Cosmotron (1953–1966) and 30 GeV Alternate Gradient Synchrotron (AGS, 1960–present), followed by the Tandem Van De Graaff, 60-inch Cyclotron**,** and Vertical Accelerator, which began operations in the 1960s. The Brookhaven Linac Isotope Producer (BLIP) became operational in 1973, followed by the National Synchrotron Light Source (NSLS) in 1982. Brookhaven's newest accelerator facility is the Relativistic Heavy ion Collider (RHIC), which was completed in 1999. The Brookhaven Graphite Research Reactor (BGRR) (1950–1969) and High Flux Beam Reactor (HFBR) (1965–1999) were major sources of high-energy neutrons for research in the fields of medicine, biology, chemistry, physics, and nuclear engineering. Medical research and nuclear medicine began at BNL in 1950, with the Medical Research Center opening in 1958, supported by the operation of the Brookhaven Medical Research Reactor (BMRR) (1959–2000).

A site visit was conducted from May 18–21, 2009, encompassing a comprehensive document review and unclassified site expert interviews. Interviews were conducted with 26 former and current BNL workers, including personnel from health physics (field and programmatic), dosimetry, medical, accelerator operations, reactor operations, support workers (i.e., maintenance and crafts), and research and development personnel. The purpose of these interviews was to hear first-hand accounts of past radiological control and personnel monitoring practices, and to better understand how operations and safety programs were implemented through time.

A comprehensive review was conducted of documents that were considered relevant, including the following:

- Select documents that were referenced in the BNL Summary Site Profile
- Documents contained in the NIOSH Site Research Query Database
- Documents obtained during a site visit to BNL on May 18–21, 2009.

The review found that the Summary Site Profile document for BNL (ORAUT 2006) does not provide adequate and sufficient information to guide dose reconstruction for a number of critical sources of historic internal and external exposure at the laboratory.

For internal dose assessment, the site profile fails to address the adequacy and completeness of BNL bioassay data to support dose reconstruction. Uniform and comprehensive historic bioassay policies have not been cited nor located for BNL. With the exception of operators at the BGRR, bioassay monitoring for isotopes other than tritium at BNL appears to have been more "event driven," rather than conducted on a routine preventive basis. A preliminary review of BNL bioassay records does not indicate that consistent long-term routine bioassay monitoring policies were in place. From a preliminary review of available BNL records and interviews with BNL health physics personnel, there is sufficient reason to question the completeness, accuracy, and accessibility of bioassay records for BNL from the late 1940s through the mid-1980s, or perhaps into the mid-1990s, when the centralized electronic Health Physics Records System (HPRS) became operational.

The site profile does not specifically address the subject of NTA film threshold. NTA film decreases in response starting at neutron energies below 1 MeV, and is almost completely insensitive to neutrons below 0.5 MeV (ORAUT 2005a, pg. 27); therefore, radiation fields containing an appreciable percentage of the total dose equivalent due to neutron exposures below 1 MeV must be evaluated carefully, with attention given to the dose missed resulting from this threshold affect. This is particularly important, as SC&A found that four out of five final dose reconstruction reports for BNL claimants, completed after the site profile was issued, did not include the neutron adjustment factors of 1.5 or 1.35 for low-energy neutrons. The site profile should address this issue, and make clear and technically sound recommendations to compensate for the incomplete neutron doses as recorded by NTA film and contained in the dose of record.

Similarly, the site profile did not directly address NTA film track fading, provide evidence that it was not a problem at BNL, or describe any procedure necessary to compensate for it. The problems associated with the NTA film threshold and track fading motivated a search by BNL (for example, Distenfeld and Klemish 1972 and Phillips 1974), as it did at other laboratories, for alternate neutron dosimeters; among those tested and selected for use were the thermoluminescent dosimeter (TLD), CR-39, and Lexan neutron dosimeters. However, these neutron dosimeters were not without their own shortcomings. There were issues with NTA film, CR-39, and Lexan neutron dose readings, and even gamma-muon readings. During the 1980s and 1990s, a number of issues were ongoing between BNL and their dosimetry vendor, Landauer, pertaining to inconsistent and unsupportable results. The BNL site profile did not mention these dosimetry problems, if they were solved, or make any recommendation on the use of the neutron dose records concerning these issues.

The present site profile document does not address key dosimetry problems associated with high-energy accelerators, the adequacy of dosimetry systems during accelerator startup periods, or if the dosimetry systems were sufficiently encompassing to accommodate the numerous operational changes that took place as accelerators were redesigned and modified. It does not discuss adjustment factors for neutron doses and if adjustments are needed to compensate for the

limitations of the dosimetry systems used as a function of time at different accelerator facilities (as illustrated in a discussion in this report concerning problems with NTA/TLD/Lexan/CR-39 neutron dosimetry systems). The site profile does not address if, where, or when muon doses were of health physics concern, or how and if they were monitored and recorded and the interpretation of those doses, if recorded. Hazards from extracted high-energy proton beams and their dosimetry were also not addressed. The main body of the Occupational External Dosimetry section of ORAUT-TKBS-0048 consists of only six pages; this obviously cannot contain sufficient information to cover the important aspects of dosimetry at the many diverse BNL facilities for an operating period of approximately 60 years. Such a limited space could not cover the many health physics aspects of accelerator dosimetry (a few of which are outlined above), in addition to those of reactors, isotope production, medical research, hot cells, the NSLS, and other facilities with potential radiation exposures at BNL.

With respect to medical x-rays, the site profile has failed to consider pertinent information on the number and types of examinations required as a condition of employment. Based on a preliminary review of the documented history of such procedures, further investigation of medical examination protocol is warranted. The statement in the site profile that posteroanterior (PA) chest photofluorography (PFG), anteroposterior (AP) lumbar spine, and lateral (LAT) lumbar spine exams were unlikely is contradicted by existing documentation. The site profile assumption that any radiograph that was not a PA chest or LAT chest was diagnostic and should not be included in dose reconstruction is likewise contradicted (the lumbar spine and forearm x-rays were required during the pre-employment and termination exams, and should not be considered diagnostic exams).

The site profile does not mention the availability or applicability of coworker internal or external dose data. Therefore, the dose reconstructor is not provided with any recommendations concerning what doses to assign when a worker's information indicates that the worker should have been monitored, but was not, or in those instances where bioassay records are unavailable. In view of the lack of a comprehensive bioassay program with established record accessibility, coupled with evidence that unmonitored BNL workers were exposed to radiation sources above background environmental levels, the availability (or lack thereof) of coworker dose information is an important issue at BNL for adequate dose reconstruction that needs to be addressed.

1.1 SUMMARY OF PRIMARY FINDINGS

Finding 1: Bioassay Monitoring Not Adequately Established

ORAUT-TKBS-0048 (TBD) does not provide sufficient information to determine which workers were monitored for what radionuclides and what criteria were used to select workers for special, routine, and spot bioassay monitoring. To perform an adequate dose reconstruction, the dose reconstructor needs to know who, when, and why workers were bioassayed at a given DOE site. This information allows the dose reconstructor to determine if the worker should have been monitored, and prompts the dose reconstructor to search for such records, if applicable (especially important because of the lack of a centralized record system at BNL). Although bioassays for some radionuclides were conducted for some workers at BNL throughout the

laboratory's operating history, sufficient documentation of written procedures and requirements for bioassays is not apparent before the 1990s; this leaves 40 years of uncertainty concerning bioassay requirements.

Finding 2: Records of Bioassay Monitoring Not Centralized or Knowingly Complete

The site profile does not address the issue of the completeness and accessibility of the bioassay records. There were numerous bioassay data recording systems and filing methods at BNL. Many of these earlier records are still located in various departments, making it difficult (as confirmed by current BNL health physics personnel) for BNL to properly and completely respond to NIOSH requests for bioassay records to be used for dose reconstruction. It is not currently known by BNL health physics personnel if all the hardcopy records have been located, are legible, and are accessible for dose reconstruction. As various departments were formed and supplanted, and as department heads came and left BNL, the hardcopy records may have survived, or they may have been destroyed or removed from the site. There is presently no method available to determine if all the records for a given employee are available for dose reconstruction purposes, particularly before the records were centrally stored in electronic databases.

Finding 3: Minimum Detectable Activity and Uncertainty Values Not Sufficiently Defined

Minimum detectable activity (MDA) is mentioned several times in Section 5 of the site profile, and a list of whole-body counter (WBC) MDA values is provided in Table 5-3, pp. 78–79) for the years 1999 through 2005. Additionally, urinalysis MDA values for some of the common radioisotopes found at BNL are listed in Table 5-3, pg. 80), mainly for 1999–2006. Therefore, a reasonable amount of MDA information for common radioisotopes is provided for 1999–2006. However, what is lacking is a comprehensive listing of urinalysis and WBC MDA values for the 1940s–1990s, such as is found in other NIOSH site profiles. Additionally, uncertainty values are not provided, and are apparently not available, for most of the bioassay reporting period from the 1950s–1990s.

Finding 4: Radionuclide Characteristics Not Sufficiently Known

Unfortunately, as stated in Section 5.10 of the site profile, specific *solubility data*, *particle size*, and *activity fractions* are not known, or are not available, for most facilities at BNL. Table 5-5 lists a few of the activity fractions, presumed to have come from stack emission data. However, stack emissions are not always a good indicator of the types of radioisotopes present, or their concentrations, in the worker's breathing zone (this also applies to Table 2-2). Interviews with BNL workers indicate that Tables 2-2 and 2-3 do not correctly reflect the historic radioisotopes present at some of the BNL facilities. Without appropriate characterization of workplace exposures, the adequacy and completeness of the internal and external monitoring programs come into question and may result in a less than favorable organ dose reconstruction. In addition, workplace specific *monitoring data* and/or *source term data* do not appear to be available.

Finding 5: No Internal Coworker Dose Database Available

The site profile does not address internal coworker dose data. In view of the issues with the lack of a coordinated, consistent bioassay program and the problems with the availability of historic bioassay records, it would be advantageous to have a viable coworker database to use to assign unmonitored dose. Unfortunately, the lack of a routine and comprehensive bioassay program before the 1990s may make it difficult to create an adequate coworker internal dose table for the dose reconstructor to bridge monitoring or recordkeeping gaps for sporadically monitored workers, monitored workers whose complete records are not available, and for unmonitored workers who should have been monitored.

Finding 6: NTA Threshold Response Not Sufficiently Investigated

The threshold energy of NTA film and the amount of dose not registered due to this limitation is important in neutron dosimetry. NTA film decreases in response starting at neutron energies below 1 MeV, and is almost completely insensitive to neutrons below 0.5 MeV; therefore, radiation fields containing an appreciable percentage of the total dose equivalent due to neutrons below 1 MeV must be evaluated carefully, with attention given to the missed dose resulting from this threshold affect. The site profile does not specifically address the subject of the NTA film threshold. The site profile should address this issue and make clear and technically sound recommendations to compensate for the incomplete neutron doses as recorded by NTA film and contained in the dose of record.

Finding 7: NTA Track Fading Not Covered in the Site Profile

The magnitude of the proton recoil tracks in NTA film resulting from neutron interactions depends on the energy of the interacting neutron. Lower-energy neutrons cause less dense proton recoil tracks; these tracks fade more rapidly with time than heavier tracks caused by more energetic recoil protons resulting from energetic neutrons (i.e., 0.5–1.0 MeV neutrons in the workplace versus 4 MeV neutrons from a calibration source). The site profile did not directly address NTA film track fading, provide evidence that it was not a problem at BNL, or describe any procedure necessary to compensate for it.

Finding 8: NTA/TLD/Lexan/CR-39 Problems

The problems associated with the NTA film threshold and track fading initiated a search for other neutron dosimeters; among those tested and selected for use at BNL were the TLD, CR-39, and Lexan neutron dosimeters. However, these neutron dosimeters were not without their own shortcomings. There were issues with NTA film, CR-39, and Lexan neutron dose readings, and even the gamma-muon readings. None of the detectors appeared to establish a long-term “gold standard” to which results could be compared. During the 1980s and 1990s, a number of issues were ongoing between BNL and their dosimetry vendor, Landauer. The BNL site profile does not cite these dosimetry problems, if they were solved, or make any recommendations on the use of the neutron dose records, given the concerns and uncertainties associated with these issues.

Finding 9: Potential Exposures at Accelerators Not Sufficiently Covered

High-energy accelerators, such as the many diverse types operated at BNL during its 60-year history, present the standard health physics problems, as well as emergent new challenges, typically unique to each type of new accelerator. There are many situations at high-energy accelerators that have the potential for unconventional exposures leading to unrecorded or under-recorded doses. The present BNL site profile does not address the unique dosimetry problems associated with high-energy accelerators, if the dosimetry systems were adequate during the startup periods, or if the dosimetry systems were sufficiently encompassing to accommodate operational changes. Nor does the site profile discuss adjustment factors for neutron doses, and if they are needed to compensate for the limitations of the dosimetry systems used as a function of time at different accelerator facilities.

Finding 10: External Coworker Dose Data Not Addressed

Section 6 of the site profile does not address or provide any coworker data for use in assigning doses to workers who should have been monitored, but were not. Coworker data are needed in cases where the worker had the potential to receive greater than environmental doses, but by the criteria at the time, the individual was not considered a radiation worker and, therefore, was not badged, or the monitoring results cannot be located.

Finding 11: Incidents and Unanticipated Events Not Addressed

The site profile does not sufficiently address incidents or unusual events that could affect external dose reconstruction. Some examples of incidents were found in the BNL documents; however, the site profile itself did not address such incidents for their implications to dose reconstruction, and whether the doses of record were correct under these exposure conditions. Likewise, specific environmental-related incidents and releases and their impact on onsite occupational doses to unmonitored workers are not addressed.

Finding 12: Potential Environment Exposures from Igloo Area Not Addressed

Nothing is mentioned in Section 4 of the site profile concerning the Igloo storage area in the Hazardous Waste Management Facility and its impact on localized environmental doses. Averaged site parameter yearly readings, and other readings inside the BNL site, may not reflect the true environmental doses received by unmonitored workers who spent any significant time in the areas outside the Igloo or other hazardous waste facility areas.

Finding 13: The Site Profile has Inadequately Characterized the Number and Types of X-rays Received by BNL Employees in Early Years

The site profile (pg. 50) states that BNL had machines capable of photofluoroscopic/ fluoroscopic exams in 1951 and 1960, but on page 50, it is concluded that only the diagnostic unit was used for routine exams, and on page 52, it is stated that it seems unlikely that the greater dose units were used for routine exams. These potential exposures were not further addressed in

the site profile. It references Brodsky 1964 as one of its reasons to conclude that only the diagnostic unit was used routinely for examinations. However, Sunderman (1947) summarized the health program used for BNL employees in September 1947. Sunderman recommended that employees of BNL be observed medically (1) upon hire at BNL, (2) routinely for employees requiring health maintenance, (3) when employees become sick or injured, and (4) when employees terminated. Candidates for employment were to receive "fluororoentgenograms of the chest, AP and LAT roentgenograms of the spine, and roentgenogram of one forearm." During Health Maintenance exams of employees, an annual fluororoentgenogram of the chest was completed.

1.2 OPPORTUNITIES FOR IMPROVEMENT

While the TBDs provided some detailed information concerning the history, developments, and facilities at BNL, there was not sufficient in-depth development in many areas to provide for adequate dose reconstruction recommendations. Some of these areas are as follows:

- Different types/sources of radiation fields and their potential exposure to workers
- Dosimetry systems, changes, and associated problems throughout the operating history of BNL
- Accuracy, availability, and adequacy of external and bioassay records
- Data integrity of dose records as record systems changed
- Coworker internal intake and external dose data and/or dose reconstruction recommendations for under-monitored or unmonitored workers

The TBD provided a large number of references at the end of each section; however, some of this material needs to be incorporated into specific recommendations in the TBD, especially for Sections 5 and 6, to ensure uniform and consistent dose reconstruction.

There are numerous opportunities for the TBD to be further developed, so that it would be more useful in dose reconstruction by building on the basic information provided in the current version.

2.0 SCOPE AND INTRODUCTION

The review of the BNL site, in Upton, New York, was authorized by the Advisory Board at its December 16–18, 2008, meeting in Augusta, Georgia, and the review was conducted during the February–August 2009 timeframe by a team of SC&A health physicists and technical personnel. All of the pertinent records reviewed were unclassified; however, two members of the SC&A team hold "Q" clearances that would have permitted unencumbered access, if needed. This review was performed in accordance with the Advisory Board's ABRWH-PROC-010, "Data Access and Interview Procedure" (ABRWH 2009a), which provides for appropriate onsite coordination and data access protocols in conjunction with the Advisory Board, NIOSH, and DOE, and ABRWH-PROC-011, "Department of Energy Classification Review of Documents" (ABRWH 2009b) which provides for appropriate security clearance reviews.

SC&A understands that site profiles are living documents, which are revised, refined, and supplemented with NIOSH technical information bulletins (TIBs) as required to help dose reconstructors. Site profiles are not intended to be prescriptive or necessarily complete in terms of addressing every possible issue that may be relevant to a given dose reconstruction. However, future revisions in the BNL site profile would serve to mitigate some of the gaps and issues raised in this report.

2.1 REVIEW SCOPE

Under the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA) and federal regulations defined in Title 42, Part 82, *Methods for Radiation Dose Reconstruction Under the Energy Employees Occupational Illness Compensation Program,* of the *Code of Federal Regulations* (42 CFR Part 82), the Advisory Board is mandated to conduct an independent review of the methods and procedures used by NIOSH and its contractors for dose reconstruction. As a contractor to the Advisory Board, SC&A has been charged to support this effort by independently evaluating a select number of site profiles that correspond to specific facilities at which energy employees worked and were exposed to ionizing radiation.

This report provides a review of the *Summary Site Profile Document for the Brookhaven National Laboratory*, ORAUT-TKBS-0048 (ORAUT 2006), issued on August 30, 2006. To date, this document has not been supplemented by site-specific TIBs, but there are several generic TIBs that provide additional guidance to the dose reconstructor.

Implementation guidance is also provided by so-called "workbooks," which have been developed by NIOSH for selected sites to provide more definitive direction to the dose reconstructors on how to interpret and apply TBDs, as well as other available information. To date, no BNL site-specific workbooks have been developed.

SC&A, in support of the Advisory Board, has critically evaluated the BNL site profile for the following:

- Determine the completeness of the information gathered by NIOSH in behalf of the site profile, with a view to assessing its adequacy and accuracy in supporting individual dose reconstructions
- Assess the technical merit of the data/information
- Assess NIOSH's use of the data in dose reconstructions

SC&A's review of this site profile document focuses on the quality and completeness of the data that characterized the facility and its operations, and the use of these data in dose reconstruction. The review was conducted in accordance with *Standard Operating Procedure for Performing Site Profile Reviews* (SC&A 2004), which was approved by the Advisory Board.

The review is directed at "sampling" the site profile analyses and data for validation purposes. The review does not provide a rigorous quality control process, whereby actual analyses and calculations are duplicated or verified. The scope and depth of the review are focused on aspects or parameters of the site profile that would be particularly influential in deriving dose reconstructions, bridging uncertainties, or correcting technical inaccuracies.

The BNL site profile document serves as site-specific guidance used in direct support of dose reconstructions for claimants. This site profile provides the health physicist who conducts dose reconstructions on behalf of NIOSH with consistent general information and specifications to support their individual dose reconstructions. This report was prepared by SC&A to provide the Advisory Board with an evaluation of whether and how the TBD can support dose reconstruction decisions. The criteria for evaluation include whether the TBD provides a basis for scientifically supportable dose reconstruction in a manner that is adequate, complete, efficient, and claimant favorable. Specifically, this review was conducted as an evaluation of whether dose reconstructions based on this site profile would provide for robust compensation decisions.

The basic principle of dose reconstruction is to characterize the radiation environments to which workers were exposed, and determine the level of exposure the worker received in that environment through time. The hierarchy of data used for developing dose reconstruction methodologies is dosimeter readings and bioassay data, coworker data and workplace monitoring data, and process description information or source term data.

2.2 ASSESSMENT CRITERIA AND METHODS

SC&A is charged with evaluating the approach set forth in the site profile that is used in the individual dose reconstruction process. This document is reviewed for completeness, technical accuracy, adequacy of data, consistency with other site profiles, and compliance with the stated objectives, as defined in *SC&A Standard Operating Procedure for Performing Site Profile Reviews* (SC&A 2004). This review is specific to the BNL site profile; however, items identified in this report may be applied to other facilities, especially facilities with similar source terms and exposure conditions. The review identifies a number of issues and discusses the degree to which the site profile fulfills the review objectives delineated in SC&A's site profile review procedure.

2.2.1 Objective 1: Completeness of Data Sources

SC&A reviewed the site profile with respect to Objective 1, which requires SC&A to identify principal sources of data and information that are applicable to the development of the site profile. The two elements examined under this objective are (1) determining if the site profile made use of available data considered relevant and significant to the dose reconstruction, and (2) investigating whether other relevant/significant sources are available, but were not used in the development of the site profile.

2.2.2 Objective 2: Technical Accuracy

Objective 2 requires SC&A to perform a critical assessment of the methods used in the site profile to develop technically defensible guidance or instructions, including evaluating field characterization data, source term data, technical reports, standards and guidance documents, and literature related to processes that occurred at the BNL site. The goal of this objective is to analyze the data according to sound scientific principles, and then evaluate this information in the context of dose reconstruction.

2.2.3 Objective 3: Adequacy of Data

Objective 3 requires SC&A to determine whether the data and guidance presented in the site profile are sufficiently detailed and complete to conduct dose reconstruction, and whether a defensible approach has been developed in the absence of data. In addition, this objective requires SC&A to assess the credibility of the data used for dose reconstruction. The adequacy of the data identifies gaps in the facility data that may influence the outcome of the dose reconstruction process. For example, if a site did not monitor all workers exposed to neutrons who should have been monitored, this would be considered a gap, and therefore an inadequacy in the data. An important consideration in this aspect of our review of the site profile is the scientific validity and claimant favorability of the data, methods, and assumptions employed in the site profile to fill in data gaps.

2.2.4 Objective 4: Consistency among Site Profiles

Objective 4 requires SC&A to identify common elements within site profiles completed or reviewed to date, as appropriate. In order to accomplish this objective, the BNL site profile was compared to other TBDs previously reviewed. This assessment was conducted to identify areas of inconsistencies and determine the potential significance of any inconsistencies with regard to the dose reconstruction process.

2.2.5 Objective 5: Regulatory Compliance

Objective 5 requires SC&A to evaluate the degree to which the site profile complies with stated policy and directives contained in 42 CFR Part 82. In addition, SC&A evaluated the site profile for adherence to general quality assurance policies and procedures utilized for the performance of dose reconstructions.

2.3 DOSE RECONSTRUCTION UNDER EEOICPA

In order to place the above objectives into the proper context as they pertain to the site profile, it is important to briefly review key elements of the dose reconstruction process, as specified in 42 CFR Part 82. Federal regulations specify that a dose reconstruction can be broadly placed into one of three discrete categories. These three categories differ greatly in terms of their dependence on and the completeness of available dose data, as well as on the accuracy/uncertainty of data.

Category 1: Least challenged by any deficiencies in available dose/monitoring data are dose reconstructions for which even a partial assessment [or minimized dose(s)] corresponds to a probability of causation (POC) value in excess of 50%, assuring compensability to the claimant. In some cases, such partial/incomplete dose reconstructions with a POC greater than 50% may involve only a limited amount of external or internal data. In extreme cases, even a total absence of a positive measurement may suffice for an assigned organ dose [based on the limits of detection (LOD)] that results in a POC greater than 50%. For this reason, dose reconstructions in this category may only be marginally affected by incomplete/missing data or uncertainty of the measurements. In fact, regulatory guidelines recommend the use of a partial/incomplete dose reconstruction, the minimization of dose, and the exclusion of uncertainty for reasons of process efficiency, as long as this limited effort produces a POC equal to or greater than 50%.

Category 2: A second category of dose reconstruction defined by federal guidance recommends the use of "worst-case" assumptions. The purpose of worst-case assumptions in dose reconstruction is to derive maximal or highly improbable dose assignments. For example, a worst-case assumption may place a worker at a given work location 24 hours per day and 365 days per year. The use of such maximized (or upper bound) values, however, is limited to those instances where the resultant maximized doses yield POC values below 50%, which are not compensated. For this second category, the dose reconstructor needs only to ensure that all potential internal and external exposure pathways have been considered, and that the approach is scientifically supportable.

The obvious benefit of worst-case assumptions and the use of maximized doses in dose reconstruction is efficiency. Efficiency is achieved by the fact that maximized doses avoid the need for precise data and eliminate consideration for the uncertainty of the dose. Lastly, the use of bounding values in dose reconstruction minimizes any controversy regarding the decision not to compensate a claim.

Although simplistic in design, the site profile must, at a minimum, provide information and data that clearly identify (1) all potential radionuclides, (2) all potential modes of exposure, and (3) upper limits for each contaminant and mode of exposure, to satisfy this type of a dose reconstruction. Thus, for external exposures, maximum dose rates must be identified in time and space that correspond to a worker's employment period, work locations, and job assignment. Similarly, in order to maximize internal exposures, highest air concentrations and surface contaminations must be identified.

Category 3: The most complex and challenging dose reconstructions consist of claims where the case cannot be dealt with in one of the two categories above. For instance, when a minimum dose estimate does not result in compensation, a next step is required to make a more complete estimate. Or when a worst-case dose estimate that has assumptions that may be physically implausible results in a POC greater than 50%, a more refined analysis is required. A more refined estimate may be required either to deny or to compensate. In such dose reconstructions, which may be represented as a "reasonable" or "best-case" estimate, NIOSH has committed to resolve uncertainties in favor of the claimant. According to 42 CFR 82, NIOSH interprets "reasonable estimates" of radiation dose to mean the following:

> *… estimates calculated using a substantial basis of fact and the application of science-based, logical assumptions to supplement or interpret the factual basis.* ***Claimants will in no case be harmed by any level of uncertainty involved in their claims, since assumptions applied by NIOSH will consistently give the benefit of the doubt to claimants.*** (Emphasis added.)

SC&A's draft report and preliminary findings will subsequently undergo a multi-step resolution process. Prior to and during the resolution process, the draft report is reviewed by the DOE Office of Health, Safety, and Security to confirm that no classified documents or information have been incorporated into the report. Resolution includes a transparent review and discussion of draft findings with members of the Advisory Board Working Group, petitioners, claimants, and interested members of the public. This resolution process is intended to ensure that each finding is evaluated on its technical basis in a fair and impartial manner.

All review comments apply to Revision 00 of the BNL site profile document, which is the most recently published version. Site expert interviews were conducted with former and current BNL site workers to help SC&A obtain a comprehensive understanding of the radiation protection program, site operations, and historic exposure experience.

An attachment to this report will be provided later. The attachment will summarize the interviews conducted by SC&A during the course of this review. The interviewees included a good cross-section of former and current BNL site workers, including health physics (field and programmatic), dosimetry, medical, accelerator operations, reactor operations, support workers (i.e., maintenance and crafts), and research and development that worked at the BNL site from 1957 through the present. The interviews were conducted at the main technical library at BNL by Joseph Fitzgerald (SC&A/Saliant Inc.) and Kathy Robertson-DeMers (SC&A/Saliant Inc.), on May 18–21, 2009.

2.4 REPORT ORGANIZATION

In accordance with directions provided by the Advisory Board and with site profile review procedures prepared by SC&A and approved by the Advisory Board, this report is organized into the following sections:

(1) Executive Summary
(2) Scope and Introduction
(3) Vertical Issues
(4) Overall Adequacy of the Site Profile as a Basis for Dose Reconstruction

Based on the issues raised, SC&A prepared a summary list of findings, which are provided in the Executive Summary. Issues are designated as "Primary Findings" if SC&A believes that they represent deficiencies in the site profile that need to be corrected and which have the potential to have a substantial impact on at least some dose reconstructions. Issues can also be designated as Secondary Findings or Observations if they simply raise questions, which, if addressed, would further improve the site profile and may possibly reveal deficiencies that will need to be addressed in future revisions. Detailed analyses of the primary and secondary findings are provided in Section 3 of this report.

3.0 VERTICAL ISSUES

Finding 1: Bioassay Monitoring Not Adequately Established

ORAUT-TKBS-0048 (TBD) does not provide sufficient information to determine which workers were monitored for what radionuclides, and what criteria were used to select workers for special, routine, and spot bioassay monitoring. To perform an adequate dose reconstruction, the dose reconstructor needs to know who, when, and why workers were bioassayed at a given DOE site. This information allows the dose reconstructor to determine if the worker should have been monitored, and prompts the dose reconstructor to search for such records, if applicable (especially important because of the lack of a centralized record system at BNL). Although bioassays for some radionuclides were conducted for some workers at BNL throughout the laboratory's operating history, sufficient documentation of written procedures and requirements for bioassays is not apparent before the 1990s; this leaves some 40 years of uncertainty concerning bioassay requirements.

Until the 1990s, the determination of "who, when, and what" radionuclides for which workers were monitored was apparently a decision made at the departmental level, as opposed to being determined according to a centralized BNL policy. Unfortunately, this mode of operation led to inconsistencies in bioassay monitoring between departments, and fragmented and ad hoc recordkeeping (a later finding in its own right). This is further complicated by the fact that many of the bioassays were concerned with tritium intake, and tritium subsequently became an indicator, or surrogate, dosimetry source term for other radionuclides. However, it is clear that this approach is not necessarily a reliable one, particularly for short-lived radioisotopes to which workers may have been exposed at the BLIP facility and at the numerous onsite accelerators located at BNL; these and other radioisotopes would exhibit a different biological behavior than tritium.

With the exception of operators at the Brookhaven Graphite Research Reactor (BGRR), bioassay monitoring for radionuclides other than tritium at BNL appears to have been more "event driven," rather than conducted on a routine preventive basis. A preliminary review of BNL bioassay records does not indicate that consistent long-term routine bioassay monitoring policies were in place. When bioassays were conducted, it appears that the emphasis was on reactor operators; however, some of the most exposed workers were likely support service workers, i.e., those fueling, modifying, and maintaining the reactors (crafts and technicians). Of the current 66 claims at BNL (as of July 2009), very few were pile/reactor operators according to the listed job titles. Therefore, the issue of the adequacy and completeness of bioassays for all categories of BNL workers is relevant to performing adequate dose reconstruction.

According to the site profile and claimant records, *Form 1720* was used to record bioassay data from 1952–1986. The following is an example of the form and the information it contained:

BROOKHAVEN NATIONAL LABORATORY BIOASSAY RECORD

NAME_____ BNL LIFE NO._____ DEPT./DIV._____ H.P. LOCATION_____

No.	DATE RECV'D	I S	COLLECTION DATE/TIME	COUNT DATE	TOTAL SAMPLE	SAMPLE TYPE	BETA D/M/DAY MFP	BETA D/M/DAY ^{90}Sr	BETA µc/l ^{3}H	ALPHA NUCLIDE	ALPHA AMOUNT	ALPHA UNITS	MISCELLANEOUS & REMARKS

A review of these forms in the claimant files indicates that there has been information entered in each space in columns 1–7, on each line, and generally column 8 for mixed fission products (MFP) contained a number, and occasionally column 9 for ^{90}Sr contained a number. While the site profile provides some history concerning the in-vitro urine analysis, there is no information concerning the technical details of the MFP analysis. For dose reconstruction, some information is needed concerning the individual radioisotope analyzed for, and the method(s) of analyses. For example, some issues that need to be addressed include the following:

- When were gross beta, alpha, and/or gamma counting used?
- When were beta, alpha, and/or gamma spectrometry methods used?
- At the time of bioassay sampling and analysis, what radioisotopes were of concern, and what were not? How did this change as a function of time and work locations (buildings)?
- What were the constituents of MFPs? Did this change as a function of time and facility?
- When did BNL start to perform bioassay analysis for different isotopes of a given radionuclide (i.e., instead of analyzing for total uranium, when did BNL start analyzing for U-234, U-238, etc.)?
- What are the radioisotopes that are the major organ dose contributors that the dose reconstructor needs to include in the dose reconstruction?

Information concerning the radioisotope of **intake** is important when performing dose reconstruction; while radioisotopes in stack emissions, inventory, etc., may provide useful information, they are not primary sources in assigning internal doses. In addition to the reactors, critical assemblies (Court et al. 1967), isotope production, and the numerous accelerator facilities at BNL produced activation products and other radionuclides that could create potential internal exposure. Accelerator beams can activate iron, copper, aluminum, and structural material, resulting in activation products that would include Na-22, Na-24, V-48, Mn-54, Fe-55, Co-57, Co-59, and Co-60. Bioassay analyses for these internal radioisotopes are not addressed in the site profile.

According to the site profile, and a review of the claimant files, the *BNL Tritium Exposure Evaluation* form was used to record tritium bioassay results from 1968–1986. The following is an example of the form and the information it contained:

HEALTH PHYSICS DIVISION

Brookhaven National Laboratory

TRITIUM EXPOSURE EVALUATION

Name …… BNL No. ……... Location ……..

Date	No. of Intervening Days	Gross µc/l Current Date	Gross µc/l Previous Date	Fraction Present of Previous Concentration	µc/l Remaining from Previous Date	Net µc/l Current Date	Tritium Body Dose for Current Date MREM	Cumulative Tritium Body Dose MREM

A review of the claimant files reveals that, in general, these forms contain data for most of the columns, especially for reactor operators. However, no documented BNL procedures have been located that establish bioassay policies laboratory-wide, and as a function of time. The site profile makes the statement in Section 5.4.2 that this form could be a secondary source of information, should Form 1720, discussed above, be missing or illegible. However, as can be seen from the column headings on the tritium exposure form, there is only information for tritium and no other radioisotopes; it is not stated how other radioisotope intakes can be determined from tritium intake data.

For a number of years, BNL was involved in monitoring the conditions and people of the Marshall Islands, where atomic tests were previously conducted. The site profile does not address the monitoring issues involved in this program, such as whether BNL personnel who traveled to the islands were potentially exposed, or information regarding bioassay requirements for BNL personnel involved in this program, the location and availability of the bioassay records, and other pertinent information to guide dose reconstruction. Based on independent investigations performed by SC&A, islands on Bikini, Enewetak, and Rongelap Atolls have elevated external radiation fields[1] and the potential for elevated internal exposures to Cs-137, if locally grown food was consumed for protracted periods of time (e.g., several months) during visits to the northern atolls.

It is mentioned on page 75 of the site profile that decontamination and decommissioning (D&D) workers were sampled for various radioisotopes during D&D operations in recent years (e.g., interviewees indicated bioassay sampling was done for transuranics and fission products during D&D of the BGRR). However, no information is provided concerning these workers, such as:

- Were these BNL employees, or outside contractors?
- Were the bioassay monitoring requirements the same or different than those of regular BNL employees?
- Was cohort or individual sampling performed?

[1] According to health physicists involved in the program, workers from BNL participating in the Marshall Islands project did not require external dosimetry for the purposes of this project. They indicated that the highest contaminated areas where they worked were on Bikini Atoll, where external dose rates were tens of microrem per hour.

- What types of bioassays were performed?
- Where are the bioassay records located and are they accessible?

More information is needed for the D&D worker bioassay program to adequately support accurate and complete dose reconstruction for that activity.

In summary, the site profile does not address the adequacy and completeness of BNL bioassay data to support dose reconstruction. Uniform and comprehensive historic bioassay policies have not been cited nor located for BNL. An adequate basis for dose estimation has not been established by the site profile for BNL.

Finding 2: Records of Bioassay Monitoring Not Centralized or Knowingly Complete

The site profile does not address the issue of the completeness and accessibility of the bioassay records. As confirmed by interviews with several veteran BNL health physicists, there were numerous bioassay data recording systems and filing methods at BNL. Many of these earlier records are still located in various departments at the laboratory, making it difficult for BNL to properly and completely respond to NIOSH requests for bioassay records to be used in dose reconstruction. It is not currently known if all the hardcopy records have been located, are legible, and are accessible for dose reconstruction. As various departments were formed and disestablished, and as department heads came to and left BNL, these original hardcopy records may have survived, or they may have been destroyed or removed from the site. There apparently is no means available at this time to determine if all the records for a given employee are available for dose reconstruction purposes, particularly before the time period when all records were entered into electronic databases. Additionally, the site profile did not address issues surrounding the transfer of bioassay data from the hardcopies to electronic databases, e.g., if the transferred data were checked for accuracy and completeness, and whether the data transfers to upgraded electronic systems were checked using quality control.

The site profile does not address the data recording and storage methods used from the late 1940s to the retroactive start of the use of Form 1720 (~1952), and the start of the use of the Tritium Exposure Evaluation Form (1968). As previously discussed, Form 1720 was used to record MFPs and Sr-90 bioassay beta count results during 1967–1986 (with some indication that bioassay information from 1950s–1966 was transferred to this form in 1967), and the Tritium Exposure Evaluation Form was used during 1968–1986. However, interviews with former and current BNL health physicists indicate that, while the individual worker file may contain records that bioassays were performed, they do not necessarily contain the results of the bioassay from the late 1940–1970s. During the 1970s and 1980s, BNL was in a state of transition from hardcopy to electronic recordkeeping; this resulted in the individual record folders becoming increasingly incomplete. Starting in the 1990s, a more systematic electronic-based Health Physics Record System (HPRS) was implemented, which provides for a more complete and centralized data storage system.

BNL started whole-body counts (WBC) in the 1970s, or earlier, but unfortunately many of the results were recorded in logbooks instead of in the individual workers' files. Additionally,

WBCs were provided primarily for BNL reactor operators and for the Marshall Islands exposure subjects; other BNL employees were counted only as WBC time became available, and there appears to be a gap in WBCs from ~1977–1981, when no WBCs were performed.

A preliminary review of claimant files shows that the DOE records used to perform dose reconstruction contain some data on Form 1720, some data on the Tritium Exposure Evaluation Form, and some WBC reports in various forms. However, in general, the records do not appear to show a continuous or correlated bioassay methodology; i.e., some claimants may have WBC records, but no urinalysis records in their DOE files. A preliminary examination of the DOE files for 23 of the current (as of July 2009) 66 BNL claimants (whose job titles would indicate the possible need for bioassay monitoring and whose work history was fairly evenly distributed over the period 1947–2002) did not reveal a consistent pattern of routine bioassay monitoring for most of these individuals. It is not possible to determine at this time whether this irregular monitoring stemmed from the lack of a need for bioassay monitoring, the lack of bioassay monitoring, or from lack of record availability. Most of the DOE files of the 23 claimant cases reviewed contain a BNL response form, **PM3421**, which states that there was no in-vitro or in-vivo measurement data for a specific worker. However, a few of the DOE files created later contain WBC and/or urinalysis (mainly tritium) data for short periods of time. This indicates that some of the records were not available during the first request for records to be used for dose reconstruction, but were located later. However, there is no way to determine if they have all been recovered.

The extent of the records retrieval problem is evident from interviews with BNL personnel monitoring staff:

> *For purposes of responding to NIOSH requests for individual EEOICPA internal dose claimant data, I am collecting whatever hardcopy internal dose records I can from various onsite sources, such as the medical program. However, there is no way of knowing whether the retrieved records are complete for individuals or programs, because there was no coherent, centralized system of recordkeeping. Some records resided with individual department heads who may have disposed of records, removed them upon departure, or transferred them elsewhere. Data may be missing, but there is no way to tell.*
>
> *For example, if someone who worked at the BGRR was potentially exposed to MFP and Sr-90, and received bioassays during their timeframe of work, their individual records may indicate that they had been given bioassays, but the results, themselves, may be missing and unavailable. The only avenue would be to search through PM's* [Personnel Monitoring] *collected records by identifier and see what is there – however, there is no way to verify that the data is complete. After the approximate time frame of 1999, there is bioassay data and chain of custody documents to support the bioassay program.*

In summary, the site profile does not sufficiently address the issue of whether complete and accurate bioassay records exist during BNL's operating history to perform adequate dose

reconstruction. As evident from the information provided above, there are sufficient reasons to question the completeness, accuracy, and accessibility of bioassay records for BNL from the late 1940s through the mid-1980s, or perhaps into the mid-1990s when the HPRS became operational.

Finding 3: MDA and Uncertainty Values Not Sufficiently Defined

Minimum detectable activity (MDA) is mentioned several times in Section 5 of the site profile, and a list of WBC MDA values is provided in Table 5-3, pages 78–79, for the years 1999 through 2005. Additionally, urinalysis MDA values for some of the common radioisotopes found at BNL are listed in Table 5-3 on page 80; mainly for 1999–2006. Therefore, a reasonable amount of MDA information for common radioisotopes is provided for 1999–2006. However, what is lacking is a comprehensive listing of urinalysis and WBC MDA values for 1940s–1990s, such as is found in some of the other DOE site profiles [i.e., ORAUT-TKBS-0012-5 (ORAUT 2007), Table 5-9, pg. 16]. Furthermore, the site profile has not considered detection limits associated with the fission track technique used in some cases for the detection of uranium and plutonium (Moorthy and Baum 1985). In addition to the MDA values for common radioisotopes, the MDA values for, or procedure for identifying, other less common (but potentially present) radioisotopes should be provided, so that the dose reconstructor can consider and assign missed dose in specific cases where other radioisotopes could be present. For example, one can compare the relatively few radioisotopes, and associated time periods, listed in Table 5-3 on page 80 that the dose reconstructor has to work with, with the many radioisotopes listed in Tables 2-2, 2-3, and 5-5 occurring over more than a 50-year period. Some MDA values are obtainable from BNL documents, one example from Miltenberger (1978) being the BNL WBC MDL for U-235, which was 800 pCi (370 μg) in 1978. Additionally, uncertainty values are not provided and are apparently not available for most of the bioassay reporting period from the 1950s–1990s.

Table 2-2 of Section 2.5 of the site profile provides an extensive list of isotopes assumed to be present at the various facilities at BNL. Although it is stated on page 37 that this table is to provide background information only, this list could be misleading, as it is reflective of the airborne radionuclides released, as opposed to the radionuclides actually present in the work areas. The site profile does not provide a reference for the data presented in the unlabeled table in Section 4.51 on page 63, nor the unlabeled table on page 64, which identifies some isotopes that are assumed to be the isotopes that were monitored in the stacks. Additionally, the lists of isotopes in the latter table do not contain all the isotopes listed in Table 4-2 on pages 65–67, i.e., it lacks Sr-90, Nb-95/Zr-95, Tc-99, TC-99m, Ru-103, Ra-226, and Th-228; it is assumed that these isotopes were monitored at ground level, and not in the stack, but this is not explicitly stated. MDA values for most of these radioisotopes are not provided prior to the late 1990s.

In summary, the site profile does not sufficiently address the MDA and uncertainty values that the dose reconstructor is to use for the different types of bioassays as a function of time, nor does it provide default MDAs and uncertainty values to use if none are available.

Finding 4: Radionuclide Characteristics Not Sufficiently Known

Tables 2-2, 2-3, and 5-5 collectively provide information on the radionuclides by facility, the solubility data, particle size, and activity fractions. References are not provided for the information compiled in these tables, making it difficult to verify the information. As stated in Section 5.10 of the site profile, specific **solubility data**, **particle size**, and **activity fractions** are not known, or are not available, for most facilities at BNL. Site experts interviewed indicated the data in these tables reflect stack emission data, rather than workplace data. The use of stack emission data is not always a good indicator of the types of radioisotopes present, or their concentrations, in the worker's breathing zone. Interviews with BNL workers indicate that Tables 2-2 and 2-3 do not correctly reflect the radioisotopes present at some of the BNL facilities. For example, the radioisotopes listed in Tables 2-2 and 2-3 for the Hot Laboratory should include As-73, Sr-82, Sr-85, Ge-68, Cu-67, Y-88, Fe-52, Sn-117m, Zn-65, Fe-55, Ni-63, Rb-84, Rb-86, Xe-127, I-123, I-122, Pd-103, Mg-28, and Mo-99; Co-58, H-3, Mn-54, Br-82, Se-75, and V-48 were present in trace quantities. Isotopes produced at the BLIP facility should include Sr-82, Sr-85, Ge-68, Cu-64, Cu-67, Y-86, Y-88, Fe-52, Sn-117m, Zn-65, Rb-84, Rb-86, Xe-127, I-123, I-122, Pd-103, Mg-28, and As-73. The relative fractions of radionuclides assumed is inconsistent with what site experts say they were handling in the workplace. In addition, there are inconsistencies between Tables 2-2 and 2-3 under the site description, and Table 5-5 in the internal dosimetry section.

Without a proper characterization of workplace exposures, the adequacy of the internal and external monitoring programs cannot be effectively evaluated. For instance, since the radionuclides at the Hot Laboratory and BLIP were absent from the characterization, the site profile could not evaluate whether workers received appropriate bioassay for what they were exposed to, and whether that bioassay was collected in a timely manner. In addition, workplace-specific **monitoring data** and/or **source term data** do not appear to be available (TBD Sections 5.12 and 5.13). Lack of appropriate radiological characterization can also affect occupational environmental dose assumptions. This could result in less than claimant-favorable assumptions for organ dose reconstruction.

There is no support or reference listed for using a reduction factor of 0.01 to convert the measured stack concentrations to ground-level concentrations, as recommended in Section 4.5.2 on page 64. It is worth noting that this "short-cut approach" for placing an upper bound on occupational environmental exposures to airborne emission was used in at least one other site profile, and it is currently under review in that venue.

Finding 5: No Internal Dose Coworker Database Available

The site profile does not address coworker data. In view of the issues with the lack of a coordinated, consistent, bioassay program and the problems with the availability of the bioassay records, it would be advantageous to have a viable coworker database to use to assign unmonitored dose. Unfortunately, the lack of a routine and comprehensive bioassay program makes it difficult to create an adequate coworker internal dose table for the dose reconstructor to use to bridge the gaps for sporadically monitored workers, monitored workers whose complete

records are not available, and unmonitored workers who should have been monitored. As previously described, the records contain sporadic bioassay data; therefore, coworker internal dose data are needed for BNL.

The site profile does not mention the availability or applicability of coworker internal dose data. Therefore, the dose reconstructor is not provided with any recommendations concerning what doses to assign when a worker's information indicates that the worker should have been monitored, but wasn't, or the bioassay records are unavailable. In view of the lack of a solid bioassay program and record accessibility, the availability, or lack of, coworker dose information is an important issue at BNL for adequate dose reconstruction.

Finding 6: NTA Threshold Response Not Sufficiently Investigated

The threshold energy of NTA film (0.5–1.0 MeV) and the amount of dose not registered because of this threshold is important in neutron dosimetry. This threshold was identified as early as 1956 in a BNL *Health Physics Summary Report for November 1956* (BNL 1956, pg. 2):

> *As expected, it was found that the film will not detect neutrons below 0.5 MeV and that the sensitivity drops off sharply in the region from 0.5 to l.2 MeV.*

In 1974, it was stated in a BNL article by L. Phillips (Phillips 1974, pg. 21):

> *A serious disadvantage of personnel neutron monitoring using NTA emulsion is the blind region from thermal energies to approximately 500 keV. The effect of a certain amount of moderation of epithermal neutrons by the body and detection by the N(n,p) reaction cannot be relied upon as a significant effect using present calibration techniques. A new albedo dosimetry technique, which reduces the error in this "blind" energy region, has recently been reported in the literature.*

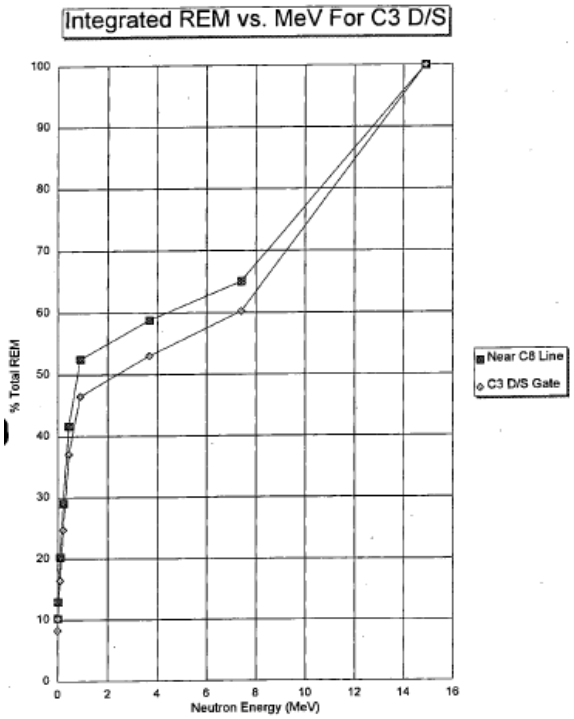
NTA film decreases in response starting at neutron energies below 1 MeV and is almost completely insensitive to neutrons below 0.5 MeV [ORAUT-TKBS-0010-6 (ORAUT 2005a), pg. 27); therefore, radiation fields containing an appreciable percentage of the total dose equivalent due to neutron below 1 MeV must be evaluated carefully, with attention given to the missed dose resulting from this threshold affect. Additionally, NTA tracks fade more rapidly with time as the interacting neutron energy decreases, resulting in more missed neutron dose (note the related "fading" issue addressed in this report for additional details).

According to BNL documents located by SC&A, neutrons with energies ranging from thermal to 1 MeV were present at various BNL facilities, in addition to the medium and higher energy neutrons (i.e., greater than 1 MeV) for much of its operating history. For example, the article by Handloser and Delihas (1955) contains various locations at the BGRR, where an energy range of thermal to fast neutrons was present.

A 1973 neutron energy spectra measurement using Bonner spheres at the BMRR patient treatment facility likewise indicated that the majority of the dose outside the treatment room,

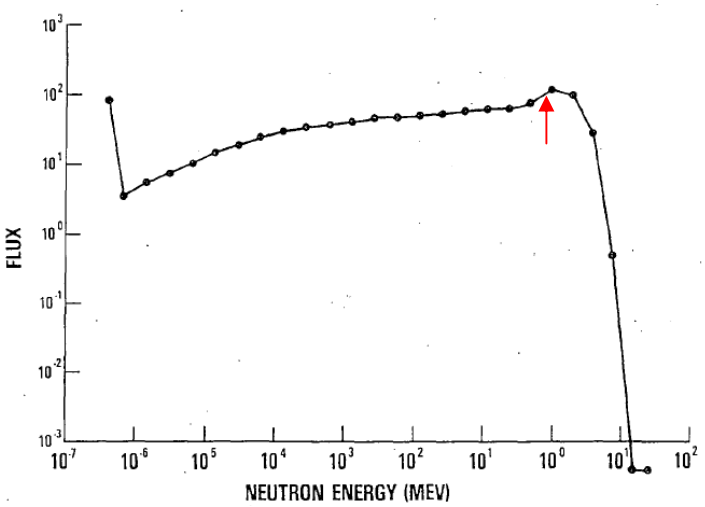
where workers may have been present, was due to low-energy neutrons; i.e., the highest dose came from neutrons with 600 keV of energy (Nelson 1973).

Another example, Schaefer 1995 (pp. 4–6), shows plots of *%Total REM* as a function of *Neutron Energy (MeV).* In these plots, it can be seen that approximately 50% of the neutron dose equivalent falls below 1 MeV for 6 locations at the Alternating Gradient Synchrotron (AGS). An example of one of these plots, which includes the results for two locations, is presented below:



Example of one of Schaefer's plots

Another example is shown in Figure 7 of G. Riel's 1995 article (Riel 1995, pg. 10), where it can be seen that a large portion of the neutron flux lies below the 0.5–1.0 MeV NTA threshold (red arrow) in the BNL workplace.



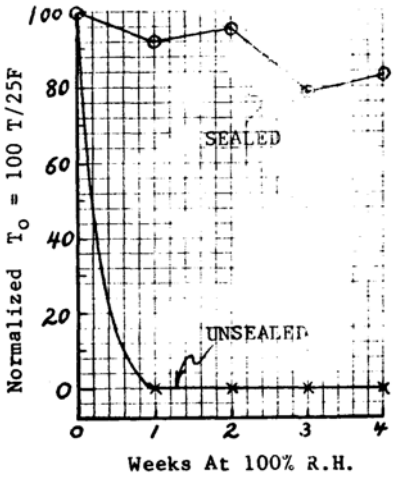
Neutron Flux vs. Neutron Energy in the BNL workplace

The site profile does not specifically address the subject of NTA film threshold. Section 6.4.1, page 91, contains a paragraph of general neutron dosimetry information. Section 6.7, page 94, lists recommended allotment of neutron energies, i.e., 0.1–2.0 MeV and 2–14 MeV, and states that NTA film was used through 1995. Bias and uncertainty values are listed for NTA film in Table 6-7 on page 97 with neutron uncertainty factors listed as 1.35 or 1.5, with a footnote that they are due to lack of knowledge of energy and geometry. The only mention made of the origin of these factors is on page 96, where there is a somewhat unclear statement concerning the fact that the values were taken from the Atomics International TBD (what SC&A found on page 12 of that document is a reference to the Hanford Site TBD), and also because of the fact that the adjusted neutron energy values are similar to, and are based on, Y-12 data (ORAUT 2005b). From this, it is unclear exactly where the values were obtained, and there is no supporting evidence to link the BNL neutron energy spectra to the other sites. The lack of details on this issue may lead to a lack of understanding on the part of the dose reconstructor of how to address low-energy neutrons in dose reconstruction. **For example, SC&A found that four out of five final dose reconstruction reports for BNL claimants, completed after the site profile was issued, did not include the neutron adjustment factors of 1.5 or 1.35 for low energy neutrons**; only the ICRP factors of 1.91 or 2.00 were used. The site profile should address this issue and make clear and technically sound recommendations to compensate for the incomplete neutron doses as recorded by NTA film and contained in the dose of record.

Finding 7: NTA Track Fading Not Covered in Site Profile

The magnitude of the proton recoil tracks in NTA film resulting from neutron interactions depend on the energy of the interacting neutron. Lower-energy neutrons cause less dense proton recoil tracks; these tracks fade more rapidly with time than heavier tracks caused by more energetic recoil protons resulting from energetic neutrons (i.e., 0.5–1.0 MeV neutrons in the workplace versus 4 MeV neutrons from a calibration source). While this issue is not addressed in the site profile, BNL was fully aware of the problem, as several BNL documents cite concerns or experiments conducted at BNL in this area. For example, in a 1973 BNL article (Phillips

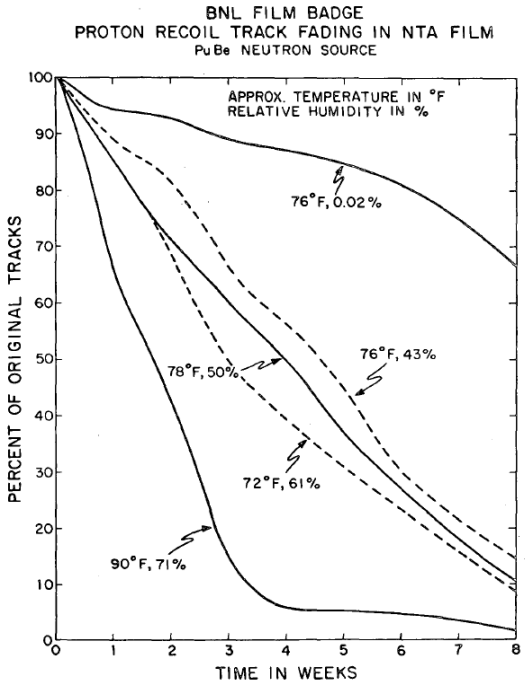
et al. 1973), NTA film was tested in sealed and unsealed packages. The unsealed NTA film lost all tracks in only 1 week at 100% relative humidity (RH), as shown in the following plot:



A 1972 BNL article (Distenfeld and Klemish 1972) states the following:

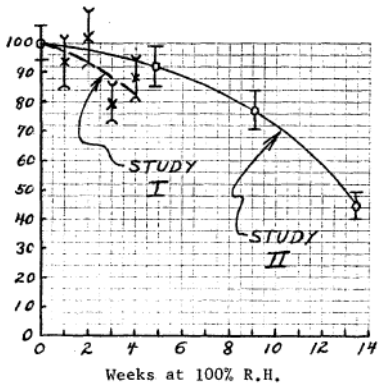
> *Film neutron dosimetry suffers prohibitive fading. Attempts by American laboratories to package NTA film have never prevented excessive fading.*

Another 1974 article by L. Phillips (Phillips 1974, pg. 18) describes tests run at BNL to determine NTA track fading. The results, using a relatively high-energy PuBe neutron source, are shown in the following plot.



Percent of original tracks vs. time

A 1975 article by L. Phillips describes a test in which two different types of packets were used to seal NTA films. The sealed NTA films were then exposed to neutrons and stored at 100% RH. The percent of the original tracks remaining (compared to the number at t_o) as a function of time is summarized in the following plot.



Percent of tracks remaining after t_o vs. weeks stored at 100% RH

At other DOE locations, such as the Mound site, NTA track fading was of sufficient concern that several experiments were conducted and exposure and reading procedures were modified to compensate for fading (ORAUT 2004a).

From these examples, it can be seen that NTA track fading is of concern when considering the accuracy of recorded neutron doses. The site profile did not directly address NTA film track fading or describe any procedure necessary to compensate for it.

From interviews with BNL health physics technicians who processed and read NTA films, it was learned that no apparent adjustments were made to account for fading:

> *We didn't do anything with the fading. The badges were developed and read within two weeks. There were 20–25 fields from the film read. BNL had about 2–3 readers who would spot check each other.*

In summary, if a fading problem does not present an issue for dose estimation with sufficient accuracy at BNL, i.e., it was accounted for in the calibration/issue/read cycle or included in the uncertainty factor, it should be explained and supported in the site profile. If not, this area needs further development.

Finding 8: NTA/TLD/Lexan/CR-39 problems

The problems associated with the NTA film threshold and track fading initiated a search for other neutron dosimeters; among those tested and selected for use at BNL were the TLD, CR-39, and Lexan neutron dosimeters. However, these neutron dosimeters were not without their own problems. From the site documents that SC&A has analyzed, the two major issues that were prevalent at BNL were (a) no single neutron detector sufficiently covered all the neutron energies encountered in the many different radiation environments; and (b) there were problems with the vendors of these detectors providing consistent and accurate neutron and photon dose results. To

facilitate the discussion of these issues, a very brief summary of personnel dosimeters and their advantages/limitations is provided.

Energy/dose response of different types of dose monitors/detectors.

i. Film and TLD-700 beta/photon detectors – Photographic film and thermoluminescence dosimeters (TLDs) respond to low LET (Linear Energy Transfer) radiation, such as betas, x-rays, gammas, and muons.

ii. NTA film – Neutron dose is determined by counting tracks in the emulsion produced by the (n,p) recoil proton. NTA film has a threshold of approximately 0.5 MeV, low sensitivity below 1.0 MeV, and the proton recoil tracks fade with time, but it has reasonable good response at higher neutron energy. NTA film will also respond to charged particles if they are able to penetrate the outer wrapper. The reading process is time consuming and prone to errors when compared to photon film dosimetry.

iii. TLD-600 – Neutron sensitive TLDs do not suffer from the threshold affect that NTA film does; in fact, TLD response is greater at lower neutron energies. However, TLD response decreases rapidly as the neutrons go above 1–2 MeV in energy (ORAUT 2005a). This makes TLDs suitable for use around moderated neutron fields (such as outside reactor shielding), but they under-respond to higher-energy neutron fields found around accelerators, which are prevalent at BNL.

iv. CR-39 – CR-39 stands for Columbia Resin, type 39 (a trademark of the PPG Industries) and is a plastic foil track-etch dosimeter. It has a neutron energy threshold around 0.2 MeV and has sensitivity an order of magnitude greater than Lexan for fast neutrons (Schaefer 1995, pdf pages 2 and 3, Ref ID 22456). Although it has a threshold around 0.2 MeV, it will significantly under-respond to neutrons less than 1.2 MeV (ORAUT 2005a). CR-39 characteristics make it useful for determining neutron doses around high-energy accelerators.

v. Lexan – Lexan (an SABIC Innovative Plastics product) is a small plastic chip that is etched from exposure to neutrons, with the pits counted under magnification to obtained neutron dose. Lexan has a threshold between 1–2 MeV for neutrons.

Two issues, one concerned with the fact that no single neutron detector sufficiently covered all the neutron energies and the other one related to problems with the results from the vendors, are interrelated because the properties of the neutron detectors were such that several types of detectors had to be used to cover the neutron energy range found at BNL; and if the readings from the vendors were not consistent, the obvious question is which detector results should have been used as the dose of record? From the BNL documents reviewed by SC&A and from interviews conducted with contemporary health physicists, it appears that there was a problem in this area, as found in several documents dating from 1987–1995, which are discussed below.

1987 – Several 1987 BNL letters/memorandums (see Casey 1987) refer to problems with the results from the vendor at that time, Landauer, Inc. There was apparently a difference in the dose readings for identical detector types evident by the statement on page 2, "Large discrepancies between duplicate badges with identical dosimeter types…", and between CR-39 and NTA film results as evident by the statement, "The reason for discrepancies between dosimeter types (CR39 and NTA) are also of significant interest, since they have impact in the field use of a particular dosimeter." To complicate the neutron dose issue, there also appears to have been a problem with monitoring for gamma-muon doses at this time, as indicated by the statement on page 3, "In another memorandum (February 24, 1987), one sees that the badges are not responding to gamma-muon doses of about 47 mrem." The details of this latter memorandum are contained on pages 9–10 of Casey 1987. As of yet, SC&A has not been able to locate documentation concerning the resolution of these problems.

1988 – In a 1988 BNL memorandum (see Musolino 1988), some of the problems with dosimetry at the accelerators were outlined. The BNL staff undertook experiments to help resolve some of these dosimetry problems. These experiments consisted of exposing different types of dosimeters and survey instruments to radiation fields around the AGS accelerator and comparing their results. There were several tests (runs) conducted; these included runs in June 1986, December 1986, May 1987, and February 1988. Additionally, NTA film was replaced by Lexan in December 1987, for use as the dose of record, but NTA film was retained in the badges for study and some comparisons were made. The following is a summary of the results of these runs:

a. **Main points of Musolino's cover memorandum of April 18, 1988:** *In short, approximately 10 times the expected collective neutron dose was reported by the recently adopted Lexan dosimeter, much of which was reported on persons that did not use their badge at all, persons not at BNL in February, or persons that did not use their badge in neutron fields. The old NTA system, which was retained in the badge for studies, indicated expected values.*

   Because Landauer and S&EP have found no plausible technical explanation for the recent events, I question how much confidence BNL should have in the Landauer neutron dosimetry system.

b. **Excerpts from June 1986 run –** *The results of the first study, which was performed from 6/13/86 to 6/27/86, was reported in the attached memo to Rohrig dated 11/17/86* [Musolino 1988, pg. 6, Table 1]. *The response of NTA relative to Lexan was inconclusive in much of the NTA (and CR-39) data, when replicate measurements, shown in the aforementioned memo, returned widely varying results.*

c. **Excerpts from December 1986 run –** *During the next SEB run beginning on 12/4/87, close inspection of the neutron dosimetry total of AGS personnel indicated continued problems in the NTA data. This was reported in the attached memo to Schopfer dated 2/24/87* [Musolino 1988, pg. 7, Table 2]. *It was of great*

concern at this point, due to the lack of dose reported with respect to active instrumentation. [Note that 12/4/87 should read 12/4/86, as evident from other contents of the article.]

To date, this question has not been satisfactorily answered by Landauer nor has the reason for the wide variances been explained. Copies of my memos had been provided to Landauer so that they could analyze this data.

d. **Excerpts from May 1987 run –** *1. Wide variances in the NTA results continued thereby reinforcing the lack of credibility in the results. 2. Lexan data was much more consistent with no catastrophic failures and much lower percent standard deviation. 3. For the second time the Lexan results were lower than the NTA values.*

The apparent reproducibility improvement and monthly exchange cycle would justify switchover to Lexan, because the under response would be offset by the lack of fading and the sensitivity for gamma-muon would improve by the doubling of exposure time.

e. **Excerpts from February 1988 run –** *The personnel results were altogether different. The anomalies and/or failures in the data are: 1. A collective neutron dose of approximately 16,000 mrem for about 150 persons when 1000–2000 mrem was expected. 2. Doses of 60, 40, 200, 40, 110 and 80 mrem neutron on control badges but minimal on the replicate and the NTA. 3. High neutron doses were even reported for individuals who were not at BNL in February or did not use their badge in pulsed radiation fields. 4. For the first time, Lexan yielded higher values than NTA.*

There is no correlation between the dose reported by Lexan and NTA; that is, high Lexan doses did not map to high NTA values.

Based on these considerations, the primary personnel neutron monitor at the AGS ***was switched from NTA to Lexan*** *in December 1987, but the NTA was retained for studies.* [Emphasis added.]

Based on this information, ***it is recommended that the NTA results should be the dose of record for February***. [Emphasis added.]

This information was sent by Carl Schopfer of BNL in a letter to Landauer, Inc., on May 5, 1988 (Schopfer 1988)), expressing concerns with the "…unreliable response by the Lexan system" and the fact that BNL needed to be assured "…that the Lexan dosimeter system is under control…" As of yet, SC&A has not been able to locate documentation concerning the resolution of these problems.

1995 – On April 19, 1995, Miltenberger of BNL expresses his concern with not having the Lexan doses included in the total dose (Miltenberger 1995).

> *However, as the AGS has been operating at higher intensities (50 to 60 TP), the fact that the **1exan dose is not being recorded has evolved into a significant problem**.*
>
> *We believe that this situation needs to be corrected immediately by **adding the three doses together**.* [Miltenberger 1995] Emphasis added.]

However, in a July 26, 1995, memorandum by Schaefer of BNL, he noted the following problem with the Lexan neutron detectors and recommended that it be discontinued (Schaefer 1995).

> *A review of the AGS neutron dose equivalent results for the first five months of 1995 as reported on the Landauer printouts shows that CR-39 responds with an overall sensitivity which is 7.4 times as great for AGS neutrons as Lexan. Given these results, and the fact that CR-39 has a reported sensitivity for fast neutrons which is an order of magnitude larger than Lexan, I strongly recommend the discontinuation of Lexan as the badge of record for neutrons, and the immediate implementation of CR-39 in its place.* [Schaefer 1995, pg. 2-3] [Emphasis added.]

Interviews with BNL health physics monitoring staff corroborated these documented concerns:

> *The discrepancies were the most critical at the low level doses. There was a wide discrepancy between the NTA, CR-39, and the Lexan system. We could see disparity up to at least 150 mrem. As the dose increased, the disparity narrowed. In general, the CR-39 read lower for low dose. The stated LLD was frequently missed. There were numerous times these issues were brought to the attention of Landauer, but there wasn't ever a consistent improvement.*

As can be seen from this brief snapshot of dosimetry problems, there were issues with NTA film, CR-39, and Lexan neutron dose readings, and even the gamma-muon readings. None of the detectors appeared to establish a long-term "gold standard" to which results could be compared. The above-cited statements (as bolded for emphasis) illustrate that there were numerous recommendations to switch back and forth between neutron detectors for the dose of record. In summary, for nearly a decade (and perhaps longer), the reliability of the dosimeter system at BNL, especially for the accelerators areas, appears to have been in question, with numerous problems and with no single reliable neutron dose detector. Considering that these major problems existed during the 1980s–1990s era, a relatively recent period when radiation detectors were considerably advanced, then there is a good probability that prior doses of record did not account for all the neutron doses received. The problems with the neutron dosimetry were significant; they were not in the dose range of the lower limits of detection (LOD) or within the values of the ± percent uncertainty. For example, in a 1986 BNL letter to Landauer (Schopfer 1986), it is stated that identical NTA detectors placed side-by-side in the same location gave drastically different dose readings of "2,390 mrem" and "minimal;" and that CR-39 detectors

exposed under the same conditions gave completely different results of "340 mrem" and "minimal."

This brings up a very important question: What dosimeter was used for the dose of record during this period; and regardless of the type of dosimeter, how can the dose of record be considered to be accurate? Based on interviews with the BNL health physics personnel monitoring staff, the apparent policy at the time was to assign the highest dose to the dose of record from that measured by the CR-39 and TLD-6, respectively, as noted in the statement below:

> *The process was to assign the highest dose to the dose of record. The CR-39 has a threshold of 500 keV. The TLD-6 would see the 500 keV and below. There was a memorandum generated telling them how to assign the dose. Sometimes you took the results from the CR-39 and the TLD. The Landauer badges had a Lexan portion and an NTA film portion to cover all energies.*

Another example is illustrated by the Miltenberger BNL memorandum of 1995 (pg. 7) (Miltenberger 1995), where the neutron dose is not included from the Lexan reading resulting in missing approximately 40% of the total (photon + neutron) AGS personnel dose for Jan–Feb 1995 (i.e., missing 8,950 mrem Lexan out of a total of 8,950 Lexan + 12,620 mrem beta/gamma + 1,000 mrem CR-39) and 90% of the total neutron dose (i.e., 8,950 mrem out of 8,950 + 1,000 mrem). The BNL site profile did not mention these dosimetry problems, if they were solved, or make any recommendation on the use of the neutron dose records, given these significant issues.

Finding 9: Potential Exposures at Accelerators Not Sufficiently Covered

High-energy accelerators, such as those at BNL, present the standard health physics problems, as well as often unexpected dosimetry challenges unique to each type of new accelerator. In the design and construction of new accelerators (especially in the early years before experience was gained and shielding calculation codes developed), there was a period of beam and dose measurements and construction changes before the machine was found acceptable for routine operation, both from an operational perspective and from a safety standpoint. After this initial phase, usually lasting several years, the machine began routine operations (in a general sense only, because an accelerator used for experiments does not have routine operating conditions like reactors or irradiators). This comes with an attendant increase in experimenter usage, accompanied by facility modifications, and sometimes increased beam current that requires additional shielding and sometimes creates potential exposure concerns. This state of operational flux creates a parallel challenge for the health physics program to address new challenges, and needed measurements, and procedures.[2]

[2] These types of concerns are discussed in considerable detail in *Health Physics Manual of Good Practices for Accelerator Facilities* by W.R. Casey, A.J. Miller, J.B. McCaslin, and L.V. Coulson, SLAC--327, DE88-010816, Stanford University, Stanford, California, April 1988.

To assist in evaluating the dose monitoring techniques and doses of record for BNL personnel, a brief and general outline of some of the typical health physics issues that need to be addressed at accelerators are as follows:

a. General work areas – After routine operations have settled in, exposure in the general working environment of an operating accelerator with adequate shielding is composed mostly of low Linear Energy Transfer (LET) radiation (photons, bremsstrahlung, and in a few cases, perhaps muons) with a Quality factor (QF) ~ 1.0, and low to mid-energy neutrons in the range of thermal to 20 MeV, with average energy around 1–5 MeV; usually having a higher LET, and hence QF $\geq$ 1. This radiation exposure can generally be measured satisfactorily using photon film/TLD and neutron NTA film/TLD badges. Sometimes Lexan and/or CR-39 neutron detectors are added to the badges if there is a potential for higher energy neutron exposure.

b. Experimental areas – However, in experimental areas, where the beam has been extracted from the main beamline, exposures can consist of high-energy radiation, such as protons, neutrons, heavier nuclear fragments, pi-mesons and K-mesons, high-energy electrons, bremsstrahlung, etc., resulting from cascades created by evaporation and spallation reactions of high-energy protons on a target in the main beamline, or in the extracted beamline. Personnel will most likely not be exposed to the charged particles outside the primary or secondary beamlines, because of the structural materials and shielding. However, if a person crosses, or looks into, a secondary beamline in an experimental area when the beam is on, large doses could result in a very short time (i.e., rad/sec), consisting of both low and high LET radiation. Dosimetry for persons potentially working around the experimental areas usually consists of some combination of NTA/TLD/Lexan/CR-39 neutron detectors to cover the wide spread of potential neutron energies. Generally, surveys with Bonner spheres (for examples, see Preisig 1992 and Preisig 1997) and threshold detectors (plastic scintillators, etc.) are used to obtain a measure of the neutron energy spectra and help determine the appropriate personnel monitoring device(s) and their calibration. Additionally, permanently mounted and portable neutron and gamma-ray survey instruments are used to measure area exposure levels (with live-time dose rate data fed back to the control room, in some cases).

c. Extremity exposure – One of the most difficult doses to evaluate in this area is from an accidental exposure to a relatively small portion of the body in an operating secondary beamline. Unfortunately, badge readings are of little use in this situation because of their single location on the body and lack of calibration/response to the radiation components of the high-energy beam.

d. Residual activation – One of the largest long-term exposure potentials for an established accelerator facility is the residual radiation fields (usually consisting of gammas and betas) resulting from activation of magnets, targets, beamstops, and structure materials. For example, the water-cooled target at the AGS reads >50 rem/[hr] at contact immediately after shutdown (ORAUT 2006, pg. 26). The dose rate usually decreases rapidly at first, in minutes/hours after shutdown, but then the remaining field decreases

more slowly. Delayed entries help to decrease accumulated doses, but use up valuable time.

e. Skyshine – Distenfeld and Klemish, Jr. provided a general definition of air scatter, usually called skyshine, in a 1972 article:

> *Neutrons emerging from the relatively thinner roof shielding of the heavily shielded biological enclosure radiate away from the ground. A large fraction of this population is energetically able to transfer energy to oxygen and nitrogen nuclei to cause an isotropic release of evaporation neutrons and protons. This neutron rain is termed skyshine. The evaporated neutrons and/or protons produce an energy spectrum that abruptly peaks about 1 to 2 MeV and tails down in energy to about 10 MeV where the population approaches zero. The range in air of a 10 MeV proton is about 150 mg/cm^2, or roughly 150 cm. Therefore the protons "inhabit" the immediate area of their formation while the neutrons have a much longer range. Skyshine is thus composed of neutrons above 1 MeV.* [Distenfeld and Klemish, Jr. 1972]

Skyshine has the potential of creating exposures to persons located away from the immediate accelerator areas, including members of the general public, as well as accelerator personnel.

f. Ground and entryway scatter – Usually the concrete shielding is not as thick in the floor as it is in the walls; therefore, radiation can penetrate the flooring and scatter off the lighter natural materials below the floor of the accelerator, creating ground scatter. Additionally, radiation can scatter out of the labyrinths used for personnel and utility entries. Usually this consists of soft neutrons and photons and is a diffused radiation source. Radiation from ground, building, roof, and equipment scatter often combines with skyshine to create somewhat of an isotopic external exposure field, which is sometimes difficult to characterize.

g. Activated cooling water – High-energy proton beams can cause radioactive products in the flowing cooling water of the magnets, targets, and beamstops. This cooling water is generally piped outside to be cooled and then recirculated. This presents a potential exposure to workers during operations, and after shutdown for some of the radionuclides. Below is an example of some of the radionuclides created in cooling water at BNL (Casey 1975):

Table 1
High Energy Proton Spallation Products in Water

Isotope	Cross section	Half life	Decay const. (sec)	Production rate $\left(\frac{mCi}{sec - uA}\right)$
^{3}H	38 mb	12.3 y	1.7×10^{-9}	9.1×10^{-6}
^{7}Be	10 mb	53 day	1.58×10^{-6}	2.1×10^{-3}
^{10}C	6 mb	27 sec	3.46×10^{-2}	29.3
^{11}Be	10 mb	19.6 s	3.54×10^{-2}	49.9
^{11}C	15 mb	20 min	5.78×10^{-4}	1.2
^{13}N	10 mb	10 min	1.15×10^{-3}	2.4
^{15}O	60 mb	2 min	5.6×10^{-3}	47.4

h. Activated air – Air can become radioactive from activation by high-energy protons/neutrons, especially in the experimental caves or other enclosed areas, and can be a source of exposure during operations and immediately after shutdown. The discharge stacks can emit radioactive air, which can be another source of exposure to workers, as well as the off-site population. Generally, activated air poses more of an internal dose, rather than an external dose hazard.

i. Intense light sources – Intense light sources, such as the NSLS (National Synchrotron Light Source), accelerate electrons to high energies (in the GeV range) to produce intense x-ray, UV, and IR sources for experimental purposes. These high-energy x-rays create neutrons through photoneutron reactions, resulting in the usual photon and neutron radiation fields with wide spectra of energies outside of the shielding. Compared to other accelerators, electron accelerators used for intense light sources are relatively clean machines and more manageable from a health physics perspective, with some photon and neutron exposures.

Note that neutrinos and antineutrinos are abundant at accelerators, but do not pose an exposure problem, because of their extremely low interaction probability with any type of matter.

Considering these possible exposure areas, SC&A searched the BNL documents **to determine conditions/situations where there may have been the potential for unreported or underreported exposures, dosimetry systems that did not match the radiation fields, and/or lack of correct monitoring methods because of unrecognized conditions at the time.** These situations could lead to the dose of record not correctly reflecting the actual received dose.

Potential areas of concern are as follows:

a. Cosmotron 1953 – Cowan wrote the following in 1953:

> *Compared with previous accelerators, the Cosmotron represents a major extension in energy and poses difficult problems in exposure measurement and evaluation. Only a start has been made toward solving these problems; in fact work along these lines will certainly continue for many years.* (Cowan 1953, pg. 6)

b. Cosmotron 1952–1959 – The Cosmotron was an undershielded experimental facility in the beginning. The path and shielding of the beamline were not initially designed for sufficient protection of the accelerator workers, other BNL personnel, or those in the surrounding areas as it went through accelerator, the workplace, and across the countryside (Cowan 1965, pp. 3 and 4).

c. AGS 1963 – Cowan, Phillips, and King states the following:

> *Evaluation of radiation hazards at GEV proton synchrotrons such as the Brookhaven AGS is difficult since the composition of the mixed radiation fields varies widely depending on location, and substantial high-energy components are often present. In addition, the machines are usually pulsed and very large work areas are involved* (Cowan et al. 1963, pg. 5).
>
> *Shortly after the Alternating Gradient Synchrotron commenced operation, it was found that a considerable flux of mu-mesons was penetrating 16 feet of heavy concrete and emerging into the experimental area. We were then faced with determining whether dosage due to this flux was being properly evaluated, particularly since high energy muons are minimum ionizing particles and the NTA film used for personnel monitoring doesn't record tracks due to such particles* (pg. 10).
>
> *Since beam intensities of 6×10^{11} protons per pulse are now obtained, we have dose rates up to 1000 mrad/hr in the exclusion area and 1 to 10 mrad/hr over a considerable portion of the adjacent work area…The mu-mesons are mostly minimum ionizing particles for which a QF of 1 is appropriate* (pg. 11).

d. AGS 1965 – Cowan states the following in a 1965 paper:

> *Exposure control at the AGS has become increasingly difficult as a result of increased intensity and multiplication of facilities. Locations of Health Physics interest are the experimental halls including an area where mu-meson dosage predominates, the accelerator ring where dosages during shutdown are presently a major problem, the linac injector, the 80" bubble chamber, and the southwest or neutrino experiment area, as well as nearby areas and buildings. A major rebuilding of the AGS is anticipated*. (Cowan 1965, pg. 3)

e. 1980s–1990s dosimetry at accelerators – As indicated earlier in previous findings, there is a lack of dosimetry consistency in the BNL accelerator areas (especially for neutron exposures). The site profile does not address these problem areas or indicate for what time periods they were prevalent, what dose values were used for the dose of records, if the problems were resolved, or make any recommendations for dose reconstruction concerning these issues.

f. RHIC – Originally named "Isabelle" (Intersecting Storage Accelerator), later called the Colliding Beam Accelerator (CBA), and still later built and operated (starting in 2000) as RHIC (Relativity Heavy Ion Collider). Because of its large diameter, the RHIC is a "thinly" shielded accelerator at some points, and heavily shielded (including muon shielding lobes) at the intersecting points of the two counter-circulating proton beams (Gollon and Casey 1984). While the health physics concerns at the RHIC are similar to other high-energy accelerators, there are several unique issues. These concerns include routine beam losses and the possibility of a catastrophic beam loss. As stated by Gollon and Casey (pg. 3), "The energy and intensity of the stored proton beams play a dominant role in determining the extent of the prompt radiation hazard." Therefore, not only are the standard HP concerns (i.e., prompt and residual radiation) present, but there is the potential for the loss of a large amount of stored beam. The maximum beam loss at linear or circular particles accelerators, without storage capability, is limited by the injection rate. However, at a beam storage facility, such as the RHIC, the injected beam can be accumulated for up to 24 hours or more, resulting in very large amounts of energy that can be instantaneously lost in a catastrophic event creating large, short-term, radiation fields. According to Gollon and Casey (pg. 7), a 20% circulating beam loss could result in a radiation field equal to 5 months of radiation doses from normal operations. The high energy of the RHIC also creates forward-directed muons fields that are not normally prevalent at other accelerators. These operating parameters create potentially unique health physics problems at the RHIC and corresponding dosimetry challenges.

g. Uncommon types of radiation –

- Spallation products: Page 91 of ORAUT 2006 mentions spallation products and the fact that the doses from them were small. Spallation products resulting from the breaking apart of nuclei by high-energy particles are highly unlikely outside of heavy shielding or secondary beamlines, because the spallation products are highly charged. The cascades of radiation resulting from the spallation/ evaporation reactions of the proton beam can be encountered outside the beamlines, but generally not the spallation products themselves. Perhaps what was being referenced by the site profile is the fact that high-energy particles can cause stars (a type of spallation) in emulsions such as are used in NTA film. Cowan 1953 (pg. 34) states, "It should be noted that when stars are observed in the emulsion, each prong is counted as a track. This practice takes some account of the large amount of energy released in such events." However, this article was written in 1953 at the beginning of the operations of the Cosmotron, and a complete reading of the document indicates that there were still a lot of unanswered questions concerning the dosimetry of high-energy radiation. At that time, they were mainly concerned with having a large enough dose-to-dose equivalent conversion factor [Radiological Biological Effectiveness (RBE), or later, the Quality Factor (QF)] to not exceed the regulatory dose limits (this was sometimes called a "Safety factor"). The subject of prong counting, what caused them, their conversion to dose, and their significances in the doses of record need

elaboration in the site profile to enable the dose reconstructor to correctly interpret the neutron entries in the doses of record.

- Muons – Although pi-mesons (272 times the mass of an electron) resulting from the spallation reactions of high-energy protons on material do not usually exist in the occupied areas around an accelerator, their decay product, **muons** (previously called mu-mesons), with a mass 207 times the mass of an electron, can exist outside heavy shielding, because of their penetrating power (resulting from their lack of Bremsstrahlung emission, because of their large mass compared to electrons). The BNL AGS was one of the first proton accelerators in which muons would dominate the radiation concerns (Patterson and Thomas 1973, pg. 146). This is supported by a statement by Cowan in 1963:

  > *There is one area at the Alternating Gradient Synchrotron (AGS) which is extremely interesting from the dosimetric point of view. This is an area where a flux of mesons, with attendant secondaries, emerges from a 16-ft thick heavy concrete shield (see Figure 1) and results in substantial dose rates* (Cowan 1963, pg. 5).

  Muons exposures and dosimetry were not addressed in the site profile.

- High energy protons – Although high-energy protons do not normally exist outside the shielding, they can be present in the experimental areas where beamlines emerge. In earlier years, sometimes personnel were present in these experimental areas and could accidentally be exposed to radiation from the beamline, or in an experimental cave (see Merkle 1952 for an incident in 1952 at BNL). In more recent years, accidental exposures may result from an experimenter assuming that a beamline is off, when it is actually on (see Distenfeld 1970 for a 1970 incident at BNL). These types of exposures are hazardous because of the large instantaneous doses that can be received, i.e., 580 rad/pulse in a 1-in diameter focused beam (Cowan 1960, pg. 3). Other factors include the fact that the beamlines are generally at chest or head level, the beam area is small compared to the whole body, and a monitoring badge most likely will not be in direct line of the beam exposure and not necessarily calibrated to the radiation components/energies of the radiation contained in the beamline. Additionally, there is a tendency to sight down a beamline during experimental setups, and if the beamline is accidentally on, this can lead to exposures that can greatly increase the probability of eye cataracts (Cowan 1960, pg. 3). The site profile did not cover the potential for high-energy proton (and accompanying radiation byproducts) exposures, any incidents of these exposures, or the dosimetry/dose assignments associated with such exposures.

As can be seen from this brief summary, there are many situations at high-energy accelerators that have the potential for unconventional exposures leading to unrecorded or under-recorded doses. The current BNL site profile does not address key dosimetry problems associated with

high-energy accelerators, the adequacy of dosimetry systems during start-up periods, or if the dosimetry systems were sufficiently encompassing to accommodate operational changes. The site profile, likewise, does not discuss adjustment factors for neutron doses and if adjustments are needed to compensate for the limitations of the dosimetry systems used as a function of time at different accelerator facilities (as illustrated in a discussion in this report concerning problems with NTA/TLD/Lexan/CR-39 neutron dosimetry systems). The site profile does not address if or where or when muon doses were of health physics concern, or how and if they were monitored and recorded, and the interpretation of those doses, if recorded. Hazards from extracted high-energy proton beams and their dosimetry were also not addressed. The main body of the Occupational External Dosimetry section of ORAUT-TKBS-0048 (ORAUT 2006) consists of only six pages; this obviously cannot contain sufficient information to cover the important aspects of dosimetry at the many diverse BNL facilities for an operating period of approximately 60 years. Such a limited space could not cover the many health physics aspects of accelerator dosimetry (a few of which are outlined above), in addition to those of reactors, isotope production, medical research, hot cells, the NSLS, and other facilities with potential radiation exposures at the BNL.

Finding 10: External Coworker Dose Data Not Addressed

Section 6 of the site profile did not address or provide any coworker data for use in assigning external doses to workers who should have been monitored, but were not. Coworker data is needed in cases where the worker had the potential to receive greater than environmental doses, but by the criteria of the time, was not considered a radiation worker and was not badged, or the monitoring results cannot be located. In a dose reconstruction report that SC&A recently audited it was found that the dose reconstructor needed external coworker dose data for BNL to perform the dose reconstruction, because the worker was potentially exposed but not monitored. In this case, the dose reconstructor was required to use data derived from studies performed for other DOE sites to complete the dose reconstruction.

This indicates that external coworker dose data are needed, but not present, in the BNL site profile.

Finding 11: Incidents and Unanticipated Events Not Addressed

The site profile does not sufficiently address incidents or unusual events that could affect external dose reconstruction. Some examples of incidents available in the BNL documents are listed below:

- Several incidents of persons being in the experiment caves/areas when the beam was on were reported:
  - A person was trapped in an experimental cave with the beam on at the Cosmotron in 1952 (Merkle 1952).
  - A person was working near a beam stop with beam on in 1970 (Distenfeld 1970).
  - Two operators were trapped inside an experimental area in 1988 (Rohrig 1988).

- Potential exposures outside of controlled areas could have exposed unmonitored workers, such as stated by Musolino in a BNL 1987 memorandum (Musolino 1987):

  > *Twice in May excessive beam losses caused high radiation levels **in uncontrolled areas**. Up to 1200 mrem/hr and 125 mrem/hr were present due to transport losses in the A and D lines respectively. In both cases, the losses were not anticipated and were found during the S&EP daily survey. Also, both times isolated thin shielding contributed to the problem.* [Emphasis added.]

- A number of potential exposure incidents (which resulted in both internal doses and external doses) that took place during 1950–1967 were described in BNL (1967); most of them were concerned with the BGRR. These incidents could have exposed unmonitored, or sporadically monitored, workers without their doses being recorded.

With respect to unplanned environmental releases, BNL 1967 provides a list of incidents for 1950–1967, mostly concerned with the BPRR, which could lead to environmental doses to unmonitored workers. The following is reproduced from BNL 1967, page 5:

BUILDING	MONTH	YEAR	REFERENCE	LOCATION/ROOM ID	ITEM	ACTIVITY/OCCURENCE
7/01/703	5	1956	BGRR Health Physics Logbook # 2 (5/1/56 – 6/11/58)	bldg 703 – front yard: old drainage line	rad activity	Rad levels could be seen on the old drainage ditch and pipe line through 3 foot of earth. Rad levels could also be detected through the ground covering as far as the road in front of the reactor.

These types of incidents/records should be taken into consideration when evaluating occupational environmental doses, especially to unbadged personnel. The present site profile does not address any specific environmental-related incidents and their impact on external doses to unmonitored workers.

Finding 12: Potential Environmental Exposures from Igloo Area Not Addressed

Nothing is mentioned in Section 4 of the site profile concerning the Igloo storage area in the Hazardous Waste Management Facility and its impact on localized environmental doses. In 1992, this was of concern to workers in the area and perhaps outside the area, considering that dose rates and skyshine were addressed in a BNL memorandum by Karr (1992), which indicated items in the Igloo area had readings of greater than 100 mrem/hr, and that skyshine was of concern and needed to be reduced. Attachment 4 of that article indicates that dose rates outside the fence could range as high as 200 microR/hr, equivalent to 400 mrem/yr for 2,000 hr/yr occupancy. This exceeds the assumed maximum public dose limit of 100 mrem/yr, as stated in Section 4.4.1 and Table 4-1 for the period 1967–present. Average yearly site parameter readings, and other readings inside the BNL site, may not reflect the true environmental doses received by unmonitored workers who spent any significant time in the areas outside the Igloo or other waste facility areas.

Finding 13: The Site Profile has Inadequately Characterized the Number and Types of X-rays Received by BNL Employees in Early Years.

The site profile, page 50, states that BNL had machines capable of photofluoroscopic/ fluoroscopic exams in 1951 and 1960, but also on page 50, it is concluded that only the diagnostic unit was used for routine exams, and on page 52 it is stated that it seems unlikely that the greater dose units were used for routine exams. These potential exposures were not further addressed in the site profile. It references Brodsky 1964 as one of the reasons to conclude that only the diagnostic unit was used routinely for examinations. SC&A located the Brodsky document and found it difficult to read, because it was the minutes of a long meeting and lacked clarity and continuity, along with many missing/incorrect words; however, SC&A read and performed keyword searches on this document and did not locate any statements indicating that photofluoroscopic/fluoroscopy exams were not performed at BNL. Statements concerning x-ray units and resulting doses were found on pages 35 and 36, but these do not necessarily eliminate the occurrence of photofluoroscopic (PFG) exams. It would be helpful to have the page number in the Brodsky document that the authors of the site profile used to reach the conclusion that PFG exams were not conducted; and hopefully at least one official reference besides these meeting notes to support this claim.

Furthermore, Sunderman (1947) summarized the health program used for BNL employees effective September 1947. The medical department at BNL was activated as of July 1, 1947, and based its examination program on those that were in operation at other Atomic Energy Commission laboratories at the time. Sunderman recommended that employees of BNL be observed medically (1) upon hire at BNL, (2) routinely for employees requiring health maintenance, (3) when employees become sick or injured, and (4) when employees terminated. Candidates for employment were to receive "fluororoentgenograms of the chest, A-P and lateral roentgenograms of the spine and roentgenogram of one forearm." During Health Maintenance exams of employees, an annual fluororoentgenogram of the chest was completed. There were special examinations for workers exposed to special hazards, such as estimations of uranium in urine for those exposed to uranium. Radon breath analysis was completed on workers handling radium. Complete records of exposure to radioactive materials were collected as a part of the exam. Employee termination exams included "fluororoentgenograms of the chest, A-P and lateral roentgenograms of the spine and roentgenogram of one forearm" (Sunderman 1947).

The site profile mentions lumbar spine x-rays on page 52 of the site profile, although Tables 3-1 through 3-4 are limited to 14-in by 17-in PA and lateral chest radiography. The statement by Sunderman (1947) contradicts the statement that PA chest PFG, AP lumbar spine, and lateral lumbar spine exams were unlikely. In addition, on page 55 of the site profile, it is assumed that any radiograph that was not a PA chest or LAT chest was diagnostic and should not be included in dose reconstruction. The lumbar spine and forearm x-rays were required during the pre-employment and termination exams, and should not be excused as diagnostic exams.

In summary, the site profile has failed to consider pertinent information on the number and types of exams required as a condition of employment. Further investigation of medical exam protocol

is warranted. Dose assignments for PFG exams should reflect the assumptions in ORAUT 2005c and ORAUT 2004b, unless site-specific data suggest more claimant-favorable assumptions.

3.1 SECONDARY FINDINGS

Finding 14: Section 4 Table 4-1 Values Need Further Development

The external gamma doses listed in Table 4-1, page 63, of the site profile are recommended for use in assigning ambient dose to unmonitored workers. It is not obvious how these values were obtained, or if they are applicable for that use. To illustrate, in terms of time periods:

- 1947–1949 – Meinhold and Meinhold (2001) state on page 9 that the activities for 1947 were mostly organizational. Therefore, it can be assumed that the ambient external doses were near zero, as listed in Table 4-1 of the site profile. However, there has been no documentation found to support zero doses for 1948 and 1949 as they are listed in Table 4-1 of the site profile. The only reference for this period is in the footnotes to Table 4-1, where it is stated that, "Data prior to 1950 are assumed based on site activities in those years."

- 1950–1965 – The document by Meinhold and Meinhold (2001) contains a discussion of external environmental doses on pages 61–63 (includes Table 6) and pages 97–98 (includes Tables IA-5 through IA-8). The values in these tables do not match those listed in Table 4-1 of ORAU 2006. For example, Table IA-5 lists the Boundary Stations average as **24** mR/year and the maximum as **46** mR/year for 1959, but Table 4-1 of the site profile lists an average of **27** mrem/y and a maximum of **39** mrem/y for 1959; most of the values for the other years could not be reconciled either. Note that taking 23% of the Monitoring Stations values (see the issue with 2,000 hours/year addressed below) would not correct this situation, but would only make it worse.

- 1967–present: Monitoring results – ORAU 2006, page 62, Section 4.1, states the following:

  > *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.*
  > [Emphasis added.]

  These statements indicate that there are onsite monitoring results available, and that some "are included…" However, in Section 4.4.1, page 62, it recommends using the public dose limit of 100 mrem/yr, because the "on-site monitoring results were no longer reported..." This appears to be a contradiction.

- 1967–present: Use of 100 mrem/yr – For this period, the site profile recommends the use of 100 mrem/year ambient dose, because this was the public exposure limit, and had only been exceeded once in prior years. During this period, BNL may have limited the dose at the boundary, so that no member of the public would receive greater than 100 mrem/year; however, this does not necessarily mean that areas within the site fence could not exceed 100 mrem/year. Therefore, it is not clear how the site boundary average doses for the public can be used to assign unmonitored on-site workers' doses (who could be closer to the radiation areas), and furthermore, to consider it a limiting (maximum) value.

- Issue of 2,000 hrs/yr – The site profile states on page 62 that the values in Table 4-1 have been adjusted to reflect 2,000 hours per year occupancy. However, if this is true, the values in the table would be only about 23% (2,000/(365 × 24) = 0.23) of the environmental station values (if the reported station values were for 24/7 sampling), and the value for 1967–present would only be 100 mrem/year × 0.23 = 23 mrem/year, instead of 100 mrem/year.

It appears that the data used in Table 4-1 on page 63 of the site profile need further development and/or clarification to support its recommendations.

Finding 15: Onsite Wells

Page 68 of the site profile states that potable water from onsite wells was used, but that no ingestion of radionuclides by this path was found. The site profile needs to address the tritium leak from the HFBR in the contents of the wells (i.e., whether they were tested and found to not contain tritium, their present status, etc.).

Finding 16: Non-Penetrating (NP) Included in Whole-Body Dose

Table 6-4 on page 94 of the site profile contains a summary of recorded dose practices. The third column, rows 2 and 3, states that the whole-body (WB) dose = nonpenetrating (NP) + photon (P) + fast neutron (FN) + tritium. However, using the generally accepted definition of these terms (and supported by the site profile's definition of these terms in the Glossary on pages 100–106), WB dose is the dose at a depth of 10 millimeters and NP dose is from beta and lower energy photons; therefore, it appears that the NP dose should not be included in determining the WB dose.

Finding 17: Adjustments to Recorded Dose Not Supported

An adjustment to the photon dose of 10% is recommended on page 95 of the site profile to compensate for penetrating low-energy photon doses not accounted for. It is only stated that, "It is estimated that a correction equal to 10% of the <250-kev values be made." No supporting documentation is provided for this recommended adjustment factor. Additionally, SC&A could not locate the statement that most of the photons at the NSLS facility are below 250 keV, and that measurements indicate a peak at 75 keV in the reference listed in the site profile, which is Preisig 1997. SC&A did find a statement in Sengupta 2000 (pg. 23) that reads, "Measurements

of NSLS indicate a photon peak about 75 KeV." However, no reference to the statement that photons are <250 keV at the NSLS was made.

Finding 18: Potential Exposures at LMFR Research and Development Facility Not Addressed

There were three operating reactors at BNL, plus an experimental liquid-metal fuel reactor (LMFR) research and development (R&D) facility (not actually a reactor, but an experimental sodium loop). The site profile provides some information concerning the design, operations, fuels, radioisotopes, radiation fields, etc., of the three major reactors; the BGRR (Brookhaven Graphite Research Reactor), the HFBR (High Flux Beam Reactor), and the BMRR (Brookhaven Medical Research Reactor). It also mentioned the LMFR on page 35 as a support and R&D facility:

> *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.*

However, this is all the information provided. There is no information concerning the amount/types/chemistry of uranium present; the design and components of the core; if critical masses were present; internal, external, and contamination radiation hazards; number of workers involved; etc. To date, SC&A has not been able to locate any relevant documents on the Site Research Data Base (SRDB) or the BNL website concerning the LMFR. SC&A did locate some BNL Nuclear Engineering Department LMFR reports for 1957, but they were mostly concerned with engineering designs, not radiation hazards. More information is needed on the LMFR facility to allow the dose reconstructor to properly assign dose to claimants who worked there, which could have been a significant portion of their employment period (up to 19 years).

Finding 19: Human Radiation Experiments

Human Radiation Experiments were conducted at BNL from 1950 through 1976. Radiation experiments included total body irradiation, neutron beam exposures, and in-vitro exposures to H-3, tritiated thymidine, C-14, Na-24, Mg-28, Cl-38, K-42, Sc-46, Ca-47, Cr-51, Mn-54, Co-57, Co-58, Co-60, Fe-59, Zn-65, Ga-72, Kr-79, Br-82, Sr-85, Tc-99m, I-123, I-124, I-131, Xe-127, and Cs-137 (DOE 1995). Although a majority of these studies involved individuals not employed at BNL, there were BNL workers who voluntarily participated in tracer study experiments. Information on the exposure of BNL employees who participated in human radiation experiments is not currently provided to NIOSH. Information on exposures of this type is typically maintained separate from the medical and radiological files maintained by researchers. Worker participation in human radiation experiments requires further investigation to determine the number of claimants affected. Any files containing additional information on radiation exposures should be requested by NIOSH as a part of the claimant response.

3.1.1 Factual or Editorial Observations

Occupational Medical Dose (Section 3)

Section 3 references not available on SRDB

- NCRP Report No. 102 is listed in the Reference list, page 61, as being in the SRDB [Ref ID 126], but it is not on the SRDB.
- ICRP Publication 34 is listed in the Reference list, page 61, as being in the SRDB [Ref ID 107], but it is not on the SRDB.

Decreased AF by 10% not documented in Section 3

On page 54, it is stated that the absorption factor (AF) was decreased by 10%; while this is claimant favorable, there is no readily apparent support in the site profile for this decrease.

Environmental Dose (Section 4)

Section 4 clarifications needed and reference not listed

- The second paragraph in Section 4.5.2, page 64, is confusing or contains a repeat of the first part of the paragraph in the second half of the paragraph. This needs to be corrected/clarified.
- The reference *(NIOSH 2002, pp. 15–16)* listed at the end of page 64 is not listed in the Section 4 Reference list (but is listed on page 89 of the Section 5 Reference list).

Internal Dose (Section 5)

Water intake conflict

Uncertainty in "average water intake" is listed as a variable in Section 4.7 on page 68; however, in Section 4.6, it is stated that water is not a pathway for intake. This is an apparent conflict.

External Dose (Section 6)

- On page 92 of the site profile, an incorrect reference date is listed in the second sentence, (it should be Patterson 1994, not 1964).
- On page 92, Section 6.5, of the site profile in the first paragraph, the last sentence should read "It appears that all **radiation** workers were…" to be consistent with Section 6.5.1, first paragraph, last sentence where it reads "All **radiation** workers were…."

- On page 92 of the site profile in the last paragraph, the term "**Missed** doses…" is the incorrect term to use here, in view of NIOSH's standard use of the term missed dose to mean doses that are too low to be detected by the dosimeter. The lack of recorded dose for unmonitored employees should be called **unmonitored** dose, not missed dose. By definition, a worker cannot have a missed dose if the worker was not wearing a dosimeter.
- Page 94 of the site profile contains Table 6-3. This table is busy and confusing and needs to be redone. For example, the neutron energy (MeV) column contains weighting factors also. The fourth column, row 3, contains two 100% default dose neutron energy ranges; this does not make sense. The fourth column, row 4, contains too much information. This table needs more columns and rows to allow for only one entry per cell. The footnotes need to contain more explanations and references for the derivation/source of the weighting and correction factors; i.e., ICRP-60, Quality Factor (QF), resulting correction factors, etc.
- Page 94 of the site profile contains the statement, "Recorded neutron doses include both thermal and fast neutrons generated by the various accelerators with energies >100 MeV …" This could be interpreted to mean that if the accelerators had energies less than 100 MeV, neutron doses were not recorded. This statement needs to be reworded for clarification.
- On page 94 of the site profile, the footnote to Table 6-4 states that Harshaw 8806 TLDs are issued only when higher energy neutrons might be present. This statement may refer to CR-39, because a neutron TLD has a higher response at lower energies and CR-39 has a higher response at high neutron energies. This needs to be reviewed for technical correctness and clarified.

4.0 OVERALL ADEQUACY OF THE SITE PROFILE AS A BASIS FOR DOSE RECONSTRUCTION

The SC&A procedures call for a "vertical" assessment of a site profile for purposes of evaluation of specific issues of adequacy and completeness, as well as a "horizontal" assessment pertaining to how the profile satisfies its intended purpose and scope. This section addresses the latter objective in a summary manner by evaluating (1) how, and to what extent, the site profile satisfies the five objectives defined by the Advisory Board for ascertaining adequacy; (2) the usability of the site profile for its intended purpose, i.e., to provide a generalized technical resource for the dose reconstructor when individual dose records are unavailable; and (3) generic technical or policy issues that transcend any single site profile that need to be addressed by the Advisory Board and NIOSH.

4.1 SATISFYING THE FIVE OBJECTIVES

The SC&A review procedures, as approved by the Advisory Board, require that each site profile be evaluated against five measures of adequacy—completeness of data sources, technical accuracy, adequacy of data, site profile consistency, and regulatory compliance. The SC&A review found that the NIOSH Summary Site Profile for BNL falls considerably short in providing the dose reconstructor with key information related to bioassay records, neutron dosimetry issues, accelerator program history, and assessing unmonitored worker dose. Section 1.1 summarizes the key issues. A detailed evaluation of these issues can be found in Section 3.0 (Vertical Issues) of this report.

4.1.1 Objective 1: Completeness of Data Sources

The breadth of data sources used as a basis for the BNL Summary Site Profile is evident in the number of reports available in the SRDB, as well as in the number of reports cited in the site profile references. Oak Ridge Associated Universities Team's (ORAUT) use of the available sources indicates an understanding of site operations, radionuclide usage, and personnel monitoring data.

However, for internal dose assessment, the site profile fails to address the adequacy and completeness of BNL bioassay data to support dose reconstruction. From a preliminary review of available BNL records and interviews with BNL health physics staff members, there is sufficient reason to question the completeness, accuracy, and accessibility of bioassay records for BNL from the late 1940s through the mid-1980s, or perhaps into the mid-1990s, when the centralized electronic HPRS recordkeeping system became operational.

4.1.2 Objective 2: Technical Accuracy

In general, the BNL Summary Site Profile favorably reflects the depth of knowledge and technical understanding of the various authors and experts who developed the documents. The analyses and recommendations are generally consistent with NIOSH guidance and the available data from the site. Some exceptions are noted below.

As stated in Section 5.10 of the site profile, specific **solubility data**, **particle size**, and **activity fractions** are not known, or are not available, for most facilities at BNL. Table 5-5 lists a few of the activity fractions, presumed to have come from stack emission data. However, stack emissions are not always a good indicator of the types of radioisotopes present, or their concentrations, in the worker's breathing zone; this applies to Table 2-2 also. Also, interviews with BNL workers indicate that Tables 2-2 and 2-3 do not correctly reflect the radioisotopes present at some of the BNL facilities.

4.1.3 Objective 3: Adequacy of Data

The present BNL Summary Site Profile document does not address key dosimetry problems associated with high-energy accelerators, the adequacy of dosimetry systems during start-up periods, or if the dosimetry systems were sufficiently encompassing to accommodate operational changes. It does not discuss adjustment factors for neutron doses and if adjustments are needed to compensate for the limitations of the dosimetry systems used as a function of time at different accelerator facilities (as illustrated in a discussion in this report concerning problems with NTA/TLD/Lexan/CR-39 neutron dosimetry systems). The site profile does not address if or where or when muon doses were of health physics concern, or how and if they were monitored and recorded, and the interpretation of those doses, if recorded. Hazards from extracted high-energy proton beams and their dosimetry were also not addressed.

The site profile does not specifically address the subject of NTA film threshold, nor directly address the issue of NTA film fading.

In addition to the MDA values for common radioisotopes, the MDA values for, or procedure for identifying, other less common (but potentially present) radioisotopes should be provided, so that the dose reconstructor can consider and assign missed dose in specific cases where other radioisotopes could be present. For example, one can compare the relatively few radioisotopes, and associated time periods listed in Table 5-3, page 80, that the dose reconstructor has to work with, with the many radioisotopes listed in Tables 2-2, 2-3, and 5-5 occurring over more than a 50-year period. Some MDA values are obtainable from BNL documents, one example from Miltenberger (1978) being the BNL WBC MDL for U-235, which was 800 pCi (370 ug) in 1978. Additionally, uncertainty values are not provided, and are apparently not available, for most of the bioassay reporting period from the 1950s–1990s.

The site profile does not mention the availability or applicability of coworker internal or external dose data. Therefore, the dose reconstructor is not provided with any recommendations concerning what doses to assign when a worker's information indicates that the worker should have been monitored, but was not, or where bioassay records are unavailable.

No background information is provided for D&D workers at BNL that would be important for dose reconstruction, such as the following:

- Were these BNL employees or outside contractors?

- Were the bioassay monitoring requirements the same, or different, than those of regular BNL employees?
- Was cohort or individual sampling performed?
- What types of bioassays were performed?
- Where are the bioassay records located and are they accessible?

More information is needed for the D&D worker bioassay program to adequately support accurate and complete dose reconstruction for that activity.

4.1.4 Objective 4: Consistency among Site Profiles

SC&A compared the guidance, proposed methods, and information base provided in the BNL Summary Site Profile with site profiles for other national laboratories and found some disparities of note, as follows.

Dosimetry information and dose estimation guidance typically provided for early neutron doses, i.e., the NTA film energy threshold and NTA film track fading, is lacking in the BNL Summary Site Profile.

The provision of coworker dose data and methods that are provided for sites where unmonitored worker exposure has been established (which is most evident for internal exposures at BNL, but also in some external exposure cases) is lacking in the case of the BNL site profile.

A reasonable amount of MDA information for common radioisotopes is provided for 1999–2006. However, what is lacking is a comprehensive listing of urinalysis and WBC MDA values for 1940s–1990s, such as is found in some of the other DOE site profiles [i.e., ORAUT-TKBS-0012-5 (ORAUT 2007), Table 5-9, pg. 16].

The site profile does not sufficiently address incidents or unusual events that could affect external dose reconstruction, as is typically done in other site profiles. Some examples of incidents were found in the BNL documents; however, the site profile did not address such incidents or if the doses of record were correct under these exposure conditions.

4.1.5 Objective 5: Regulatory Compliance

SC&A reviewed the site profile with respect to Objective 5, which requires SC&A to evaluate the degree to which the site profile complies with stated policy and directives contained in 42 CFR 82. In addition, SC&A evaluated the site profile for adherence to general Quality Assurance policies and procedures utilized for the performance of dose reconstructions. No issues were found in this regard that require attention, albeit, SC&A has raised questions regarding the validity of the neutron adjustment factors used in dose reconstruction, as well as other questions surrounding neutron dosimetry at BNL.

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ATTACHMENT: SUMMARY OF SITE EXPERT INTERVIEWS

(To be provided)