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ADVISORY BOARD ON RADIATION AND WORKER HEALTH

National Institute for Occupational Safety and Health

REVIEW OF THE CARBORUNDUM SPECIAL EXPOSURE COHORT (SEC) PETITION-00223 AND THE NIOSH SEC PETITION EVALUATION REPORT

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S. COHEN & ASSOCIATES: ***Technical Support for the Advisory Board on Radiation & Worker Health Review of NIOSH Dose Reconstruction Program***

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ABBREVIATIONS AND ACRONYMS

AEC	Atomic Energy Commission
AMAD	activity median aerodynamic diameter
ANP	Aircraft Nuclear Propulsion
CFR	Code of Federal Regulations
DCAS	Division of Compensation Analysis and Support
DCF	dose conversion factor
DOE	(U.S.) Department of Energy
DOL	(U.S.) Department of Labor
DR	dose reconstruction performed by NIOSH
DSA	DCAS SEC Application
DU	depleted uranium
DWA	daily weighted average
EDE	effective dose equivalent
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ER	(SEC Petition) Evaluation Report
EU	enriched uranium
FGR	Federal Guidance Report
FOIA	(U.S.) Freedom of Information Act
FOIL	(New York State) Freedom of Information Law
FR	Federal Register
H*(10)	ambient dose equivalent
$H_p(10)$	personal dose equivalent
HASL	Health and Safety Laboratory of the AEC
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
IREP	Interactive RadioEpidemiological Program
MED	Manhattan Engineer District
NRC	Nuclear Regulatory Commission
ORAUT	Oak Ridge Associated Universities Team

ORNL	Oak Ridge National Laboratory
PER	Program Evaluation Report
ROS	regression of order statistics
SC&A	Sanford Cohen & Associates
SEC	Special Exposure Cohort
SRDB	Site Research Database
TBD	Technical Basis Document
XRD	x-ray diffraction

1 INTRODUCTION

During the meeting of the Advisory Board on Radiation and Worker Health (ABRWH) held in Idaho Falls, Idaho, on July 23, 2015, S. Cohen & Associates (SC&A) was tasked by the Board to review the NIOSH SEC Petition Evaluation Report of Petition SEC-00223 — Carborundum Company (Jessen and Scalsky 2015).[1]

According to the ER, NIOSH had performed 90 dose reconstructions (DRs) for former Carborundum[2] workers. SC&A had previously audited one of these DRs: Our audit produced six findings, five of which had the potential for significant increases in doses to the worker in question, with implications for increased doses to other workers at this site. The DR methodology referred to in the ER represents a significant departure from the methods applied to the DR which we had previously audited. Adoption of this revised methodology by NIOSH and the Board would require NIOSH to review the DRs performed using the earlier methods and assumptions.

1.1 Scope

The scope of this review addresses specific issues of concern raised in the petition and NIOSH's response to these concerns, as given in the ER. In the course of its assessment, SC&A reviewed selected documents and other data that were considered relevant to the petition, including:

- documents referenced/cited in the ER
- other documents contained in the NIOSH Site Research Database (SRDB)
- a general search of the Internet
- archives of news articles maintained by the New York Times
- the website of the Health Physics Society
- the website of ORAU Health Physics Historical Instrumentation Museum Collection
- email communication with Paul Frame, who is associated with the museum
- results of a request under the Freedom of Information Act (FOIA) to the U.S. Nuclear Regulatory Commission
- response to a request under the Freedom of Information Law (FOIL) to the New York State Department of Health

[1] This report is referred to by the acronym ER in this review.

[2] The Carborundum Company will be referred to as "Carborundum" in this review.

- communication with Joel Lubenau, the author of an article about the hazards of x-ray diffraction equipment (XRD)

The purpose of this review is to provide the Board with an independent assessment of issues and concerns that surround the petition and NIOSH's response and proposed methods for accommodating these issues/concerns. Findings identified in SC&A's review are intended to provide the Board with an overview of potential issues that may impact the feasibility of dose assessment. Following a formal, multi-step issues resolution process, any unresolved findings may then be used by the Board for determining whether radiation doses can be estimated with sufficient accuracy, as defined in 42 CFR §83.13(c)(1); since this final determination lies within the prevue of the Board and occurs at the end of a formal resolution process, SC&A does not draw conclusions from its findings in this report.

1.2 Technical Approach and Review Criteria

The approach used by SC&A to perform this review follows the protocols described in the draft report prepared by SC&A entitled "Board Procedures for Review of Special Exposure Cohort Petitions and Petition Evaluation Reports, Revision 1" (SC&A 2006), and the "Report of the Working Group on Special Exposure Cohort Petition Review (1/16/06 Draft)" (SC&A 2006, Appendix A). The latter is a set of draft guidelines prepared by a Board-designated work group[3] for evaluation of SEC petitions performed by NIOSH and the Board. The former is a set of draft procedures prepared by SC&A and approved for use by SC&A on an interim basis at the 38th Meeting of the Advisory Board on Radiation and Worker Health on June 16, 2006. The procedures are designed to help ensure compliance with Title 42, Part 83, of the Code of Federal Regulations (42 CFR 83) and implement the guidelines provided in the report of the working group.

Key review criteria identified in the report of the work group include the following; the individual criteria have differing degrees of applicability depending on the details of a particular SEC petition and evaluation report:

- timeliness
- fairness
- comprehensibility
- consistency
- credibility and validity of datasets, including pedigree of the data, methods used to acquire the data, relationship to other sources of information, and internal consistency

[3] The term "working group," occasionally used during the earlier years of the ABRWH, has since been replaced by the standardized term "work group."

- representativeness and completeness of the exposure data with respect to the area of the facility, the time period of exposure, the types of workers, and processes covered by the data

The work group guidelines also recommend that NIOSH include in its SEC evaluation a demonstration that it is feasible to reconstruct individual doses for the cohort, including sample DRs.

SC&A's implementation of the SEC review process includes the following steps:

- conduct a critical review of the petition and relevant reports, documents, and data that are enclosed and/or referenced in the petition/reports;
- identify additional issues/concerns that emerged from SC&A's document review, which are independent of those stated in the petition;
- as part of the SEC review, develop a technical position for issues identified in the petition, as well as SC&A's independent findings.

SC&A's report with its findings will subsequently undergo a multistep resolution process. Resolution will include a transparent review and discussion of draft findings with members of the Board's Carborundum Work 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.

2 BACKGROUND

According to the ER:

> In 1943 and 1944 the Carborundum Company at its Globar Plant and Buffalo Avenue locations was engaged in various phases of Manhattan Engineer District (MED) programs to determine suitable methods for engineering and shaping uranium rods. This work also involved the forming, coating, and canning of uranium rods for the MED pile. From 1959 through 1967, the company used powder fabrication techniques to manufacture uranium, plutonium, and carbide pellets for an AEC research program. The Hanford facility supplied Carborundum with materials during that period. . .
>
> During the period of residual contamination, as designated by the National Institute for Occupational Safety and Health and as noted in the dates above, employees of subsequent owners and operators of this facility are also covered under EEOICPA.

2.1 Timeline

The following subsections summarize developments on the Carborundum site. The events described in each section are in chronological order; however, there are temporal overlaps among the various sections.

2.1.1 Program Evaluation Report (PER-054)

On July 25, 2014, Allen (2014a) issued a program evaluation report (PER-054) which noted two changes to the DR methodology for Carborundum:

> The depletion factor in ORAUT-OTIB-0070 [(Sharfi 2012)] is used to estimate a reduction in contamination levels during the residual period. The revision to OTIB-0070 changed this factor so that the contamination is assumed to decrease more slowly. This causes an increase in the dose estimate in most years of the residual period.
>
> Also, the year 1943 was added to the covered period. For many of the Carborundum claims, the employment was originally verified by the Department of Labor outside the bounds of the covered period. In those situations, NIOSH only estimated dose during the covered period. With a change to the covered period, the NIOSH dose estimate would now have to be reconsidered.

As a result of these changes, the doses for "[58] Carborundum claims that were completed prior to [March 5 2012] that had a probability of causation [POC] below 50%. . . [were] recalculated using the revised OTIB-70 depletion factor and 1943 as a covered year (if applicable)." (Allen 2014a) Furthermore, nine later claims were reviewed to ensure that they used the correct depletion factor. These reviews led to two additional claims with POCs >50%.

2.1.2 SEC Petition

[redacted] and [redacted] (2014) filed an SEC petition on behalf of former Carborundum employees and their survivors that was received by NIOSH on November 19, 2014. In a Federal Register Notice dated February 11, 2015, NIOSH Director John Howard (2015) announced that the petition has met the minimum qualifications for review and evaluation.

On June 3, 2015, NIOSH issued its evaluation report of the Carborundum SEC petition (Jessen and Scalsky 2015).

2.1.3 SC&A Audit of Dose Reconstruction for a Carborundum Worker

On March 24, 2015, SC&A issued a final report of our audit of a DR for a Carborundum worker that produced six findings. This audit report was the subject of a "one-on-one" teleconference between two members of the Advisory Board and SC&A staff members held on July 13, 2015.

2.1.4 ABRWH Meeting: July 23, 2015

Tomes (2015) presented an overview of the ER at the ABRWH meeting held in Idaho Falls, Idaho, on July 23, 2015. During his oral presentation, Mr. Tomes stated that the first AWE period, which had previously been expanded to span 1943 (one reason for issuing PER-054), is now being contracted to June–September 1943. Both DOE and DOL have been notified of the proposed change and have concurred with the NIOSH recommendation. He also informed the Board that example DRs were not yet available since NIOSH had recently changed the DR methodology and needed more time to prepare the examples. (Examples DRs, along with a report explaining the NIOSH DR methodology and an Excel workbook utilized in DR assessments—dated July 23, 2015, the day of the meeting—were posted on the restricted DCAS website).

Following Mr. Tomes' presentation, Board Member Josie Beach reported having participated in the review of a case audit for the Carborundum site (cited in section 2.1.3 of the present review) and noted that there were six findings, which is the highest number of findings in any case review she had come across. Ms Beach recommended that a work group look at the ER. Board Member Paul Ziemer asked if NIOSH used a resuspension factor of 10^{-5} m^{-1}—Mr. Tomes confirmed that they did. Dr. Ziemer then observed that the ER used methodology developed by Lubenau et al. (1969) to assess exposure to XRD units employed at Carborundum and asked if SC&A has reviewed this methodology. Mr. Tomes replied he did not know. (Reviewer's note: The Carborundum DR audited by SC&A did not evaluate exposures from XRD, which was the basis of one of our six findings. The present review is our first opportunity to review this aspect of NIOSH's methodology.) Dr. Ziemer agreed with Ms Beach that the ER needed further review.

Board Member Henry Anderson questioned if the uranium airborne activity concentration from machining listed in TBD-6000 (Allen 2011) was bounding for the experimental centerless grinding performed at Carborundum. Other board members asked questions about other details of the ER dose assessment methodology, which were followed by responses by NIOSH staff.

After hearing comments by the two petitioners, Board Chairman James Melius tasked SC&A with reviewing the ER and announced that the Board would set up a new work group to review Carborundum.

2.1.5 Carborundum DR Methodology: July 23, 2015

On July 23, 2015, NIOSH posted a report entitled "Carborundum DR Methodology: July 23, 2015" on the restricted DCAS website, along with two supporting documents: "Carborundum Example Dose Reconstruction Report: July 23, 2015" and an Excel file named "Carborundum Methodology 2015-07-23 FINAL.xlsx." These three documents contain NIOSH's proposed prescriptions for DRs for Carborundum workers. We will refer to them by the abbreviated titles "DR Methodology," "Example DR," and "Methodology.xlsx," respectively, in the remainder of this review. The three documents will be collectively referred to as "DR Documents."

3 REVIEW OF SEC PETITION

The SEC petitioners are the son and daughter of a Carborundum employee who died of lung cancer. The petitioners presented some information about the employment history of their father and stated that they knew of no radiation monitoring at the plant. However, during a CATI interview in connection with his father's DR, Mr. [redacted] stated that his father had physical exams at the site, but did not know if they included medical x rays.

4 REVIEW OF EVALUATION REPORT (ER)

Because there is no formal TBD or site profile for Carborundum, we have changed the usual sequence of topics in our review, and begin with a review of the ER. We will address only those sections of the ER that are relevant to DR methodology as presented in "DR Documents" and which merit comments. The discussion in this section of the review is keyed to the sections of the ER.

The ER contains iterative descriptions of the radiological operations at Carborundum, first describing the processes during the two operational and two residual periods, followed by a listing of internal exposure sources during the four periods, then of external exposures during the same four periods. However, little prescriptive methodology is presented—such methodology is described in "DR Documents," which were issued after the ER was completed. Since our object is to evaluate the NIOSH DR methodology and determine if this methodology supports NIOSH's assertion that it has sufficient data to perform DRs for Carborundum with sufficient accuracy, we will perform a detailed analysis these documents, referring back to the ER for supportive information as necessary. We will therefore present a general overview of the ER, commenting on those areas which merit improvement, but will not discuss nor critique every statement in the ER if it has no bearing on the DR methodology proposed by NIOSH.

4.1 ER Section 3.1: Petitioner-Requested Class Definition and Basis

According to the ER, "The petitioner requested that NIOSH consider the following class: All employees who worked in any area of the Carborundum Company facility on Buffalo Avenue, Niagara Falls, NY from January 1, 1943 through December 31, 1976." The petition requested a starting date of 1941. NIOSH changed the starting date to match the starting date of the covered period as defined by the Departments of Energy (DOE) and Labor (DOL) at the time of issuance of the DR. (As cited in section 2.1.4 of the present review, the starting date is being changed to June 1, 1943.) The change should be clarified in the ER.

4.2 ER Section 3.3: NIOSH-Proposed Class(es) to be Added to the SEC

According to the ER: "Based its analysis of . . . available resources, NIOSH found no part of the class under evaluation for which it cannot estimate radiation doses with sufficient accuracy." This statement is tantamount to a recommendation that the Board deny the SEC petition.

4.3 ER Section 4.0: Data Sources Reviewed by NIOSH to Evaluate the Class

NIOSH performed an extensive data search to document and support its analyses of activities at Carborundum that are related to the SEC petition. However, we were able to obtain additional reference material not cited by NIOSH, as described below.

We searched the *New York Times* archives (available at http://www.nytimes.com/) and found an article describing the acquisition by Carborundum of five thickness gauges utilizing sealed sources of ^{90}Sr (Freeman 1952). These sources, which may have continued to be used during the second AWE period (1959–1967) and could therefore impact DR assessments of workers employed during that period, are discussed in section 5.1.6 of the present review.

It is not clear if Carborundum required a license from the Atomic Energy Commission (AEC) to procure these sources. In 10 CFR 30, the Nuclear Regulatory Commission (NRC), which was formed in 1975 and inherited the licensing authority of the AEC, cited the Atomic Energy Act of 1954 as its authority to regulate byproduct material (NRC 2015). Although the Atomic Energy Act of 1946 which created the AEC (AEC 1965) authorized the commission to regulate byproduct materials, we were not able to determine if such regulations were in place in 1952. If these gauges continued to be used after regulations governing their use were in place, it is likely that they would have been eventually licensed by the AEC, and later by New York State, which became an AEC Agreement State in 1962. We filed a Freedom of Information Act (FOIA) with NRC for any information regarding a Byproduct Materials License issued by the AEC to the Carborundum Company, Niagara Falls, NY, in 1952 and/or later years, and were informed that no such information was located. We also filed a Freedom of Information Law (FOIL) request with the New York State Department of Health, the agency that currently administers radiation safety in New York, seeking similar information. This agency also responded that no records were available. However, we did obtain information on thickness gauges containing ^{90}Sr that were produced by the Industrial Nucleonics Corporation, which was identified by Freeman (1952) as the supplier of the thickness gauges purchased by Carborundum. This information is discussed in section 5.1.6 of the present review.

We also contacted Joel Lubenau (2015), whose work was referenced in the ER (Lubenau et al. 1969), and obtained additional information on radiation exposures from XRD operations, which is discussed in section 4.16.1 of the present review.

We observe that NIOSH overlooked these reference sources in its data search.

4.4 ER Section 4.3: Facility Employees and Experts

According to the ER: "NIOSH interviewed six former Carborundum employees . . . [who] worked at Carborundum after the 1950s." In fact, NIOSH interviewed seven individuals: six former workers and one survivor. Four of the workers began working between 1950 and 1956, while the other two started in 1960 and 1962, respectively. Only three of these had worked with uranium and/or plutonium and could provide information on these operations. One of the former workers, [redacted], mentioned [redacted], another former Carborundum employee

who worked on the second floor of Building 1, where the XRD work was performed, and provided his phone number (ORAUT 2015a). We found no records indicating that NIOSH followed up on this additional contact.

4.5 ER Section 5.1.2: First Residual Period (1945-1958)

According to the report of an interview of [redacted], a worker from the first residual period: "You also stated you made thorium oxide and thorium carbide in the early stages of your work (~1955)" (ORAUT 2015a). This work was performed outside the AWE periods; however, there is a possibility that it was weapons-related, in which case the AWE period would need to be extended. NIOSH should verify this. In any case, the work areas were potentially contaminated with thorium, inasmuch as, in a subsequent interview with the author of the present review, Mr. [redacted] said that the thorium was provided as a powder, and confirmed that spills were likely. Since there is no record of a cleanup prior to the second operational period, workers employed during that period could have been exposed to residual thorium contamination. Such exposures should be addressed in evaluating doses during the second operational period.

Furthermore, the ER states: "Beginning in 1955, Carborundum was involved with the production of silicon carbide for structural materials for the Aircraft Nuclear Propulsion [ANP] Department of General Electric Company." These "structural materials" were, in fact, components of reactor fuel assemblies. The silicon carbide was blended with uranium oxide to produce high-temperature fuel elements for an air-cooled nuclear reactor to be used in a nuclear powered airplane. Since the ANP project was not related to the production of nuclear weapons, exposures to uranium in the nuclear fuel are properly excluded from dose assessments during the first residual period. However, NIOSH should determine if any potential contamination of Carborundum facilities from this nuclear material could contribute to doses during the subsequent second operational period.

4.6 ER Section 5.1.3: Second Operational Period (1959-1967) Process Descriptions

The ER provides a comprehensive summary of the operations at Carborundum under various contracts with the AEC and subcontracts to the United Nuclear Corporation, an AEC contractor. SC&A reviewed the 14 SRDB documents that are referenced in Table 5-2 of the ER, which presents a summary of activities starting in May 1959 and ending February 28, 1967. This summary provides background information that forms the basis of the DR methodology. Since the DR methodology is not presented in the ER but in "DR Documents," we will postpone a detailed discussion of the radiological operations to the analysis of these documents in section 5 of the present review.

A potentially significant source of external exposure is the XRD analysis of the (U,Pu)C pellets produced at Carborundum. This source is discussed in greater detail in section 4.16.1 of the present review.

4.7 ER Section 5.2.1.3: Second Operational Period (1959-1967)

According to the ER: "The plutonium source term for [the second operational] period is assumed to be the 10-year-aged 12% plutonium mix that has been used to bound the doses (see Section 7.2.2.1)." The same assumption is repeated in ER section 7.2.2.1. However, "DR Documents" use a different plutonium isotopic mixture. NIOSH needs to resolve this discrepancy.

4.8 ER Section 5.2.2: External Radiological Exposure Sources from Carborundum Co. Operations

In discussing the calculation of neutron exposures, which was performed with MCNP6 (not MCNPX, as stated)**,** the ER incorrectly states that doses were calculated at 30 cm and 1 m from the face of the glove box, whereas the actual doses were calculated over rectangular volumes of air that were 35 cm and 1 m from the center of a fuel pellet in a horizontal direction and displaced approximately 4.4 cm vertically. The discrepancies in the description should be corrected.

4.9 ER Section 5.2.2.3: Second Operational Period (1959-1967)

The ER states that "On September 19, 1962, Carborundum notified the Nuclear Regulatory Commission (NRC) of the closeout of contract AT(40-1)-2558 and to obtain their instructions for the disposal of the radioactive material they possessed (Contract Closeout, 1962)." The cited reference is a letter to the AEC—the NRC did not come into existence until 1975. Such a historical inaccuracy, while it does not affect dose reconstructions, should nevertheless be corrected.

In a discussion of x-ray diffraction machines, the ER states: "Operators usually sit safely nearby the device during normal operation. Operators are not usually monitored for radiation exposure, because of the small likelihood of the very small beams interacting with the small dosimeter device." This last statement refers to the difficulty of monitoring worker exposures, not that there is no need for such monitoring. According to Lubenau (2015), who responded to a question from the present author regarding the surveys reported by Lubenau et al. (1969):

> I'm unable to offer suggestions about extrapolating exposure rates to the fingers, hands, and arms from the table edge measurements other than to state the obvious, they were surely higher. For that reason we [the Commonwealth of Pennsylvania] recommended (and later required by regulation) issuance of finger and wrist film badges to operators.

The mere fact that the Public Health Service, Bureau of Radiological Health cosponsored a conference on "Radiation Safety in X-Ray Diffraction and Spectroscopy" (Moore et al. 1971) indicates that these procedures posed radiation hazards to personnel operating such equipment.

4.10 ER Section 6.1: Available Carborundum Company Internal Monitoring Data

ER Table 6-1: Carborundum Uranium Air Dust Samples, lists the analytical results from three uranium samples collected on April 5, 1961. However, the table incorrectly cites the results in terms of dpm/m^3, whereas the report of the survey performed by the Health and Safety Laboratory (HASL n/d) of the AEC lists the results as dpm/sample. These data are interpreted correctly in the calculations of uranium aerosol concentrations in "DR Documents"; however, the table in the ER is potentially confusing and needs to be corrected. The value of "GA Furnace Room" collected on November 9, 1959, of 6 dpm/m^3 is in the correct units. As an editorial note, it would be preferable to list the samples in chronological order, instead of listing the November 9, 1959 after the ones collected in April 1961. Finally, it would be preferable to omit reference to an illegible sample report from which not even the sample date can be discerned—the table lists the date the sample was received by the laboratory, not the date it was collected.

ER Table 6-2: Carborundum Plutonium Air Dust Samples, lists the results for eight samples collected on April 5, 1961, and another set of nine samples taken on June 7, 1961. The seventh sample in the first set is erroneously listed in the table as 2.2 dpm/sample—the value in the HASL report appears to be 22 dpm/sample.[4] The 2.2 dpm/sample value was used to derive airborne plutonium concentrations in "Methodology.xlsx."

4.11 ER Section 7.2: Evaluation of Bounding Internal Radiation Doses at Carborundum Company

According to the ER: "NIOSH has not found any information regarding the use of enriched uranium at Carborundum other than the contract information listed in Table 5-2 of this report, which appears to be a limited-scope operation performed under contract AT (30-1)-2899." This statement is inconsistent with other sections of the ER, such as 5.2.1.3, which states: "At the time Carborundum closed out contract AT(40-1)-2558 for source and special nuclear material, it had in its possession various amounts of depleted and 10% enriched uranium powder." Furthermore, Strasser and Taylor (1962b) report tests on $(U_{0.8}Pu_{0.2})C_{0.95}$ fuel pellets made with 24% enriched uranium. Finally, Mr. [redacted], the former Carborundum workers interviewed by both the ORAU Team (ORAUT 2015a) and by SC&A (section C.1 of the present review) recalled working with both depleted and enriched uranium (EU), although he stated that the quantities of EU were limited due to criticality concerns.

In reality, the degree of uranium enrichment has little effect on the calculations of internal doses, since intakes of uranium are based on the results of air sampling data, which were reported as total α. Thus, the total activity of uranium taken in by inhalation or ingestion is unaffected by

[4] Although the two digits (22) in the sample sheet are slightly separated, there is no sign of a period in between. Furthermore, the description of sample 4C is "same as #2," which we presume refers to sample 2C, which also has a value of 22. In fact, the ER table describes the two samples as being taken in the same location during successive time periods only 5 minutes apart. It is unlikely that two duplicate samples would differ by a factor of 10. Other duplicate samples on the same sheet are either identical or similar (e.g., 0.6 vs. 0.8).

the enrichment. Since NIOSH assumes the entire intake to be ^{234}U, the isotopic mix of the naturally occurring uranium isotopes does not affect the calculated doses. The enrichment could affect the estimates of external doses from uranium. However, since NIOSH uses a bounding estimate of the dose rate from a large rectangular ingot, the relatively small quantities of EU present at Carborundum would most likely not have led to these doses being exceeded.

Nevertheless, the ER should explicitly address this issue rather than appearing to minimize it.

4.12 ER Section 7.2.1: Evaluation of Bounding Process-Related Internal Doses

In the subsection "Second Operational Period (1959–1967)," the ER discusses work with uranium and plutonium that was performed during this period and states: "however, two former employees stated that the work was done in glove boxes." It would have been more accurate to say that *some* of the work was done in gloveboxes.

According to the NIOSH report of the interview with one of these workers, [redacted], (who did not respond to an SC&A email request for a follow-up interview):

> When the work was first started people were not familiar with the dangers of working with any of the material. There were 50-80 pounds (estimate) of uranium powder in a metal cage. The uranium oxide powder was screened and people had to wipe it off the desks. (ORAUT 2015b)

Thus, although he might have worked in gloveboxes—the interview report does not state that the radioactive material was *always* handled in a glovebox—the uranium was obviously not always contained by the gloveboxes.

The second worker, Mr. [redacted], discussed work with enriched uranium. According to the interview report: "This was not in a glove box, but in a room under negative pressure." This statement is quoted later in this section of the ER. The ER should avoid giving the impression that the gloveboxes protected workers from airborne radioactive dust.

The ER describes the uranium dust sampling data (HASL n/d), correctly stating that the sample date of the one illegible report is unknown, contrary to ER Table 6-2, which erroneously assigns the date the sample was received by the laboratory. Such inconsistency should be avoided.

The ER also describes the plutonium dust samples collected on April 5, 1961 (HASL n/d): "Two were identified as general area samples, two were identified as breathing zone samples, and four were either without description or the description was illegible." The two samples that the ER refers to as breathing zone are in fact labeled "GA BZ," so it cannot be determined if they are from the general area or the breathing zone. We have a similar objection to the ER's characterization of the June 7, 1961, HASL data: "Six of the samples were identified as breathing zone samples, while two were identified as general area samples." In fact, four are labeled "GA," two are marked "BZ," while two others have the notation "BZ GA." This distinction is significant, because in the following section, the ER states:

> The general area air concentrations are suitable for radiological production support personnel and, after adjustment, for supervisors and other worker categories. Therefore, these values will be doubled (or scaled up from the values used for support personnel), consistent with DR methods and approaches using similar data, to estimate exposures for operators.

Thus, assigning ambiguous samples to the breathing zone category potentially reduces the calculated intakes. The distinction would appear to be moot, since in ER section 7.2.2.1, NIOSH states that the results derived from all samples, breathing zone and general air, will be doubled in calculating intakes of operators.[5] However, this procedure was not followed in "DR Documents," in which the results of all the plutonium dust sample analyses were used in calculating intakes of operators, while the intakes of workers in other job categories were scaled down from these values. This is a significant discrepancy which requires resolution.

The ER further states: "Plutonium intakes are . . . assigned as 12% 10-year aged plutonium." However, as mentioned in section 4.7 of this review, "DR Documents" use a different mix of radionuclides for the plutonium internal dose assessments.

4.13 ER Section 7.2.2.1: Methods for Bounding Operational Period Internal Dose

The ER reports that "a statistical analysis of [the uranium] samples results in a GM of 1.666 dpm/m^3, a GSD of 2.5111, and a 95th percentile of 7.578 dpm/m^3." We disagree with NIOSH's statistical methods, which are discussed in greater detail in section 5.2 of this review. Our results for the uranium air samples lead to slightly lower air concentrations than the NIOSH values. We likewise disagree with NIOSH's statistical analysis of the plutonium dust samples. In this case, our 95th percentile airborne plutonium activity concentration is approximately 16% larger than the NIOSH value. A corresponding increase would apply to intakes during the second residual period due to residues from the second operational period.

4.14 ER Section 7.3.1 Evaluation of Bounding Process-Related External Doses

The ER states: "Based on the machining (grinding) work performed at Carborundum, slug production was selected from the processes found in Battelle-TBD-6000 to evaluate and bound Carborundum doses." In fact, machining, not slug production, is the appropriate surrogate for the centerless grinding performed at Carborundum. Although external doses from uranium metal—the largest component of external dose—are the same for both operations, the photon and beta doses from a contaminated floor are orders of magnitude higher. We note that "DR Documents" do use the correct TBD-6000 dose rates; however, the ER should be corrected to maintain consistency.

The ER then describes the various job categories to be used in determining internal and external doses. Absent is any direction to dose reconstructors on assigning individual claims to one or

[5] This procedure is consistent with TBD-6000, Table 7.5, which assigns the general laborer one-half the DWA (daily weighted average) air concentrations of the operator of centerless grinding.

another of the listed categories. An appropriate and claimant-favorable assumption would be to assume that the claim was for an operator unless there is definitive evidence to the contrary. One precedent for such a procedure is the site profile for General Steel Industries (Allen 2014b), which directs that each worker be assigned doses to radiographers unless it can be established that he or she was an administrative worker who did not routinely work in the plant.

4.15 ER Section 7.3.2: Carborundum Company Occupational X-Ray Examinations

According to the ER:

> In a letter dated October 11, 1944 from the E.I. du Pont Engineering Department to the Medical Director discussing the companies that performed work on T metal, it is stated that Carborundum performed experimental grinding of T metal in June 1943. It further states that there was very limited exposure with no medical supervision necessary . . . Therefore, NIOSH will not assess medical X-rays for the first operational period.

The letter does not preclude the occurrence of medical x rays during the first operational period—it merely states that they were not contractually required. The CATI interview with the son of a deceased worker cited in section 3 of the present review states that his father had physicals on site. If any workers had physical exams during this period, and if it can be established that is likely that these exams included medical x rays, then such x rays should be included in the assessments of external doses.

With respect to the second operational period, the ER states:

> NIOSH has not identified information that indicates medical X-ray examinations were NOT performed at the Carborundum Company. Therefore, NIOSH will assume that pre-employment, annual, and termination PA radiographic chest X-ray screenings were performed for workers during the second operational period.

Again, since there is no information that medical x-ray examinations were *not* performed at Carborundum during the first operational period, only that they were not required under the terms of the contract with du Pont, it is inconsistent to assign doses from x rays during the second period but not the first. Finally, we note that "Example DR" does not assign any medical x-ray doses to the hypothetical worker who was employed during both operational periods.

4.16 ER Section 7.3.3.1: Methods for Bounding Operational Period External Dose

According to the ER: "External doses for uranium exposures during the operational periods are assessed using the exposure, R, dose equivalent organ DCF (dose conversion factor)." Although claimant favorable, such a procedure is not scientifically correct, and could be potentially unfair

to claimants from other worksites which used the correct DCFs.[6] The external doses from uranium metal were taken from TBD-6000, and were based on the dose rates listed in Table 6.1 of that document. These in turn were calculated as doses to a slab phantom, also known as personal dose equivalent, $H_p(10)$. Organ doses from this exposure pathway should be assigned using the DCFs corresponding to this dosimetric quantity.

Exposure to a contaminated floor, as well as from submersion in a radioactive cloud, was calculated in terms of exposure and listed in units of R; therefore, the doses from such sources should utilize the DCFs for exposure. We note, however, that the latter two sources comprise a fraction of 1% of the numerical value of the external doses from uranium metal.

Later in the same section, in the subsection "Second Operational Period (1959-1967)" under the subhead "Uranium photons," the ER states: "External doses from uranium exposure during this period are corrected using the deep dose equivalent organ DCF." Such inconsistency is confusing to the reader and to anyone attempting to review DRs for this worksite. The problem is compounded by "DR Methodology," which states: "External doses from uranium exposure during [the Second Operational Period] period are corrected using the exposure, R, dose equivalent organ DCF."

Under the subheads "Plutonium photons" and "Neutrons" which follow, the ER describes the MCNP6 calculations of doses from (U,Pu)C fuel pellets in a glovebox. This description, which is the same as was discussed in section 4.8 of the present review, is not consistent with the actual calculations and needs to be corrected.

4.16.1 X-Ray Diffraction

A subsection of ER section 7.3.3.1 presents a discussion of x-ray diffraction (XRD) as a source of external radiation. The exposure assessment uses as a starting point the maximum scattered radiation of 2 mR/h at the edge of the table reported by Lubenau et al. (1969), based on surveys of three XRD units in Pennsylvania. The assumptions to be used in assessing exposures to the XRD apparatus specify that only the upper anterior portion of the body is exposed, that the beam has an energy of 8.1 keV, and that "the fraction of time that tissue is exposed to the diffracted beam is proportional to the ratio of the diffracted beam size (area) to the area potentially exposed (front upper torso)." These assumptions do not provide sufficient guidance to a dose reconstructor to perform a DR. In fact, no XRD dose is assigned in the "Example DR."

Furthermore, we have several issues with the prescribed NIOSH methodology. First, it is based on the assumption that the operator's entire body was at or beyond the edge of the table. According to Lubenau (2015), doses to fingers, hands, and arms "were surely higher." Second, the measurements reported by Lubenau et al. (1969) utilized either a Victoreen 440RF or a Nuclear Chicago 2586 ion chamber survey meter. Els (1971, Table 2) reported a correction

[6] The DCFs for converting exposure to 30-to-250-keV photons to organ dose in the anteroposterior (AP) geometry, listed in OCAS-IG-001, are higher than the corresponding factors for $H_p(10)$ for every listed organ except skin, for which no $H_p(10)$ DCFs are listed.

factor of 2.42–2.48 for the Victoreen 440RF exposed to a copper-target x-ray tube. Lubenau (2015) agreed that it would be appropriate to apply the higher of these factors to the measurements reported by Lubenau et al. (1969) in order to obtain a result that "erred on the high side." Next, scattered radiation from a low-energy x-ray beam tends to be isotropic—the concept of a beam size, which is applicable to a direct beam or to a beam diffracted by a single crystal, is inapplicable to the measurements of scattered radiation reported by Lubenau et al.

We also question the assumption that Carborundum used XRD tubes with copper targets, which were the basis of the scattered radiation measurements the from XRD apparatus reported by Lubenau et al. (1969). According to Strasser and Taylor (1961), at least some of the XRD analyses were performed on solid pellets. Yakel (1974) points out the difficulty of performing XRD studies of uranium alloys due to the high absorption coefficient of Mo K_α x rays, which have an energy of 17.479 keV (Mo $K_{\alpha 1}$). According to Hubbell and Seltzer (2004), uranium has a mass absorption coefficient of 47 cm^2/g at 17.2 keV vs. 311 cm^2/g at 8 keV, the energy of Cu K_α x rays; it is therefore possible that Carborundum would have employed molybdenum target x-ray tubes, which were in use as early as 1935 (Smith et al. 1936). According to Lubenau et al., such x-ray tubes had operating voltages as high as 100 kVp and maximum tube currents of 50 mA, in contrast to the General Electric XRD apparatus with a copper target operated at 50 kVp and 16 mA which was surveyed by these authors. It is difficult to extrapolate the scattered radiation exposures reported by Lubenau et al. to higher tube potentials and higher atomic numbers of x-ray tube targets, but the radiation levels are expected to increase significantly for such an apparatus. Without additional data, it is difficult to put an upper bound on the exposure rates at the edge of the table, let alone the exposures to hands and forearms that may well have been closer to the XRD apparatus.

Applying the methodology described in the ER to the XRD units used at Carborundum would require site-specific data which, according to the ER, are not available for Carborundum. Neither the ER nor the "DR Documents" give an example of how the prescribed methodology would be applied to XRD at Carborundum, nor are any parameters cited other than the measurement of 2 mR/h reported by Lubenau et al. (1969). NIOSH needs to give more specific instructions or an example calculation before we can determine if NIOSH can bound the doses from the XRD units.

4.17 ER Section 7.3.3.2: Methods for Bounding Residual Period External Doses

According to the ER: "External doses during the residual contamination periods were estimated using the Exposure-to-Dose Coefficients in EPA-FGR-12 and the estimated surface and air contamination levels at Carborundum." It is unclear why NIOSH chose to use the Federal Guidance Report 12 (Eckerman and Ryman 1993) to calculate doses from air submersion and surface contamination rather than the conversion factors listed in TBD-6000, Tables 3.9 and 3.10. There are several objections to the NIOSH approach. The first is one of consistency—since TBD-6000 is used for some dose calculations for this site, as well as for many other sites, it should be used throughout whenever applicable. Second, FGR 12 lists effective dose equivalents (EDE), calculated using an anthropomorphic phantom. EDE is an obsolete

dosimetric quantity, which is based on ICRP 26 tissue weighting factors (ICRP 1977), and has been superceded by effective dose (ICRP 1991). Third, OCAS-IG-001 (OCAS 2007) does not list DCFs for converting either EDE or effective dose to organ dose equivalent, nor should it. Both quantities are computed from the calculated doses to individual organs, with appropriate weighting factors. There would be little logic in deconvoluting these quantities to calculate organ doses. Finally, EDE is different from deep dose, which is defined as the dose at a depth of 1 cm in a slab phantom and is typically higher, especially for low-energy photons. "Methodology.xlsx" uses a value of 1.14×10^{-13} rem dpm^{-1} h^{-1} for converting uranium surface contamination to dose, while TBD-6000, Table 3.10, lists 3.94×10^{-13} R dpm^{-1} h^{-1} m^{-2}, which is ~3.5 times greater. The dose coefficient listed in "Methodology.xlsx" is ~9% higher than the EDE coefficient that we calculated by using the weighted average of the coefficients for uranium isotopes, in secular equilibrium with their short-lived progenies, listed in FGR 12, so it is possible that NIOSH attempted to account for the difference in deep dose vs. effective dose, but that is not explained. The submersion dose factor used by "DR Methodology" is about twice the value in TBD-6000, Table 3.9, which is claimant favorable. Nevertheless, NIOSH should use a consistent methodology throughout its DRs.

The ER further states that "external doses for the non-operational areas are assumed to be 10% of the operational areas, per guidance found in [TBD-6000]." In fact, TBD-6000 states that nonoperational areas would have about 1% of the uranium air concentration in heavy production areas, and commensurate surface concentrations. Furthermore, since it cannot be determined which areas were occupied by which workers during the residual periods, the doses during such periods should be based on the residual contamination in the operational areas.

5 ANALYSES OF DR METHODOLOGY FOR CARBORUNDUM

"DR Methodology" was accessed from the restricted DCAS website on October 9, 2015. We observe that this method of presenting the DR methodology is inconsistent with the general NIOSH procedure of posting all relevant DR information on its public website. Such a transparent process gives claimants and their advocates access to the information used by NIOSH to adjudicate their claims.

5.1 External Dose

Both the ER and "DR Methodology" state that there are no existing external dosimetry records for Carborundum workers. However, NIOSH did not indicate if any effort was made to search the computerized external dosimetry records maintained by Landauer, Inc., which was a provider of external dosimetry services since its inception in 1954, well before the second operational period at Carborundum, or other providers of external dosimetry services in the relevant time periods. NIOSH did obtain such records from Landauer for at least one work site—General Steel Industries (GSI)—for the years 1964–1972, which overlap the second operational period at Carborundum. In the interest of the completeness of data sources, NIOSH should either request that Landauer perform such a record search or explain why this is not possible, and investigate other providers of such services during that era.

5.1.1 First Operational Period (6/1/1943 to 9/27/1943)

"DR Methodology" states that the doses from external exposures during the first operation period will be based on the doses from exposure to uranium metal presented in TBD-6000. Given the limited quantity of uranium present at Carborundum during this period, this is a bounding, claimant-favorable assumption. However, we find several issues with the doses listed in the table entitled "External Dose from 1st Operational Period (6/1/1943 to 9/27/1943)." First, the heading of the second column, "Deep dose (R/calendar day)," should specify the units as rem, not R (roentgen). Roentgens are units of exposure, not dose—listing the incorrect units could be confusing to a dose reconstructor who must assign the correct DCF, listed in OCAS-IG-001 to convert the listed quantity to organ dose. For the same reason, the term "deep dose" should be replaced by "personal dose equivalent, Hp(10)," since "deep dose" is not listed in the DCFs for exposures to photons. In the column headed "Shallow," the units are again incorrectly labeled "R," whereas they should be specified as rads. It would be more useful if this column was headed "dose to other skin"—the meaning of "other" would be clear if this column followed the column headed "hands & forearms." A larger error is found in the values in this column. The dose to the other skin of the operator in TBD-6000, Table 6.3 is 25.0 rads/y, which is equal to 6.85×10^{-2} rads/calendar day, whereas "DR Methodology" lists it as 7.12×10^{-2}. The values in the last column, headed "hands & forearms," are calculated correctly from Table 6.3. In the interest of accuracy and fairness to workers at other facilities which utilize the data in TBD-6000, these values should be corrected and listed in the correct units.

5.1.2 Second Operational Period (1959-1967)

"DR Methodology" specifies that workers should be assigned external doses from uranium or from plutonium—actually a mixed source of (U,Pu)C—whichever is most favorable, but that this assignment should be consistent with the assignment of internal doses. We agree that the source of external radiation should be selected on the basis of which source produces the highest organ dose in a particular DR; however, we do not agree that the sources of external and internal doses should be linked—such linkage will be discussed later in this review. We agree that operators and "rad production support" personnel should be assigned doses from either uranium metal or the (U,Pu)C pellets, since it is unlikely that they would spend 50% of their workday exposed to one source and the other 50% exposed to the other source. However, the same is not true of personnel in the nonrad production area, who are assumed to be exposed to one such source 25% of the time. It is not out of the question that they could also be exposed to the other source during 25% of the time, so the doses from the two scenarios should be added for these personnel. The same procedure should be applied to administrative personnel, whose doses are calculated on the basis of being exposed to one source for the equivalent of 2.5% of their time.

Uranium

"DR Methodology" assigns external doses from uranium based on TBD-6000. In the table headed "External Dose from 2nd Operational Period for Uranium (1959-1967)," the operator is assigned a deep dose of 2.088 "R/year." As stated in section 5.1.1 of this review, R (roentgens) is

not the correct unit for deep dose, which should be stated in rem. The "shallow" doses, which are also incorrectly assigned units of R, are overstated by ~4% compared to TBD-6000, Table 6.3. These discrepancies need to be resolved. A more significant issue is the instruction: "External doses from uranium exposure during this period are corrected using the exposure, R, dose equivalent organ DCF (dose conversion factor)." Deep dose is the same quantity as personal dose equivalent (Hp[10]). The DCFs for that quantity, which are listed in OCAS-IG-001, Appendix A, should be used in calculating organ dose.

Uranium/Plutonium Carbide Mixture

"DR Methodology" assigns external doses from (U,Pu)C pellets handled in a glovebox based on calculations performed using MCNP6 (not MCNPX, as stated). NIOSH originally developed a glovebox exposure scenario in connections with its development of correction factors for dosimeter response of glovebox workers presented in TIB-0010, which underwent four revisions, the latest being DCAS-TIB-0010, Rev. 4 (DCAS 2011).

"DR Methodology" states: "Dose rates were calculated at 35 centimeters and one meter from the center of a single pellet." The 35-cm distance was used to assign doses to the operator. This is inconsistent with the previous glovebox scenario:

> While some workers with longer arms might have been able to reach the back of the glovebox, a comfortable working distance for most workers would be between 10-14 inches between the source and the lower torso with a central tendency estimated at approximately 12 inches [30.48 cm]. This is used as the source distance. (DCAS 2011)

In the table headed "External Dose from 2nd Operational Period for Plutonium (1959 to 1967)," "DR Methodology" lists the annual doses to workers in various job categories from photons and neutrons in several energy ranges, and indicates that the listed values should be multiplied by the deep dose equivalent organ DCFs. This is potentially confusing because, while the neutron DCFs in OCAS-IG-001 are identified as deep dose equivalent, the corresponding photon DCFs are listed under "Personal Dose Equivalent." This inconsistent terminology should be resolved in any future revision to OCAS-IG-001. In the meantime, "DR Methodology" should specify the two differently labeled DCFs for photons and neutrons.

We have performed an extensive review of these calculations. Whereas we found that the calculations were carried out in a technically correct manner, given the input parameters, we disagree with the general approach and with some of the assumptions that underlie these calculations.

The MCNP[7] calculations utilized, in part, an MCNP model of a glovebox that was developed by NIOSH in support of the development of correction factors for the personal dosimeters worn

[7] MCNP is a generic term that can be applied to the MCNP family of codes that includes MCNP5, MCNPX, and MCNP6.

by glovebox workers, as presented in DCAS-TIB-0010, Rev. 3 (DCAS 2010). However, following discussions of this model during meetings of the ABRWH Subcommittee on Procedures Review, NIOSH issued DCAS-TIB-0010, Rev. 4 (DCAS 2011), which deleted the MCNPX calculations. Therefore, the DCAS-TIB-0010 MCNPX model should not be used for the present scenario. We also disagree with the isotopic composition of the (U,Pu)C fuel pellets utilized by the NIOSH MCNP simulations and with the calculational method. A detailed discussion of the NIOSH MCNP calculations and of the alternative MCNP analysis performed by SC&A is presented in Appendix B to the present review.

5.1.3 Residual from First Operations (9/28/1943-1944)

According to "DR Methodology": "External doses during the residual contamination periods were estimated using the Exposure-to-Dose Coefficients in EPA-FGR-12 and the estimated surface and air contamination levels at Carborundum." These dose assessments are discussed in section 4.17 of the present review.

The beta doses listed in the "DR Methodology" table headed "Residual External Dose from 1st Operational Period (9/28/1943–1944)" are calculated using the combined FGR 12 skin dose coefficients for surface contaminated with natural uranium. As stated earlier, NIOSH should have used TBD-6000, Table 3.10, which lists a conversion factor of 3.82×10^{-8} mrad dpm^{-1} h^{-1} m^{-2}, instead of the factor of 2.77×10^{-8} mrad dpm^{-1} h^{-1} m^{-2} derived from FGR 12. Not only is it not claimant favorable, it is inconsistent with other NIOSH dose calculations.

5.1.4 Residual from Second Operational Period (1959-1967)

NIOSH also used FGR 12 dose coefficients to calculate external doses during the second residual period. The same comments presented in section 5.1.3, above, apply to this period.

5.1.5 X-Ray Diffraction

"DR Methodology" presents a discussion of XRD as a source of external radiation that is copied verbatim from the ER. The radiation exposure to this sources is discussed in section 4.16.1 of the present review.

5.1.6 Additional Source of External Exposure

According to Freeman (1952), Carborundum acquired five thickness gauges utilizing sealed sources of ^{90}Sr in 1952. Called the Accuracy gauge, they were manufactured by the Industrial Nucleonics Corporation of Columbus, Ohio. As mentioned in section 4.3 of the present review, both the NRC (the successor agency to AEC) and the New York State Department of Health informed us that they had no records pertaining to radioactive materials at the Carborundum plant in Niagara Falls during the time period in question. However, we were able to obtain licensing information pertaining to Industrial Nucleonics, which was licensed to possess 150 Ci of ^{90}Sr. Individual gauges produced by this company contained 10 mCi–2 Ci of ^{90}Sr. The licenses limited the exposure rate to 5 mR/h at a distance of 1 ft. A license application dated

September 30, 1963, stipulated that no person would receive an annual dose >0.5 rem. This is consistent with AEC regulation 10 CFR 20 that went into effect January 1, 1961, which limited whole body doses from external exposure in an unrestricted area to 0.5 rem in any one calendar year (AEC 1960). Prior to that date, the AEC limited doses from external exposure in unrestricted areas to 2 mrem/h or 100 mrem/week, assuming continuous occupancy (AEC 1957). No limit on doses to exposed individuals is mentioned in Industrial Nucleonics licenses prior to 1963. It should therefore be assumed that the gauges conformed to the existing AEC limits at the time they were sold.

In the absence of information that allow an estimate of actual exposures to the five ^{90}Sr sources that were acquired by Carborundum in 1952 and are presumed to have still been in use during the second operational period, it must be assumed that the doses were limited only by the AEC regulations in effect at the time. Therefore, it is possible that an individual in continuous proximity to such a source, such as the operator of the sandpaper processing machinery, would receive a dose of 2 mrem/h or 80 mrem per week during the years 1959–1960, for an annual dose of 4 rem from this source. During the years 1961–1967, the worker should be assumed to receive doses of 0.5 rem/y, unless NIOSH can find more specific surrogate data.

5.2 Internal Dose

5.2.1 First Operational Period (6/1/1943 to 9/27/1943)

During the first operational period, "DR Methodology" assigns intake rates for workers in various job categories based on intakes due to machining operations prior to 1951 that are listed in TBD-6000, Tables 7.8 and 7.9. In most cases, such assignment would be inappropriate because the data that are the basis of Tables 7.8 and 7.9 do not meet the temporal requirement, one of the Advisory Board's five surrogate data criteria. In referring to the air sampling data that form the basis of these intakes, TBD-6000 states: "These results are typical of the state of technology in the late 1950s, as surveyed by Harris and Kingsley" which was about 15 years earlier.

To determine if the proposed intakes are bounding, we note that the operator is assigned an intake of 43,632 dpm per calendar day as the median of a lognormal distribution with a GSD of 5. The arithmetic mean of this distribution is 159,323 dpm per calendar day, which corresponds to an average breathing zone concentration of 29,077 dpm/m^3. The highest concentration for unventilated centerless grinding cited by Harris and Kingsley (1959) is 13,000 dpm/m^3. The average value derived from the distribution proposed by NIOSH is more than twice this value. We therefore conclude that, given the limited quantity of uranium metal in the present case, the values listed in TBD-6000 are sufficiently bounding.

5.2.2 Second Operational Period (1959–1967)

Intakes of uranium during the second operational period are based two sets of air samples. One set of six samples was collected on November 9, 1959, while another set of three samples was collected on April 5, 1961. Intakes of plutonium are based on a set of eight samples that was

also collected on April 5, just before the uranium samples, and a second set that was collected on June 8, 1961.

"DR Methodology" states that intakes of uranium *or* plutonium should be assigned to the claimant, whichever scenario is more favorable, and that the internal intake scenario should be consistent with the assigned external exposure scenario for the second operational period. We disagree with this procedure because contamination with uranium and plutonium dust was not confined to separate, discrete areas of the plant. In fact, uranium and plutonium oxides and other compounds were mixed to produce the (U,Pu)C pellets. Therefore, claimants should be assigned doses from intakes of *both* uranium and plutonium.

Uranium

A table headed "Statistical Analysis of Six Dust Samples[8] (Nov. 1959 and April 1961)" presents the geometric mean, GSD, and 95th percentile derived from the reports of uranium samples collected on the two dates cited above. The calculations are shown in "Methodology.xlsx."

The report of the survey performed by HASL on November 9, 1959, which lists partial data, shows only one numerical result—a value of 6 dpm/m^3 (HASL n/d). Five of the remaining six boxes in this column which has the printed heading "results" followed by handwritten units of "d/m/m^3," contain a horizontal line.[9] However, NIOSH used the partial, and partly illegible, entries on the survey report to impute results for the other five samples. Following the sample description are two columns headed with the printed headings "sampling rate" and "sampling time." The "rate" column shows the numeral 3 followed by a much smaller mark that is difficult to interpret. It appears to be a circle 1.5 mm in diameter touching the "3" which is 5 mm high. NIOSH interprets this as 30 L/min, although no units are indicated in the sample report. The other air dust survey sheets for Carborundum list sampling rates in "c/m," the abbreviation for cfm or ft^3/min. It is more likely that the sampling rate in this survey is 3 cfm, especially since all the Carborundum samples sheets appear to be in the same handwriting and contain the instructions to route results to "[redacted]" or "[redacted]," who is also identified as the collector on the sheet in question plus one other, with the remaining ones collected by "[redacted]" or "[redacted]," most likely the same person. It is likely that [redacted] would have used a flow meter calibrated in the same units throughout. The "sampling time" column lists numbers that are barely legible but range from 20 to 23, presumably minutes, which are the units shown on two other Carborundum sample sheets. These times can be confirmed by comparing them to the start and stop times listed for each sample. NIOSH has chosen to assign a uniform sampling time of 25 min to all six samples. NIOSH used these assumed values to derive a sampling volume of 0.75 m^3, which is far smaller than the volumes of 6.2–12.7 m^3 for the other three sets of Carborundum air samples. Following the sampling-time column is an unmarked column with numbers ranging from 1 to 18, two of which are partially illegible. NIOSH interprets these as gross counts, but neglects to subtract the control value of 2. The next unmarked column, which

[8] The analysis summarized in this table is actually based on nine samples.
[9] The sample sheet lists a total of six samples and one control.

has uniform values of 15, except for one value of 16, is interpreted as count time. Finally, NIOSH assumes a counting efficiency of 0.25 count/dpm and uses this assumption, plus the interpreted values which, in some cases, are contradicted by the legible entries on the sample sheet, to assign uranium concentrations to all six samples.

It is our position that the NIOSH procedure for assigning values to samples which HASL chose to mark with a line, which we interpret as no value, is not valid. Instead, we recommend that NIOSH use the regression of order statistics (ROS) method prescribed by OTIB 19 (Brackett 2005), as shown in Appendix A. This method explicitly accounts for the samples for which no results are recorded without attempting to assign values to these samples. Combining the value of 6 dpm/m^3 with the clearly legible sample results of the April 5, 1961, survey produces a geometric mean of 0.634 dpm/m^3, a GSD of 4.446, and a 95th percentile of 7.383 dpm/m^3, as compared to the NIOSH values of 1.666 dpm/m^3, 2.511, and 7.578 dpm/m^3. The 95th percentile obtained by the ROS method is thus slightly smaller than the NIOSH value, but does not rely on questionable assumptions.

Since the results are based on general air samples, NIOSH assigns an inhaled intake to "Rad production support" personnel that has a fixed value of 49.83 dpm per calendar day, derived from the 95th percentile air concentration. Operators are assigned twice this value. We agree with this procedure. NIOSH may choose to use the slightly lower values based on the ROS analysis, which would result in inhaled intakes of 48.548 dpm per calendar day for "Rad production support" personnel and 97.097 dpm per calendar day for operators, with other job categories scaled from these values in the usual manner. NIOSH would then need to make a corresponding change of uranium intake rates by ingestion. We agree with the assumption regarding recycled uranium.

Plutonium

As stated earlier, intakes of plutonium are based two sets of eight samples each that were collected on April 5 and June 8, 1961. In both surveys, the results were reported as dpm/sample. The plutonium activity concentrations can be calculated by dividing by the volume of air from which each sample was collected. The volume is determined by multiplying the sampling rate by the time. For the April 5 survey, the flow rate was 8.5 cfm, while the sampling time was 40 min, resulting in an volume of 340 ft^3 (9.628 m^3) of air passing through the collection filter. NIOSH used "Methodology.xlsx" to perform these calculations. We observed two errors in the transcription of the April 5 sampling data. Sample 3F was entered in the spreadsheet as 2.2 dpm/sample, while the recorded value was 0.2. Sample 4C was entered as 2.2 dpm/sample, while the actual entry was 22.

The June 8 survey also comprised eight samples; however, four samples had zero counts. NIOSH arbitrarily assigned these samples a value of 0.01 dpm/sample. We can find no justification for such a substitution. We recommend that NIOSH use the ROS method described for the uranium dust samples that is presented in Appendix A. The ROS analysis again explicitly accounts for the four samples with readings of zero. The result is a geometric mean of

0.0271 dpm/m^3, a GSD of 9.821, and a 95th percentile of 1.164 dpm/m^3, as compared to the NIOSH values of 0.026 dpm/m^3, 9.288, and 1.005 dpm/m^3. The 95th percentile obtained by the ROS method is approximately 16% larger than the NIOSH value: The intake by operators is estimated to be 7.651 dpm per calendar day vs. 6.606 calculated by NIOSH. We recommend that NIOSH adopt that ROS value, which is consistent with NIOSH procedures as prescribed by OTIB-19, does not rely on questionable assumptions, and is claimant favorable. The intakes by workers in other job categories, as well as ingestion intakes, should be adjusted accordingly.

"DR Methodology" assigns isotopic ratios to plutonium based on a preliminary planning report (Taylor 1960) that was issued prior to the actual start of plutonium operations, which listed the composition of plutonium obtained from the Dow Chemical Company as shown in the second column of Table 1, below. However, according to Strasser and Taylor (1962a), during the period of September 15, 1961 to December 31, 1961, fuel pellets were produced from powder prepared by Hanford Atomic Products Operations, which had the plutonium isotopic composition listed in the fourth column of this table. Strasser and Stahl (1965) state that PuO_2 was prepared by the Dow Chemical Company at the Rocky Flats Plant, while $(U_{0.8}Pu_{0.2})O_2$ was prepared by the General Electric Co., Hanford Atomic Operations.

In order to determine which isotopic ratio is more claimant favorable, we calculated the effective dose per unit intake of plutonium from the two suppliers.[10] The plutonium air samples are reported as total α. Since ^{239}Pu and ^{240}Pu have almost identical organ DCFs, the different ratios of these isotopes are not significant in terms of internal dosimetry. However, aside from the very small fraction of ^{241}Pu atoms that decay by α emission (~0.0025%), the amount of this isotope that was taken in by the workers is inferred from the assumed isotopic ratios. The ratio of the specific activity of each radionuclide to the total α activity of the mixture that has been aged for one year to allow ingrowth of ^{241}Am (as assumed by NIOSH) is shown in the third column.[11] The fourth column lists the effective dose per unit inhaled intake of the mixture, calculated using the dose coefficients for the inhalation by workers for 5 ìm AMAD particles of Type *M* plutonium and americium isotopes listed by ICRP (1994). The next three columns list the corresponding quantities for the Hanford mixture. However, we based the calculation on fresh fuel, which produces a higher effective dose than 1-y-old fuel: decay of ^{239}Pu during this period more than offsets the ingrowth of ^{241}Am. However, since the plutonium operations at Carborundum lasted more than 6 years, it is plausible that some fuel was made from 5-y-old plutonium; consequently, we calculated the effective dose from the inhalation of such a mixture. This is of interest because, as will be discussed in Appendix B, 5-y-old fuel produces a higher external dose than fuel that has aged for a shorter time.

As shown in Table 1, the inhalation of either fresh or 5-y-old Hanford fuel leads to higher effective doses than the 1-y-old Dow fuel assumed by NIOSH. NIOSH should use the isotopic

[10] Effective dose is a weighted average of organ dose equivalents and can thus be used as a surrogate for comparing doses to unspecified organs.

[11] We independently calculated the activity ratios and derived slightly different values, most likely due to different values of half-lives, atomic masses, and/or branching ratios of the various radionuclides. Our values were derived from the Evaluated Nuclear Structure Data Files as listed by LANL (2012) and from Audi et al. (2003).

composition of fresh Hanford material in its DR methodology, which is more claimant favorable than the other two mixes, unless it can determine that other data on plutonium isotopes are more representative of this period of operations. For consistency, a DR should assume either fresh or 5-y-old Hanford fuel for both internal and external dose calculations and select the one that is more claimant favorable.

Table 1. Mass Fractions of Plutonium Isotopes at Carborundum

Radio-nuclide	Source of plutonium							
	Dow			Hanford				
	Age fuel:	1 y		Age fuel:	Fresh		5 y	
	f[a]	α[b]	ED[c]	f[d]	α	ED	α	ED
^{239}Pu	93.5	0.801	2.56e-05	90.7	0.739	2.36e-05	0.678	2.17e-05
^{240}Pu	5.9	0.185	5.92e-06	7.9	0.235	7.53e-06	0.216	6.91e-06
^{241}Pu	0.6	8.177	4.74e-06	1.2	15.540	9.01e-06	11.750	6.82e-06
^{242}Pu	0	—	—	0.1	0.000	1.60e-09	0.000	1.47e-09
^{241}Am	0	0.013	3.62e-07	0	0.025	6.88e-07	0.106	2.86e-06
Total			3.67e-05			4.09e-05		3.83e-05

[a] Mass fraction (Taylor 1960)

[b] Ratio of specific activity to total α activity

[c] Effective dose per unit intake (Sv/g)

[d] Mass fraction (Strasser and Taylor 1962a)

5.2.3 Residual Periods

Post-Operations (9/28/1943-1944) and First Residual Period (6/1/1945-1958)

There is a lack of clarity in both "DR Methodology" and the ER in the definition of the first residual period, which is partially related to a change in the designation of the first AWE period, that NIOSH has determined extends from June through September 1943, as discussed in section 2.1.4 of the present review. It would be logical and less confusing to designate the first residual period as commencing immediately after the end of AWE operations. In any case, "DR Methodology" calculates intakes of uranium during the period between the end of the first operational period and the start of the second operational period by using the methodology recommended by OTIB-70 (Sharfi 2012). SC&A has verified that the OTIB-70 methodology is being correctly applied by NIOSH. We do have comments on the table headed "Residual from 1st Operations (9/28/1943-1944)." First, the heading is misleading, since the first operational period *ended* on September 27, 1943, and the table is applied to the period from September 28, 1943 to 1959, the beginning of the second operational period. Second, the table lists intakes through 1992, which decrease year by year. This is inconsistent with OTIB-70, which states that there should be no further depletion of the source after the first 30 years, contrary to the continuing decrease after 1974 listed in the "DR Methodology" table.

Residual from Second Operational Period (1959-1967)

"DR Methodology" calculates intakes of uranium during the second residual period by applying the OTIB-70 methodology, using as a starting point the calculated uranium airborne activity concentrations during the second operational period. These should be decreased slightly should NIOSH adopt the uranium concentrations calculated by the ROS methodology described earlier in this section of the present review. "DR Methodology" also applies this methodology to the plutonium air concentrations during this period. The plutonium values listed in the tables headed "Residual from 2nd Operational Period (1959-1967) Production Areas" and "Residual from Second Operational Period (1959-1967) Non-Production Areas" should be increased to account for the revised intakes calculated by the ROS methodology described previously.

6 AUDITS OF DOSE RECONSTRUCTIONS

As stated in section 2.1.3 of the present review, SC&A audited a DR for a former Carborundum employee who, as it happens, was the [redacted]. Due to the extensive changes in the NIOSH DR methodology that were made subsequent to our audit, the results are not relevant to this review. Instead, as part of Task 4, auditing dose reconstructions performed by NIOSH, we reviewed the example DR provided by NIOSH.

6.1 External Dose

The example DR is for a hypothetical worker who was employed from June 1, 1943, until December 31, 1992. His employment thus spanned the entire period of covered operations: the two operational periods and the two residual periods that followed. The purpose of this audit is to determine if NIOSH followed the rules and instructions presented in the ER and in "DR Methodology." We have stated any disagreements to these methods in the preceding discussions of these documents, so they shall not be restated here. He had cancers of the lung, prostate, skin on the back, kidney, and liver. He was assumed to be an operator for the purpose of this DR, and was thus assigned the corresponding radiation exposures. Although described as a single individual, the DRs treat each cancer separately by assigning the worker different exposure scenarios for different cancers.

During the first operation period, he was correctly assigned the deep and shallow dose listed in "DR Methodology" for this period. The table heading incorrectly reports these units in R (roentgens), while they should be in rem and rads, respectively, although it is permissible to report skin dose in rem. During the first residual period, he was correctly assigned the external dose from photons and β rays in the production areas, where he was presumed to have worked.

During the second operational period, doses from exposure to uranium metal were assessed separately from those from (U,Pu)C pellets in a glovebox: the worker was to be assigned whichever dose is most favorable. This is not a realistic assumption for the first two years of this period (1959–1960), since Carborundum did not receive any plutonium until March 1961. Therefore, the external doses for these two years should be based on exposures to uranium. During the remainder of the second operational period (1961–1967), external exposures to both

sources need to be considered. Although the deep dose from plutonium operations is clearly higher, there is no beta dose, since ^{241}Pu is the only significant β emitter and its β rays have low energies that would be absorbed by the glovebox window.

The worker was assigned doses during the second residual period based on either the residue from the first operational period or the second, based on the assumption that the operations took place in separate buildings. Only beta doses are assigned, since the photon doses are <1 mrem/y.

6.1.1 Photon Dose

According to "Example DR": "exposure, R, dose equivalent organ DCFs were used to adjust organ dose during both operational periods." This is inconsistent with "DR Methodology," which states that "photon and neutron doses [calculated by MCNP] are treated as a constant distribution and then multiplied by the deep dose equivalent organ DCF."

6.2 Internal Dose

6.2.1 First Operational Period

Internal doses were assigned based on the ER and "DR Methodology." During the first operational period, the assigned intakes of uranium aerosols by inhalation and ingestion were the same as those listed in "DR Methodology" for this period, which in turn are the same as those for the machining operation in TBD-6000, Tables 7.8 and 7.9, respectively. During the first residual period—September 28, 1943, to January 1, 1959—uranium intakes were assigned on the basis of the intakes for this period tabulated in "DR Methodology," which in turn were based on the procedures in OTIB-0070. We agree with these assumptions.

6.2.2 First Residual Period

The worker was assigned intakes of uranium dust from the end of uranium machining operations on September 27,1943, until the start of the second operational period January 1, 1959, that were listed in "DR Methodology." We agree that the intakes were correctly assigned during this period.

6.2.3 Second Operational Period

As discussed in section 5.2 of the present review, we reanalyzed the air sampling data which are the basis of the assigned uranium intakes during the second operational period. Our results produced slightly lower intakes; consequently, although we disagree with the methodology of the NIOSH analyses, we find the assigned intakes to be acceptable and claimant favorable. We agree with NIOSH's including in the intake the minor radioactive contaminants characteristic of recycled uranium.

We agree that the isotopic mixture of plutonium and the daily intakes listed in "Example DR" are consistent with the values listed in "DR Methodology." However, as discussed in section

5.2, we disagree with both the analysis of the plutonium airborne dust sampling results and with the assumed isotopic composition of the plutonium.

6.2.4 Second Residual Period

Intakes during the second residual period are based on residual contamination from either the first or second operational periods. We agree with the assignment of uranium intakes based on the first residual period for the years 1968–1973. However, the intakes continue to decrease until the date of cancer diagnosis. As stated earlier, the intakes for the years starting in 1974 should be the same as in 1973, since OTIB-0070 states that there should be no further depletion of the source term after 30 years following the initial deposition.

We agree that the assigned uranium intakes based on the second residual period are consistent with the values listed in "DR Methodology," which we found to be claimant favorable, even though we disagreed with the NIOSH analysis of the uranium air sampling data. We agree that the assigned plutonium intakes based on the second residual period are consistent with the values listed in "DR Methodology." However, we disagree with the NIOSH calculation of the plutonium airborne activity concentrations, as discussed in section 5.2 of the present review, and with the assumed mix of radionuclides.

6.3 Audit of DR Results

"Example DR" calculated doses to five organs: lung, prostate, skin, kidney, and liver. We performed detailed audits of external and internal doses to all these organs except the prostate, employing the parameters specified by NIOSH but using an independent methodology.

6.3.1 Audits of External Doses

We audited external doses to four organs by following the methodology described in "Example DR." In cases where the NIOSH methodology used DCFs that were not consistent with the external dosimetric quantity to which they were applied, we repeated the calculation using the appropriate DCFs.

Lung and Skin

The external doses to the lung and the skin are due to the following exposures:

- penetrating (photon) radiation from natural uranium metal during the first and second operational periods
- nonpenetrating (β) radiation from natural uranium metal during the first and second operational periods (skin only)
- penetrating and nonpenetrating (skin only) radiation from floor contaminated with natural uranium during the first and second residual periods

Liver and Kidney

The external doses to the liver and kidney are from the same sources as the lungs during the first operational and first residual periods. Doses during the second operational period are from exposures to photon and neutron radiation from the (U,Pu)C pellets handled in a glovebox.

Calculated External Doses

The external doses to the four organs are shown in Table 2. As was discussed in section 4.16 of the present review, the ER incorrectly specified the use of the exposure (R) DCFs for calculation of organ dose equivalents from external exposure to direct penetrating radiation from uranium metal. The doses are based on TBD-6000, which cites values calculated in a slab phantom, which is the definition of $H_p(10)$. The doses in the column headed "SC&A-1" were calculated by applying the $H_p(10)$ DCFs to the external exposures to uranium metal, while the doses under "SC&A-2" represent an attempt to match the NIOSH results by applying the exposure (R) DCFs to that scenario. As shown in Table 2, the two sets of SC&A calculations produced doses that are 7%–37% less than the corresponding NIOSH values. Even when we used the organ DCFs for exposure, our results are 7%–11% less than NIOSH's. We do not understand the reason for these differences. Although the NIOSH results are claimant favorable, they should be corrected or further clarified in the interest of transparency and consistency with DR methods used for other worksites.

Table 2. Comparison of Internal Doses to Four Organs (rem)

Organ	External			Internal			Total	
	SC&A-1[a]	SC&A-2[b]	NIOSH[c]	DCAL[d]	ICRP[e]	NIOSH	SC&A[f]	NIOSH
Lung	12.190	17.290	19.338	435.481	481.263	482.062	447.671	501.400
Skin	200.537[g]	200.537[g]	226.053	0.940	1.126	6.071	201.4772	232.124
Liver	25.573	26.637	28.789	9.729	9.991	26.851	35.302	55.640
Kidney	25.573	26.637	28.789	10.495	11.326	45.931	36.068	74.720

[a] Doses calculated using $H_p(10)$ DCFs for external exposure to uranium metal

[b] Doses calculated using exposure (R) DCFs for external exposure to uranium metal

[c] Source: "Example DR"

[d] Calculated employing integrated doses derived using ORNL's DCAL computer code

[e] Limiting doses based on ICRP (2001) dose coefficients

[f] Totals combine values in columns headed "SC&A-1" and "DCAL"

[g] OCAS-IG-001 does not list DCFs for converting $H_p(10)$ doses from external exposure to skin dose equivalents, so exposure (R) DCFs were used for both columns

6.3.2 Audits of Internal Doses

We audited internal doses to four organs by performing independent calculations using integrated doses derived from the DCAL computer code (ORNL 2006). DCAL is "a comprehensive software system for the calculation of tissue dose and subsequent health risk

from intakes of radionuclides or exposure to radionuclides present in environmental media" (Eckerman et al. 2006). This totally independent methodology allows us to audit the doses using the same ICRP models and parameters that are employed by IMBA. We have previously employed this methodology to audit DRs under EEOICPA, most notably [redacted], which was for a former Carborundum employee, and obtained virtually identical results. We did not audit the internal dose to the prostate, which is not one of the organs included in the ICRP 60 effective dose model (ICRP 1991), because that would have involved a lengthy assessment of each nonmetabolic organ to find the one with the highest dose to use as a surrogate.

Lung and Skin

The internal doses to the lung and the skin are due to the following intake regimes:

- inhalation of natural uranium during the first operational period and the first and second residual periods
- ingestion of natural uranium during the first operational period and the first and second residual periods
- inhalation of recycled uranium during the second operational period
- ingestion of recycled uranium during the second operational period

Liver

The internal dose to the liver is due to the following intake regimes:

- inhalation of natural uranium during the first operational period and the first residual period
- ingestion of natural uranium during the first operational period and the first residual period
- inhalation of plutonium during the second operational period and the second residual period
- ingestion of plutonium during the second operational period and the second residual period
- inhalation of recycled uranium during the second residual period
- ingestion of recycled uranium during the second residual period

Kidney

The internal dose to the kidney is due to the following intake regimes:

- inhalation of natural uranium during the first operational period and the first and second residual periods
- ingestion of natural uranium during the first operational period and the first and second residual periods
- inhalation of plutonium during the second operational period
- ingestion of plutonium during the second operational period

We used our DCAL-based methodology to calculate the internal doses to the four organs, using the daily intakes by inhalation and ingestion of each radionuclide—and mix of nuclides in the case of 1-y-old plutonium and recycled uranium—listed in "Example DR." The results, listed in Table 2 in the column headed "DCAL," show that our calculations produce doses that are 10%–85% less than the NIOSH values. Lung doses from inhalation were calculated assuming all radionuclides were of Lung Absorption Type *S*, while doses to other organs assumed that the nuclides were Type *M*. Although some uranium compounds are of Type *F*, the ER specifies that only uranium Type *M* or *S* was evaluated during the first operational period, and is silent on types of uranium during other periods. "Example DR" specifies uranium Type *M* or *S* without any restriction on which period was being evaluated. All doses from ingestion assumed the highest f_1 value for a given radionuclide.

As an additional check, we performed a set bounding calculations in which we summed the entire intake of a given radionuclide by a given pathway (inhalation or ingestion) and multiplied this value by the corresponding 50-year dose commitment[12] extracted from ICRP (2001), using the same assumptions regarding Lung Absorption Types and f_1 values. This was tantamount to assuming an acute intake of the entire activity that was actually taken in over a multi-year period. Even this bounding assumption produced doses that were up to 81% smaller than those reported by NIOSH. We do not understand the reason for these differences.

7 CONCLUSIONS

NIOSH has performed extensive research into the operations at Carborundum, including reviews of 92 documents and other data sources and interviews with seven site experts. NIOSH has sufficient information to bound most radiation exposures that were incurred at Carborundum.

7.1 Sources Requiring Further Consideration

Three groups of sources merit further examination: the five thickness gauges containing ^{90}Sr which were reported in the *New York Times* (Freeman 1952), the XRD units, and thorium that, according to [redacted], a former Carborundum worker who was interviewed by both the

[12] A 45-y dose commitment was used for plutonium and americium, since these intakes took place closer to the end of the evaluation period (i.e., the date of cancer diagnosis).

ORAU Team and SC&A, was used to make fuel pellets, as discussed in section C.1.1 in Appendix C.

7.1.1 Thickness Gauges Containing ^{90}Sr

Sources that merit further consideration include the five thickness gauges containing ^{90}Sr (Freeman 1952). There is no site-specific information on these sources. These gauges were used for quality control in the manufacture of sandpaper: such a process would most likely not have required the area to be under radiation control. A condition in a 1963 license application by the manufacturer of the gauges, Industrial Nucleonics Corporation, is that they meet the radiation standards for uncontrolled areas in existence at that time (AEC 1964). The radiation exposure to these sources would have to be addressed only during the second operational period (1959–1967). According to 10 CFR 20 that was in effect in 1959, no licensee shall use

> licensed material in such a manner as to create in any unrestricted area from radioactive material and other sources of radiation in his possession:
>
> (1) Radiation levels which, if an individual were continuously present in the area, could result in his receiving a dose in excess or two millirems in any one hour, or
>
> (2) Radiation levels which, if an individual were continuously present in the area, could result in his receiving a dose in excess of 100 millirems in any seven consecutive days.

Furthermore, weekly doses to critical organs are restricted to 10% of the limits in 10 CFR 20 Appendix A, which include skin, blood-forming organs, and gonads. We can conjecture that the license conditions were adhered to by Carborundum, although neither NRC nor the New York State Department of Health has any records of such a license for Carborundum. In such a case, these limits could be the basis of establishing bounding exposures from these sources.

By 1961, 10 CFR 20 was revised, and lower limits on radiation exposures in unrestricted areas were promulgated. Such limits could be used to bound doses from these sources during the years 1961–1967.

7.1.2 X-Ray Diffraction Apparatus (XRD)

Analytical x-ray equipment, including XRD, was a source of concern to radiation safety regulators during the time period that includes the second operational period at Carborundum (Lubenau et al. 1969). NIOSH needs to re-examine the assumptions used to bound the doses from the procedure, especially to the skin of the hands and forearms. We are not aware of any state or federal oversight of the use of industrial x-ray equipment during the second operational period, when exposures from such equipment would have to be addressed. Consequently, regulatory limits, such as those suggested for ^{90}Sr sources in section 7.1.1 of the present review, would not apply.

7.2 Dose Assessment Methodology Proposed by NIOSH

Some of the dose assessment methodologies proposed by NIOSH that are discussed in the present review are not scientifically correct and/or are inconsistent with established NIOSH procedures. While this issue does not, in principle, vitiate NIOSH's ability to perform bounding assessments of radiation doses to Carborundum workers, these inherent technical deficiencies need to be remedied before any final conclusions can be drawn about NIOSH's response to the present SEC petition. In addition, we note that results listed in "Example DR" are inconsistent with the methodology described in that document.

8 FINDINGS

Finding 1. NIOSH Failed to Prescribe a Methodology to Assess Doses to Skin of Hands and Forearms to X-Ray Diffraction (XRD) Apparatus

The ER does not present a detailed, quantifiable, verifiable description of how NIOSH intends to assess doses to operators of XRD equipment. Lubenau et al. (1969) is cited to suggest that the dose rates would not exceed 2 mR/h at the edge of the table. However, in a personal communication with the author of this review, Lubenau (2015) stated that the dose rates on top of the table, where the operator might place his hands and forearms, would "surely be higher." The ER refers to a methodology adopted by NIOSH to limit the exposures to such an apparatus at Sandia National Laboratory—Livermore (Guido et al. 2007), but then observes that "the method was site-specific, based on detailed accounts of the equipment and technical factors; however, the same level of detail has not been found for Carborundum." Nevertheless, the ER then presents a set of assumptions which, according to NIOSH, would allow it to apply the Sandia methodology to Carborundum. (According to a [redacted] at Carborundum that was interviewed by SC&A—reported in section C.2 of the present review—there was no positive interlock that would prevent the operation of the equipment with an unshielded port.) Absent a more detailed discussion and/or an example calculation, we cannot determine how NIOSH intends to bound the doses from XRD at Carborundum.

Finding 2. NIOSH Failed to Address Thorium as a Possible Radiation Source

The ER cites information on the use of thorium at Carborundum obtained during an interview with a former worker, but makes no further mention of this material except in citing two documents in Table A1-1: "Data Capture Synopsis for Carborundum Company." The former worker, who was also interviewed by SC&A, reported that he produced fuel pellets made from ThO_2 and ThC. This apparently took place prior to the second operational period. The use of thorium at Carborundum needs to be further investigated. If these pellets were weapons-related, there would be reason for NIOSH to inform DOE and DOL that the period of covered operations might need to be extended.

Finding 3. NIOSH Failed to Account for the Use of 90Sr in Thickness Gauges at Carborundum

The 1952 acquisition of five thickness gauges by Carborundum for quality control in the manufacture of sandpaper was reported in the New York Times (Freeman 1952). However, NIOSH was unaware of this information. AEC licensing documents related to the Industrial Nucleonics Corporation, the supplier of these gauges, obtained by SC&A from the NRC Public Documents Room, indicate that such devices can contain as much as 2 Ci of ^{90}Sr. Strontium-90 is in secular equilibrium with its short-lived progeny, ^{90}Y ($t_{½}$ = 64 h), which emits β rays with a maximum energy of 2.28 MeV. Thus, although both ^{90}Sr and ^{90}Y are almost pure β emitters, the high-energy ^{90}Y β rays create a strong source of bremsstrahlung x rays, which can contribute to doses from penetrating radiation, in addition to posing a radiation hazard to the skin of a worker. NIOSH needs to obtain more information on the use of such sources at Carborundum—failing that, it needs to adopt a strategy for assigning doses to potentially affected workers.

Finding 4. NIOSH Failed to Assign Doses from Medical X Rays During the First Operational Period

As stated in section 4.15 of the present review, NIOSH failed to assign medical x rays during the first operational period on the basis of internal correspondence at du Pont, a wartime government contractor, that said that the grinding of uranium at Carborundum did not require medical supervision. This is irrelevant to routine physical examinations, which might include medical x rays. According to DCAS-IG-003, doses from screening x rays are to be assigned if they were part of a required annual physical examination, not that they were related to a particular job assignment. The ER is inconsistent in prescribing the assignment of medical x rays during the second operational period but not the first.

Finding 5. "Example DR" Failed to Assign Doses from Medical X Rays During the Second Operational Period

According to the ER, "NIOSH will assume that pre-employment, annual, and termination PA radiographic chest X-ray screenings were performed for workers during the second operational period." However, "Example DR" explicitly states that no medical x-ray doses were assessed to the hypothetical worker who was employed during both operational periods. This inconsistency needs to be resolved.

Finding 6. Inappropriate and Incorrect Use of FGR 12

The ER used several scenarios described in TBD-6000 to estimate internal and external doses from intakes of uranium dust and from exposure to uranium metal. However, NIOSH then used FGR 12 to calculate doses from submersion in a cloud of radioactive dust and from exposure to contaminated surfaces instead of using the values listed in TBD-6000 Tables 3.9 and 3.10. The value of the photon dose coefficient from a surface contaminated with uranium that is entered in "Methodology.xlsx" is only ~29% of the value in Table 3.10. This procedure is furthermore inconsistent with the use of TBD-6000 for other pathways and for DRs at other worksites. Also,

it is not scientifically correct, since NIOSH does not have a prescribed method of deriving organ dose equivalents from EDE. However, in the case of Carborundum, the external doses from penetrating radiation displayed in "Methodology.xlsx" for the residual periods are a few mrem/y (not <1 mrem/y, as stated in the ER), so these discrepancies are not highly significant.

Doses to the skin from nonpenetrating radiation from uranium-contaminated surfaces are on on the order of a few hundred millirem during the first few years of the first residual period.

Consequently, the value derived from FGR 12 skin doses that is entered in "Methodology.xlsx," which is ~72.5% of the value in TBD-6000 Table 3.10, could affect the outcome of a DR.

Finding 7. Dose Calculations in "Example DR" Are Not Reproducible

The SC&A audit of doses to four of the five organs presented in "Example DR" resulted in significant differences in both internal and external doses. NIOSH did not show details of its calculations—"Example DR" simply listed annual intakes and external dose rates during the relevant periods and the final organ doses, but did not present the details of the intermediate calculations used to obtain these doses. Consequently, it was not possible for us to identify the reasons for the different results. As stated in section 1.2 of the present review: "The work group guidelines also recommend that NIOSH include in its SEC evaluation a demonstration that it is feasible to reconstruct individual doses for the cohort, including sample DRs." Until we can verify the results of sample DRs, we cannot conclude that NIOSH can reconstruct doses to Carborundum workers.

9 OBSERVATIONS

We have a number of observations regarding the ER and the "DR Documents," which, while not rising to the level of findings, should nevertheless be addressed by NIOSH in a future revision of the ER and any supporting documents. We have presented them in the form of comments and observations through this review, so we will not reiterate them here.

Appendix A
Regression Analyses of Air Sampling Data

A.1 Regression Analysis of Uranium Data

The regression of order statistics (ROS) method was used to fit a lognormal distribution to the , including the six nondetect values. A plot of the logarithms of the data versus the normal score for each observation is shown in Figure A-1. (The figure omits the five samples for which no results are listed in the survey report.) The plot also contains a regression line which best fits the plotted data points. The slope and intercept of the regression line are also shown on the figure.

Although the data approximately follow the regression line, the data points are below the regression line at both ends of the plot, while they are above the regression line in the middle of the plot. The value of $R^2 = .9584$ indicates an excellent fit to a lognormal distribution.

The slope and intercept of the regression line are used as estimates of the parameters of a lognormal distribution. The characteristics of this lognormal distribution are shown in Table A-1. The estimate of the 95th percentile is slightly lower than the value obtained by NIOSH.

Table A-1. Lognormal Distribution Parameters for Uranium Dust Estimated using ROS Method

Parameter	Result
Intercept (μ)	-0.4552
Slope (σ)	1.4921
R^2	0.8781
Geometric mean (dpm/m^3)	0.6343
GSD	4.4463
95th %ile (dpm/m^3)	7.3834

A.2 Regression Analysis of Plutonium Data

Figure A-2 shows a plot of the plutonium sampling data. The value of $R^2 = .8766$ indicates a good fit to the regression line for the lognormal distribution. (The figure omits four nondetect data points included in the distribution.) The characteristics of this distribution are shown in Table 2.

Table A-2.
Lognormal Distribution Parameters for Plutonium Dust Estimated using ROS Method

Parameter	Result
Intercept (μ)	-3.6066
Slope (σ)	2.2846
R^2	0.8766
Geometric mean (dpm/m^3)	0.0271
GSD	9.8213
95th %ile (dpm/m^3)	1.1635

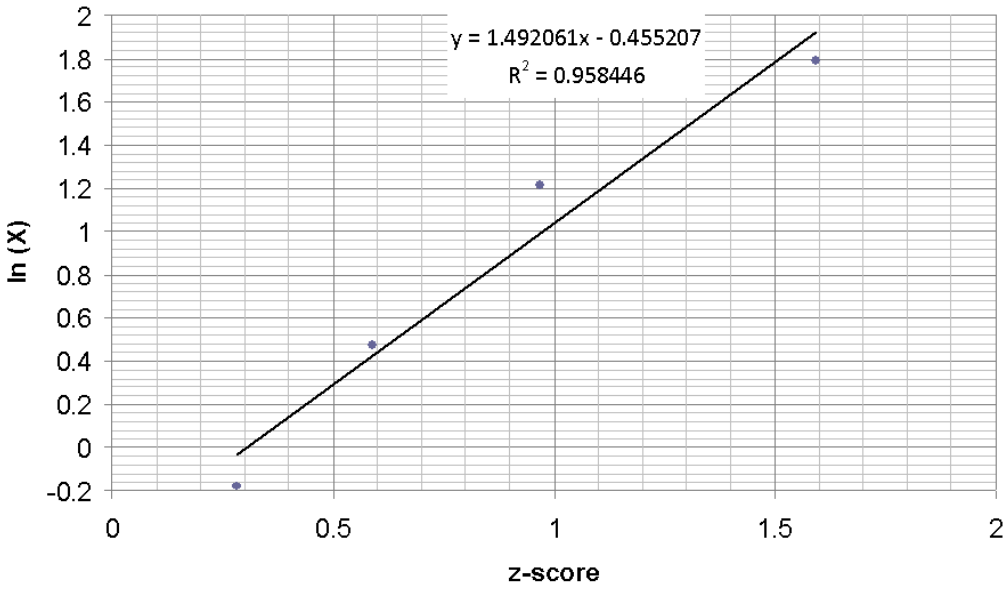

Figure A-1. Lognormal Distribution of Uranium Data, Using Regression on Order Statistics (ROS)

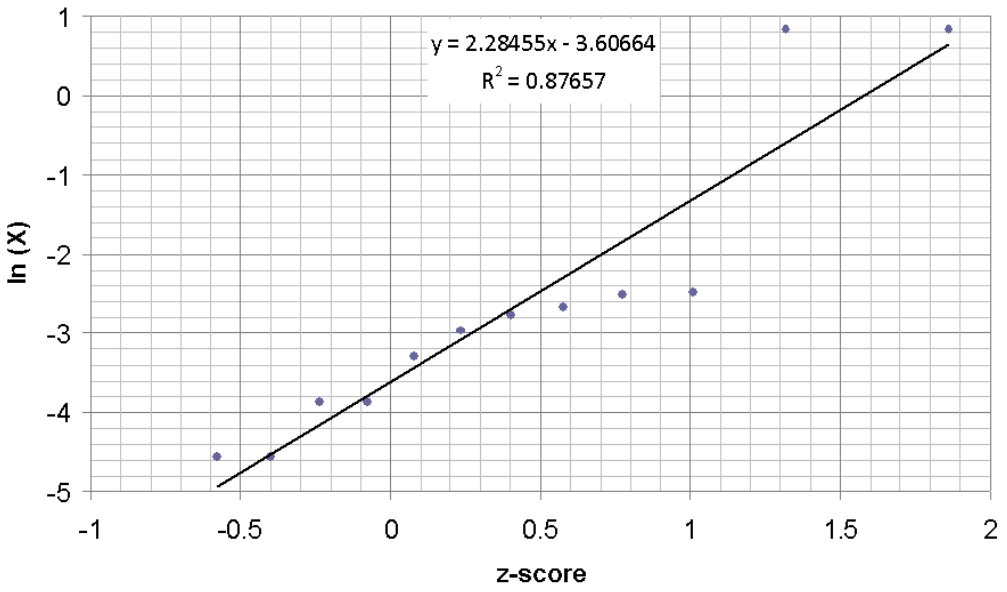

Figure A-2. Lognormal Distribution of Plutonium Data, Using Regression on Order Statistics (ROS)

Appendix B
Review of MCNP Analyses

We have reviewed the MCNP6 analyses in Attachment 1 to "DR Methodology" (incorrectly described as MCNPX in the heading of the attachment) and the MCNP6 input and output files that were furnished by DCAS. We have several issues with these analyses.

Our first issue is the distance from the source to the operator. As stated previously in section 5.1.2 of the present review, TIB-0010 specifies a distance of 12 in (30.48 cm) from the source to the receptor, not 35 cm as used in the MCNP "DR Methodology" analysis. Next, the analysis calculated the average dose over a rectangular cell 8 × 8 × 2 cm in depth, the center of which was approximately 5 cm above the center of the fuel pellet. This is not an appropriate geometry for estimating the dose to the operator, which should be determined at the surface of the body at a point opposite the source. As stated earlier, the analysis employed an MCNP model that was developed for TIB-0010, Rev. 3, and was discarded in the final version.

Our next issue is the isotopic composition of the fuel pellets. As previously stated in this review, the isotopic ratios listed in Table 1 for plutonium from Hanford represent a valid and claimant favorable composition. There is no information on the age of the fuel when it was supplied to Carborundum. Since the plutonium was first supplied in 1961 and since the plutonium operations continued through 1967, a reasonable and claimant-favorable assumption is that the fuel was, on average, about 5 years old. Therefore at least 5 years of ingrowth of ^{241}Am should be assumed, rather than 1 year as was used in the NIOSH analysis. Since ^{241}Am is a far stronger γ emitter than the plutonium isotopes, such additional ingrowth makes a strong contribution to the external dose. We also disagree with the isotopic composition of the uranium component of the fuel pellet which is assumed to consist of depleted uranium (DU) with a 0.37% ^{235}U content. Various reports indicated that the fuel pellets were made from DU, but also from natural uranium and enriched uranium (EU). Rose (1962) refers to DU as well as 10% EU being on hand at Carborundum. Strasser and Taylor (1962a) report tests using 24% EU. In an interview with ORAU Team staff, [redacted], a former Carborundum employee, reported using both DU and EU to make fuel elements. In the interest of a bounding analysis, a 24% enrichment should be utilized to calculate the isotopic composition of uranium, bearing in mind that the ^{234}U activity increases much more than that of ^{235}U.

A final issue is the design of the glovebox. Saulino et al. (1962) state that the glove boxes had "full-side safety plate glass windows." A poorly reproduced photograph appears to show that the gloveboxes had vertical glass fronts. A current online vendor of laminated safety glass states that the default thickness is ¼ inch. Therefore, it would be more appropriate to model the glovebox as having a vertical, ¼-inch glass window. Since glass is approximately twice as dense as the acrylic window in the NIOSH glovebox model and has a higher effective atomic number, such a window would have a lower transmission of the low-energy γ rays emitted by the plutonium isotopes and by ^{241}Am. This would be slightly offset by the vertical orientation, which would present a slightly shorter transmission path to radiation coming off in a horizontal direction than the sloping front in the NIOSH model.

B.1 Independent MCNPX Analyses

In order to verify the photon and neutron doses from plutonium reactor fuel listed in "DR Methodology," we performed independent MCNPX analyses. Our source was a pellet of $(U_{0.8}Pu_{0.2})C_{0.95}$ in the form of a right circular cylinder 0.508 cm high with a radius of 0.273 cm. The pellet has a density of 11.13 g/cm^3, which is the average of nine densities listed by Strasser and Stahl (1965). It was composed of carbon, 24% enriched uranium, and plutonium from Hanford with the initial isotopic composition listed in Table 1 of this review which was aged 5 years. The exact atom fractions are listed in Table B-1.

Table B-1. Composition of (U,Pu)C Fuel Pellet

Nuclide or element	Atom fraction
Carbon	0.4421
U-234	0.0007
U-235	0.0902
U-238	0.2814
Pu-239	0.0845
Pu-240	0.0073
Pu-241	0.0009
Pu-242	0.0001
Am-242	0.0928

The glovebox had five sides of 0.635-cm-thick (0.25 in) Type 304 stainless steel. The front window, which was in the vertical plane, consisted of two sheets of 0.318-cm plate glass, with a 0.051 cm layer of polyvinyl butyral sandwiched in between. The source term for the photon analyses was based on the γ-ray and x-ray spectra of the listed radionuclides taken from the Evaluated Nuclear Structure Data Files as listed by LANL (2012), multiplying the intensity of each radiation by the fractional activity of the given radionuclide in the fuel pellet. We used the computer code Sources 4C (LANL 2002) to generate the neutron spectrum. To account for backscattering of the emitted radiation, we placed the glovebox in a stylized concrete cylindrical structure, 10 m in diameter and 3 m high, with 1-ft-thick walls, floor, and ceiling.

The photon and neutron doses were reported as ambient dose equivalents. The results of the MCNPX analyses were scaled up to account for the maximum of 100 g of elemental plutonium being in the glovebox at any one time. The results of the analysis are shown in Table B-2, below. The dose rates are reported in terms of ambient dose equivalents, H*(10), in units of mrem/h. The NIOSH doses are totals for all energies and were taken directly from the output of the MCNP6 analyses, scaling the results to a batch of pellets with a total mass of 500 g.

The results show that the SC&A photon doses at the operator's location are about 50% higher than the NIOSH doses, which is due primarily to the differences in the source term as well as the closer location. These factors are offset by the greater attenuation of the glass window. The SC&A neutron doses are lower, presumably due to the greater attenuation and scatter by the

glass window. NIOSH should consider repeating the analyses, using a revised model of the glovebox and a revised source term.

Table B-2.
Ambient Dose Equivalent, H*(10), Rates from External Exposure to (U,Pu)C Pellets (mrem/h)

SC&A			NIOSH		
Distance	Photons	Neutrons	Distance	Photons	Neutrons
1 ft	6.318	0.202	35 cm	4.244	0.282
1 m	0.624	0.026	1 m	0.500	0.035

Appendix C
Interviews with Former Carborundum Workers

C.1 [redacted]

[redacted] had been interviewed by ORAU Team members Karin Jessen and Ed Scalsky on February 16, 2015. Robert Anigstein, SC&A Task Manger for Carborundum, contacted Mr. [redacted] by email to arrange a follow-up interview. The interview was held by telephone on January 11, 2016, at approximately 9:45 AM.

Mr. [redacted] was asked if he had information about an XRD unit that was used at Carborundum. He said he knew that there was such a unit, but that it was on another floor than where he worked and he knew nothing about it. He suggested that another worker, [redacted], whom he had also mentioned during his ORAUT interview, worked on that floor and may be familiar with the XRD work.

Mr. [redacted] was asked if he knew anything about a thickness gauge that contained a ^{90}Sr source that was used to control the thickness of sandpaper produced at Carborundum. He said he never heard of that device. We next discussed his work in the production of nuclear reactor fuel. The SC&A interviewer was particularly interested in his mention of work with thorium oxide and thorium carbide during his ORAUT interview. Mr. [redacted] confirmed that he worked with thorium and was told at that time that the material was not radioactive, which he now knows was not correct. Thorium was provided as a powder; it was used in an open laboratory with no special ventilation. In response to a question about spills, he said they it was likely that they occurred. The time of this work was in the late 1950s, which would possibly place it prior to the second operational period. He worked under a [redacted] as well as [redacted].

Mr. [redacted] confirmed that he had worked with both enriched and depleted uranium. He also worked with uranium nitrides. He said that not much enriched uranium was used, due to criticality concerns.

A copy of the above interview report was sent to Mr. [redacted] by email on January 12. In a follow-up phone call on January 19, 2016, at 5 PM, Mr. [redacted] confirmed the accuracy of the report. In a further discussion of the use of thorium at Carborundum, he very firmly stated that it was "way before" the other nuclear fuel work—could have been anytime in the 1950s. He recalled the thorium oxide, which he called a "mock-up," being placed in a "protective cocoon" of boron carbide. He thought thorium might have been used for practice—a beginning step prior to working with (known) radioactive material.

C.1.1 Interviewer's Comments

Mr. [redacted]'s report of thorium is not documented in any of the reports from Carborundum that were examined as part of this review, nor was thorium mentioned in the ER. However, his report seems quite credible and consistent with the earlier ORAUT interview. NIOSH needs to investigate this as a possible source of radiation exposure and contamination. Thorium had been

studied as a possible reactor fuel in the early days of the atomic era. Given Mr. [redacted]'s statement that he did not know at the time that thorium was radioactive, it is plausible that Carborundum considered it to be a safe practice material.

C.2 [redacted]

Mr. [redacted] had mentioned [redacted] during his ORAUT interview and had provided his phone number. Robert Anigstein, SC&A Task Manger for Carborundum, contacted Mr. [redacted] by telephone at approximately 10:30 AM on January 11, 2016.[13] Mr. [redacted] was primarily asked [redacted]. In response to a question about the XRD unit, he stated that it employed a copper-target x-ray tube. In response to a further question, he said he had no knowledge of a molybdenum-target tube at Carborundum. In a written response to a transcript of the interview, he added: I seem to remember 1.54 Å, which is Cu. His work with XRD was occasional—he primarily worked [redacted] in the adjacent room. He knows the spectroscopy employed optical methods, referred to as u.v. [ultraviolet] spectroscopy, and did not use an x-ray source. When asked about the manufacturer of the XRD unit, he asked me to suggest some names. He said it wasn't a GE (General Electric) but might have been made by Norelco. He also mentioned Philips and Siemens as possible manufacturers. When I asked about the operating voltage of the x-ray tube, he couldn't recall it, but when I suggest 50 kV (as reported by Lubenau [1969]) he said that sounded familiar.

Mr. [redacted] believed quite firmly that the XRD unit was safe and knew of no incidents of accidental exposures. No one that he knew of had suffered skin burns. He appears to have been very safety conscious, was well aware of the hazards of operating the x-ray tube with an open port, but said there was no mechanical arrangements that would make such operation impossible. Signs in the x-ray room alerted visitors of x-ray equipment in operation. He thinks he wore a film badge some of the time but did not remember the exact circumstances. He did say someone from the company performed occasional x-ray surveys for stray radiation of the unit. All in all, he believed that he had worked in a safe environment.

C.2.1 Interviewer's Comments

Mr. [redacted]'s interview does not support this reviewer's conjecture that Carborundum could have employed a molybdenum target tube. However, given his limited duties with XRD, such a possibility is not ruled out.

[13] A draft of the following account of the interview was mailed to Mr. [redacted] on January 13, with a letter requesting comments. The final account incorporates his written corrections and additions, which were received by mail on January 25, 2016.

REFERENCES

Allen, D. 2011. "Site Profile for Atomic Weapons Employers that Worked Uranium Metals," Battelle-TBD-6000 Rev. 1. http://www.cdc.gov/niosh/ocas/awedocs.html#b6000

Allen, D. 2014a. "Program Evaluation Report," DCAS-PER-054, Revision No. 0. http://www.cdc.gov/niosh/ocas/pdfs/pers/dc-per54-r0.pdf

Allen, D. 2014b. "Site Profiles for Atomic Weapons Employers that Worked Uranium Metals: Appendix BB – General Steel Industries," Battelle-TBD-6000, Appendix BB, Revision No. 1. http://www.cdc.gov/niosh/ocas/pdfs/tbd/b-6000-apbb-r1.pdf

Atomic Energy Commission (U.S.) (AEC). 1957. "Title 10—Atomic Energy; Chapter 1—Atomic Energy Commission: Part 20—Standards for Protection Against Radiation. *Federal Register, 22*(19), 548–554.

Atomic Energy Commission (U.S.) (AEC). 1960. "Title 10—Atomic Energy; Chapter 1—Atomic Energy Commission: Part 20—Standards for Protection Against Radiation. *Federal Register, 25*(224), 10914–10924.

Atomic Energy Commission (U.S.) (AEC). 1964. "Byproduct Material License, Licensee: Industrial Nucleonics Corporation, License Number: GL 136 (D65)." FOIA request via NRC Public Document Room: 8304010153 830131, PDR FOIA, STEPHAN82-619 PDR.

Atomic Energy Commission (U.S.) (AEC). 1965. "Atomic Energy Act of 1946 (Public Law 585, 79th Congress)." https://www.osti.gov/atomicenergyact.pdf

Audi, G., A. H. Wapstra, and C. Thibault. 2003. "The 2003 NUBASE and Atomic Mass Evaluations, The Ame2003 atomic mass evaluation: (II). Tables, graphs and references." *Nuclear Physics A, 729*(1)337–676.

Brackett, E. M. 2005. "Analysis of Coworker Bioassay Data for Internal Dose Assignment," ORAUT-OTIB-0019, Revision No. 1. http://www.cdc.gov/niosh/ocas/pdfs/tibs/or-t19-r1.pdf

Code of Federal Regulations, *Title 10, Energy*, Part 30, "Rules of General Applicability to Domestic Licensing of Byproduct Material" (10 CFR 30) http://www.nrc.gov/reading-rm/doc-collections/cfr/part030/full-text.html

Division of Compensation Analysis and Support (DCAS). 2010. "Best Estimate External Dose Reconstruction for Glovebox Workers," DCAS-TIB-0010, Rev. 3. http://www.cdc.gov/niosh/ocas/pdfs/arch/tibs/dc-t10-r3.pdf

Division of Compensation Analysis and Support (DCAS). 2011. "Best Estimate External Dose Reconstruction for Glovebox Workers," DCAS-TIB-0010, Rev. 4. http://www.cdc.gov/niosh/ocas/pdfs/tibs/dc-t10-r4.pdf

Eckerman, K. F., et al. 2006. "User's Guide to the DCAL System," ORNL/TM-2001/190. http://ordose.ornl.gov/documents/dcalman.pdf

Eckerman, K. F., and J. C. Ryman. 1993. "External Exposure to Radionuclides in Air, Water, and Soil," Federal Guidance Report No. 12, EPA 402-R-93-081. Washington, DC: U.S. Environmental Protection Agency, Office of Radiation and Indoor Air.

Els, R. A. "The Response of Various Survey Instruments to Low Energy X Rays." *In* Moore, T. M, W. E. Gundaker, and J. W. Thomas, Eds. 1971. "Radiation Safety in X-Ray Diffraction and Spectroscopy," DHEW Publication No. (FDA) 72-8009, BRH/DEP 72-3. Proceedings of a Conference held on January 6-7, 1970, at the University of Pennsylvania, Philadelphia, Pennsylvania. U.S. Department of Health, Education, and Welfare, Public Health Service, Food and Drug Administration, Bureau of Radiological Health, Rockville, Maryland 20852. SRDB Reference ID: 32635.

Freeman, W. M. 1952. "New Way Devised to Make Abrasives: Carborundum's Process Joins Use of Beta Rays with Fully Automatic Controls." *New York Times*, June 8. http://query.nytimes.com/mem/archive/pdf?res=9B0DE4D6103CE53ABC4053DFB0668389649EDE

Guido, J., et al. 2007. "SEC Petition Evaluation Report Addendum: Sandia National Laboratories – Livermore, Petition SEC-00059-Addendum." http://www.cdc.gov/niosh/ocas/pdfs/sec/sandiaca/snleradd.pdf

Harris, W. B., and I. Kingsley. 1959. "The Industrial Hygiene of Uranium Fabrication," *A.M.A. Archives of Industrial Health, 19*, 540–565.

Health and Safety Laboratory, U.S. Atomic Energy Commission (HASL). n/d. "Sample Results, 1947-1961, Radiological Sample Result of Different Types, 1947 through 1961." SRDB Ref ID: 11452.

Howard, J. 2015. "Decision to Evaluate a Petition to Designate a Class of Employees from the Carborundum Company in Niagara Falls, New York, to be Included in the Special Exposure Cohort." *Federal Register*, *80*(28), 7605. http://www.cdc.gov/niosh/ocas/pdfs/sec/carbco/fr021115-223.pdf

Hubbell, J. H. and Seltzer, S. M. 2004. "Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients," Version 1.4. http://physics.nist.gov/PhysRefData/XrayMassCoef/ElemTab/z92.html

International Commission on Radiological Protection (ICRP). 1977. "Recommendations of the International Commission on Radiological Protection," ICRP Publication 26, *Annals of the ICRP 1*(3). Oxford: Pergamon Press.

International Commission on Radiological Protection (ICRP). 1991. "1990 Recommendations of the ICRP," ICRP Publication 60. *Annals of the ICRP, 21*(1-3). Oxford: Pergamon Press.

International Commission on Radiological Protection (ICRP). 1994. "Dose Coefficients for Intakes of Radionuclides by Workers," ICRP Publication 68. *Annals of the ICRP, 24*(4). Tarrytown, NY: Elsevier Science, Inc.

International Commission on Radiological Protection (ICRP). 2001. The ICRP Database of Dose Coefficients: Workers and Members of the Public, Version: 2.0.1. [Computer software]. Pergamon.

Jessen, K., and E. Scalsky. 2015. "SEC Petition Evaluation Report: Petition SEC-00223 Report," Rev #: 1. http://www.cdc.gov/niosh/ocas/pdfs/sec/carbco/carbcoer-223-r1.pdf

[redacted] and [redacted]. 2014. "Special Exposure Cohort Petition." DSA Reference ID: 120430.

Los Alamos National Laboratory (LANL). 2012. "ENDF/B-VII.1 Decay Data." http://t2.lanl.gov/nis/data/endf/decayVII.1.html

Los Alamos National Laboratory (LANL) and Texas A&M University. 2002. SOURCES-4C: Code System For Calculating alpha,n; Spontaneous Fission; and Delayed Neutron Sources and Spectra, RSICC Code Package CCC-661. Oak Ridge, Tennessee: Oak Ridge National Laboratory.

Lubenau, J. 0., J. S. Davis, D. J. McDonald, and T. M. Gerusky. 1969. "Analytical X-Ray Hazards: a Continuing Problem." *Health Physics 16,* 739–746. SRDB Reference ID: 142196.

Lubenau, J. 0. 2015. "Re: Radiation exposures from x-ray diffraction" November 11, 2015, personal email to Robert Anigstein, SC&A, Inc.

Moore, T. M, W. E. Gundaker, and J. W. Thomas, Eds. 1971. "Radiation Safety in X-Ray Diffraction and Spectroscopy," DHEW Publication No. (FDA) 72-8009, BRH/DEP 72-3. Proceedings of a Conference held on January 6-7, 1970, at the University of Pennsylvania, Philadelphia, Pennsylvania. U.S. Department of Health, Education, and Welfare, Public Health Service, Food and Drug Administration, Bureau of Radiological Health, Rockville, Maryland 20852. SRDB Reference ID: 32635.

Nuclear Regulatory Commission (U.S.) (NRC). 2015. "General Provisions: § 30.1 Scope." http://www.nrc.gov/reading-rm/doc-collections/cfr/part030/part030-0001.html

Office of Compensation Analysis and Support (OCAS). 2007. "External Dose Reconstruction Implementation Guideline," OCAS-IG-001, Revision No. 3. www.cdc.gov/niosh/ocas/pdfs/dr/oc-ig-001-r3.pdf

ORAU Team Dose Reconstruction Project for NIOSH (ORAUT). 2015a. "Carborundum Company Interview: [redacted]; February 16, 2015; 10:00 AM (EST)." SRDB Reference ID: 142193.

ORAU Team Dose Reconstruction Project for NIOSH (ORAUT). 2015b. "Carborundum Company Interview: [redacted]; February 13, 2015; 11:00 AM (EST)." SRDB Ref ID: 142192.

Oak Ridge National Laboratory (ORNL), Life Science Division, Dosimetry Research Group. 2006. DCAL: Dose and Risk Calculation System, Version 8.4. [Computer software and manual]. http://ordose.ornl.gov/resources/DCAL01_setup.exe

Rose, C. G. 1962. "Close-out of Contract AT(40-1)-2558: Source and Special Nuclear Materials." Letter to U.S. Atomic Energy Commission, September 19. SRDB Ref ID: 46754.

S. Cohen & Associates (SC&A). 2006. "Board Procedures for Review of Special Exposure Cohort Petitions and Petition Evaluation Reports," Revision 1. SCA-TR-TASK5-0002.

Saulino, F. A., J. C. Andersen, and K. M. Taylor. 1962. "Research Facility for the Synthesis and Fabrication of Refractory Plutonium Materials." *10th Hot Lab Proceedings, ANS*, Nov. 277–286. SRDB Ref ID: 56948.

Sharfi, M. M. 2012. "Dose Reconstruction during Residual Radioactivity Periods at Atomic Weapons Employer Facilities," ORAUT-OTIB-0070, Rev. 01. http://www.cdc.gov/niosh/ocas/pdfs/tibs/or-t70-r1.pdf

Smith, M. E., M. W. Lisse, and W. P. Davey. 1936. "The Effect of Certain X-Rays on the Electrophoretic Mobility of Escherichia Coli." *Journal of Bacteriology, 31*(3), 275–286. http://jb.asm.org/content/31/3/275.full.pdf

Strasser, A., and D. Stahl. 1965. "Carbide Fuel Development: Final Report, Period of May 15, 1959 to October 15, 1965," UNC-5134, vol. 1. SRDB Ref ID: 53617.

Strasser, A., and K. Taylor. 1961. "Carbide Fuel Development: Progress Report, Period of February 1, 1961 to April 30, 1961." NDA 2162-3. SRDB Ref ID: 61981.

Strasser, A., and K. Taylor. 1962a. "Carbide Fuel Development: Progress Report, Period of September 15, 1961 to December 31, 1961." SRDB Ref ID: 61996.

Strasser, A., and K. Taylor. 1962b. "Carbide Fuel Development: Progress Report, Period of January 1, 1962 to March 31, 1962." UNC-5013. SRDB Ref ID: 61995.

Taylor, K. M. 1960. "Status of Carbide Fuel Development at the Carborundum Company." SRDB Ref ID: 46759

Tomes, T. 2015. "Carborundum Company: Special Exposure Cohort Petition Evaluation Report." http://www.cdc.gov/niosh/ocas/pdfs/abrwh/pres/2015/dc-carborundum-072315.pdf

Yakel, H. L. 1974. "A Review of X-ray Diffraction Studies in Uranium Alloys." Conference on Physical Metallurgy of Uranium Alloys, Vail, Colorado, February 12, 1974. http://www.osti.gov/scitech/servlets/purl/4306144