# Memorandum

To: Work Group on Carborundum Company
From: Robert Anigstein, SC&A, Inc.
Date: November 25, 2020
Subject: Review of "Site Profile for The Carborundum Company"

## Background

On April 23, 2020, the Oak Ridge Associated Universities Team (ORAUT) issued a site profile for the Carborundum Company (ORAUT, 2020). On May 26, 2020, Rashaun Roberts, Designated Federal Officer to the Advisory Board on Radiation and Worker Health (ABRWH), requested SC&A to review this document. In the present memo, we discuss the remaining issues that we found in the Carborundum site profile. Our review is centered on the proposed methodology for dose reconstruction (DR); we will not discuss details of the site history and process descriptions that do not materially impact DRs. We will follow the sequence of topics as they appear in the site profile.

## Occupational Medical Dose

### *First Operational Period, 1943*

The first operational period lasted from June 1 to September 27, 1943. ORAUT (2020) assumed that workers employed during this period received a single medical x ray. This appears, at first sight, to be inconsistent with ORAUT-OTIB-0006 (ORAUT, 2018) ("OTIB-0006"), which prescribes preemployment, annual, and termination x rays. However, we note that this operational period had a duration of less than 4 months. Most workers would have received at most a single x ray during this period. However, a worker who had been employed a year or more prior to the end of this period could have received an annual x ray during the time. If this worker were terminated prior to the end of the period, he could have received a second (termination) x ray. Consequently, SC&A recommends that the employment and termination dates of workers employed during this period be examined, and a second x-ray examination be assigned if it is plausible that the worker could have received two x rays during this period.

**Observation 1: Workers employed prior to the first operational period whose employment terminated during this period should be assigned two medical x rays if it is plausible that they could have undergone both an annual and a termination x ray during this period.**

### *Second Operational Period, 1959 to 1967*

Following the guidance of OTIB-0006, ORAUT (2020) assigned preemployment, annual, and termination chest x rays to workers during the second operational period.

## Occupational Internal Dose

### *First Operational Period, 1943*

ORAUT (2020) assigned intakes of uranium aerosols by inhalation and inadvertent ingestion during the first operational period to three categories of workers—operators, laborers, and supervisors—based on intakes by such workers in the machining scenario listed by Battelle-TBD-6000 (NIOSH, 2011) ("TBD-6000"), as previously agreed to by the ABRWH Work Group on Carborundum Company (WGCC) and SC&A.

### *First Residual Period, 1943 to 1958*

The inhaled intakes assigned to all workers during the first residual period were calculated according to the guidance in TBD-6000. ORAUT (2020) calculated a surficial activity concentration based on 30 d of settling of the airborne activity generated by the machining operation during the first operational period. This surficial activity was resuspended, assuming a resuspension factor of $10^{-5}$ $m^{-1}$. The inhaled intakes during the first year of the residual period were assigned to workers during this period, assuming the default breathing rate of 1.2 $m^3$/h and a 48-h workweek. ORAUT (2020, table 5-3) lists the intakes, in dpm per calendar day, starting at the beginning of the residual period, through 1992. During the first 30 y, ORAUT applied adjustment factors prescribed by ORAUT-OTIB-0070 (ORAUT, 2012) (+table"OTIB-0070") to account for source depletion during this period. The intakes during 1951–1955 were reduced to account for the shorter (44-h) workweek during this period, as assumed by TBD-6000. Beginning with 1956, the intakes were again reduced to account for a 40-h workweek. These intakes have been previously reviewed by SC&A (2016, section 5.2.1) and were found to be correctly calculated.

Intakes via the inadvertent ingestion pathway during the first year of the residual period were set equal to the intakes during the first operational period, which are based on the intakes of an operator in the machining scenario listed by TBD-6000. These intakes are listed as 403 pCi (895 dpm) per calendar-day for the pre-1951 time period. The intakes were calculated using the methodology described in OCAS-TIB-009 (NIOSH, 2004). ORAUT (2020, table 5-3) evaluated intakes during the remainder of the first residual period by applying adjustment factors prescribed by OTIB-0070 (ORAUT, 2012) to the intakes during the first year to account for source depletion during this period. They were further reduced to account for the changes in the assumed workweek during this period.

This procedure of calculating intakes from inadvertent ingestion was addressed by the ABRWH Subcommittee for Procedure Reviews (SCPR) during meetings held on November 1, 2012, and February 5, 2013. During these meetings, it was brought out that the National Institute for Occupational Safety and Health (NIOSH) had incorrectly assigned the ingestion rate during the residual periods at some sites by estimating it to be equal to 20 percent of the airborne activity from resuspension of the surficial contamination levels during the residual period. All parties involved—the SCPR, NIOSH, and SC&A—agreed that this was an underestimate. NIOSH proposed that the ingestion rate at the start of the residual period be set equal to that at the end of the operational period and then reduced by OTIB-0070 annual depletion factors. This methodology was accepted by SC&A and the SCPR, and the issue was closed. Consequently, the

procedure for calculating the ingestion rate during the first residual period at Carborundum is consistent with NIOSH policy.

### *Second Operational Period, 1959 to 1967*

Anigstein and Mauro (2017, p. 8) examined the inhaled intakes of an operator and a general laborer assigned by NIOSH during the second operational period and found that they were consistent with airborne activity measurements during this period and with the methodology prescribed by NIOSH for assigning inhaled intakes based on such measurements. SC&A pointed out a minor discrepancy in assigning intakes via inadvertent ingestion based on OCAS-TIB-009 (NIOSH, 2004) during this period—ORAUT (2020) has resolved this discrepancy. ORAUT (2020, tables 5-4 and 5-5) correctly lists the intakes of uranium (in 1959–1967) and of plutonium (in 1961–1967) by inhalation and ingestion, respectively, of workers in four labor categories: operator, laborer, supervisor, and clerk.

Workers known to have been assigned to the Globar Plant, a Carborundum facility not involved in Atomic Weapons Employer (AWE) work during the second operational period, are to be assigned radiation exposures that are specified for the first residual period. All other workers are assigned intakes of uranium during 1959–1960 (before there was any plutonium on site), and intakes of either plutonium or uranium during 1961–1967, whichever is more claimant favorable. The plutonium intakes would have the activity ratios of the isotopic constituents of the 5-y-old weapons-grade plutonium to total α activity of the mixtures that are listed by ORAUT (2020, table 5-8). These ratios are consistent with SC&A (2016, table 1).

### *Second Residual Period, 1968 to 1992*

ORAUT (2020) observed that workers in areas of the Carborundum site that had residual uranium contamination from the first operational period would experience higher uranium intakes during the second residual period than workers exposed to residual uranium contamination from the second operational period. (We confirmed that this was the case.) Workers would have been exposed to only one of these two sources because the area of the plant housing the uranium laboratory—the source of uranium contamination for the second residual period— was built after the end of the first operational period. Consequently, workers during the second residual period should be assigned uranium intakes based on the first residual period, for the appropriate years, or intakes of residual plutonium contamination for this period, whichever is more claimant favorable. We verified that ORAUT (2020, table 5-9) correctly listed the gross α intakes of the plutonium mixture shown in ORAUT (2020, table 5-8).

## Occupational External Dose

### *First Operational Period, 1943*

ORAUT (2020) estimated the external exposure of workers to uranium metal during the first operational period by assuming that the source term was 10 slugs that had been shipped to Carborundum in June 1943. As we stated in a previous review (Anigstein and Mauro, 2017, p. 2),

> NIOSH adopted a personal dose equivalent ($H_p[10]$) rate of 0.524 mrem/h to an operator, which is 10 times the dose rate from a single slug at a distance of 1 ft

> (30.48 cm) that was listed in TBD-6000 ([NIOSH,] 2011, table 6.1). NIOSH assigned this dose during the 119 days of the first AWE period—June 1 through September 27, 1943—assuming a [48-h workweek]. . . .
>
> This source term was approved at the March 13, 2017, meeting of the Work Group on Carborundum Company, who voted to close the issue.

ORAUT (2020) correctly listed the external penetrating doses to an operator, a laborer, and a supervisor and clerk. ORAUT (2020, p. 34) further specified that the doses should be applied using "*deep* dose equivalent ($H_p(10)$) to organ dose equivalent (HT) dose conversion factor (DCF) values in accordance with OCAS-IG-001" [emphasis added]. To avoid ambiguity, we recommend that ORAUT replace "deep dose equivalent" with "personal dose equivalent," which appears in the tables listing DCFs for photon exposures in OCAS-IG-001 (NIOSH, 2007). (This is an editorial comment which does not reflect a shortcoming in the ORAUT report.)

ORAUT (2020) followed the guidance of TBD-6000 (p. 36) in estimating the external nonpenetrating (beta) dose to the skin of an operator at a distance of 1 ft (30.48 cm) from the uranium metal slug as 10 times the penetrating (photon) dose, obtaining a dose rate of 0.524 mrad/h from a single slug. SC&A (2018) performed an independent analysis using MCNPX and derived a dose rate of 0.54 mrad/h from the same slug, a difference of 3 percent. Given the good agreement between the two results, we conclude that the ORAUT value is acceptable. ORAUT assigned 50 percent of this value to a laborer and 10 percent of the laborer's dose rate to a supervisor, as recommended by TBD-6000. Given the uncertainty of job assignments of Carborundum workers, ORAUT assigned the supervisor's beta dose to other workers, such as clerical personnel.

According to TBD-6000 (p. 36), the beta dose estimates discussed above are "for dose to other skin on the worker's body that is not in direct contact with uranium metal, but is nearby (for example, a worker's neck and face when the hands are in contact with metal)." ORAUT (2020) neglected to specify a beta dose to the skin of the hands and forearms that is presumed to be in direct contact with the uranium metal.

**Observation 2: ORAUT should specify doses to the skin of the hands and forearms from direct contact with uranium metal slugs.**

We make this an observation rather than a finding, since it addresses an oversight rather than an error on the part of ORAUT.

Addressing additional sources of external exposure, ORAUT (2020) assigned external exposures from penetrating and nonpenetrating radiation from a contaminated floor and from submersion in airborne contamination. The airborne activity concentration of 5,480 dpm/$m^3$ listed in TBD-6000 (table 7.5) for the exposure of an operator in the uranium machining scenario was combined with the external dose conversion factor listed by TBD-6000 (table 3.9) to derive an external exposure rate for submersion in a cloud of uranium aerosols. The external exposures from a contaminated floor were calculated by applying external dose conversion factor listed by TBD-6000 (table 3.10) to the surficial activity concentration based on 30 d of settling of the airborne

activity generated by the machining operation. We verified that these results were accurate and correctly applied.

### *First Residual Period, 1943 to 1958*

The initial penetrating and nonpenetrating external exposure rates during the first residual period from exposure to a contaminated floor were set equal to those during the first operational period. These exposure rates were reduced during subsequent years by applying adjustment factors prescribed by OTIB-0070 to account for source depletion during this period. The rates during 1951–1955 were reduced to account for the shorter (44-h) workweek during this period, as assumed by TBD-6000. Beginning with 1956, the intakes were again reduced to account for a 40-h workweek. These results were confirmed by SC&A.

### *Second Operational Period, 1959 to 1967*

There were three sources of external exposure during the second operational period: uranium metal, an x-ray diffraction apparatus, and fuel pellets made from a mixed uranium-plutonium carbide (1961–1967 only). Since these sources were located in different areas of the Carborundum plant, a worker could have been exposed to only one of the first two sources during 1959–1960, before there was any plutonium on site, and to any one of the three sources during 1961–1967. ORAUT (2020) directs that the most claimant-favorable source is to be used for the appropriate time period. These three sources are discussed in the following sections of the present memo.

### *Uranium Metal (Second Operational Period)*

ORAUT (2020, attachment A) summarized radiological contract work at Carborundum during the second operational period. The largest batch of uranium metal cited in the table is in a request for 10 lb (4.5 kg) of uranium shot. ORAUT (2020) modeled the source of external exposure as a flat metal plate, one of the shapes for which dose rates are listed by TBD-6000 (table 6.1). The plate has a mass of 3.1 kg (6.9 lb), calculated from the dimensions provided by Anderson and Hertel (2005). This shape has the highest ratio of external dose rate to mass of any of the shapes in TBD-6000 (table 6.1). The mass is consistent with the largest batches cited by ORAUT (2020, Attachment A) as processed during this period, “30 g to 6 lb [2.7 kg],” and only somewhat smaller than the 10 lb of shot, the largest amount that had been requested. The dose rate from the plate is bounding for the present scenario. ORAUT correctly calculated the external penetrating doses from such a source to an operator, a laborer, and a supervisor and clerk, based on the dose rates listed by TBD-6000 (table 6.1) and following the guidance in that document. The nonpenetrating (beta) doses are based on an MCNP analysis (SC&A, 2018) and correctly apportioned to the three categories of workers according to the guidance of TBD-6000 (section 6.3).

As was the case for exposure to uranium metal during the first operational period, ORAUT failed to assign doses to the hands and forearms from direct contact with the uranium metal.

**Observation 3: ORAUT should specify doses to the skin of the hands and forearms from direct contact with a flat uranium plate.**

We make this an observation rather than a finding, since it addresses an oversight rather than an error on the part of ORAUT.

To assess additional sources of external exposure, ORAUT (2020) calculated the exposure from submersion in airborne contamination and exposure to a contaminated floor. ORAUT cited an airborne activity concentration of 14.77 dpm/$m^3$. This is twice the 95th percentile concentration of 7.38 dpm/$m^3$ derived from the uranium air samples collected in 1959 and 1961. These were identified as general air samples; they were used by ORAUT to derive the inhaled intake of a laborer. Since the operator's breathing zone air concentration was presumed to be higher, the operator was correctly assigned twice the intake of a laborer. However, the surficial activity concentration of the contaminated floor is the result of deposition of the airborne activity over a wide area, which is derived from the general air samples. SC&A derived a surficial activity concentration of $1.44 \times 10^4$ dpm/$m^2$, based on 30 d of settling of the 95th percentile airborne activity. ORAUT (2020, p. 37) lists a concentration of $2.87 \times 10^4$ dpm/$m^2$, which is based on the airborne activity of 14.77 dpm/$m^3$ cited above.

**Observation 4: ORAUT doubled the airborne activity concentration derived from air sampling data in deriving the surficial activity concentrations used to calculate exposure rates and dose rates from beta radiation. Although this difference leads to a trivial change in doses in the present case, it should be corrected in the interest of accuracy and to not set a precedent for other sites.**

We make this an observation instead of a finding because of the minimal impact on DRs.

### *Plutonium-Uranium Carbide Fuel Pellets (Second Operational Period)*

ORAUT (2020) modeled the external exposure to plutonium-uranium carbide fuel pellets during the second operational period, using MCNP 6.2. The source was a single cylindrical pellet, 0.51 cm in diameter and 0.51 cm high. The elemental composition was specified by the empirical formula $(U_{0.8}Pu_{0.2})C$ with a small admixture (0.003 percent) of americium. This is a deviation from the empirical formula $(U_{0.8}Pu_{0.2})C_{0.95}$ in a progress report on the same project (Strasser and Taylor, 1962) that was cited by SC&A (2016, p. 17).

**Observation 5: ORAUT should use the correct empirical formula, $(U_{0.8}Pu_{0.2})C_{0.95}$, as cited in the carbide fuel development progress reports for Carborundum.**

Anigstein (2018) performed an audit of a previous analysis reported by NIOSH (2018), which produced three findings. One dealt with the ambient dose equivalent (H*[10]) fluence to dose conversion coefficients for photons. NIOSH (2019) produced new data to support their method of calculating these coefficients; however, ORAUT (2019), which contains the MCNP input and output files from the current analysis, corrected two of the values that were in error. The second finding was the use of source biasing that was incorrectly implemented in MCNP 6.1, the version of the code NIOSH (2018) had used in its analysis. NIOSH (2019) resolved this finding by reporting the use of the current version, MCNP 6.2, in the ORAUT (2019) analysis.

The third finding was that the source and simulated dosimeter geometry implemented in the MCNP analysis resulted in the shielding of portions of the dosimeter by the floor of the glovebox containing the source. In its response, NIOSH (2019) concurred with the solution recommended

by SC&A and agreed to position both the pellet and the dosimeters at an elevation of 24 cm above the floor of the glovebox. ORAUT (2019) includes a file named "GB_CRBRNDM.AM.Ph.tmplt_.i." As the name implies, this file appears to serve as a template for the exposure geometry for the MCNP input files for photon doses. The file places the bottom of the pellet at a height of 24.3175 cm above the floor of the glovebox, resulting in the center of the pellet being ~24.57 cm above the floor, slightly different from the 24-cm height described by ORAUT (2020). However, the two simulated dosimeters are both centered at a height of 20 cm above the floor, or 4.57 cm below the center of the source. All of the MCNP input files for the simulation of doses from photon-emitting radionuclides that we examined use this same geometry. The MCNP input file for the neutron analysis places the dosimeters in the same position as in the photon files but places the center of the source ~20.57 cm above the floor, which is close to being aligned with the dosimeters. However, the geometry differs from the description by ORAUT (2020) and is different from that used in the photon analysis.

**Finding 1: The two simulated dosimeters in the MCNP input files for the photon dose simulations are centered at an elevation of 20 cm above the floor of the glovebox, which does not agree with the description by ORAUT (2020) and places them 4.57 cm below the center of the source. Furthermore, the geometry in the neutron dose analysis is different than that in the photon dose simulations, although both analyses are of the same exposure scenario.**

The neutron source term, part of the input to the ORAUT (2019) MCNP analysis, was calculated with the computer code Sources 4C (LANL, 2002). However, we note errors in the discussion of this analysis by ORAUT (2020, p. 39), which refers to the calculation of neutron spectra in 760 groups, with a maximum energy of 4.49 MeV. In fact, the calculation utilized 749 energy groups (the maximum permitted by the code), with a maximum energy of 7.49 MeV. These are editorial errors that should be corrected; however, they do not affect the reported results.

Another discrepancy in the ORAUT (2019) neutron MCNP analysis is the isotopic composition of the fuel pellet. The composition was correctly specified in the input to Sources 4C, except for the difference in the carbon constituent that is due to the use of the empirical formula $(U_{0.8}Pu_{0.2})C$ instead of the formula $(U_{0.8}Pu_{0.2})C_{0.95}$ reported by Strasser and Taylor (1962). This resulted in an approximately 5 percent increase in the carbon constituent, but only a 2.6 percent increase in the concentration of $^{13}C$ in the input file, compared to the input file prepared by SC&A for our analysis of this problem. The discrepancy may be due to the use by ORAUT of a different isotopic abundance of $^{13}C$. SC&A used an abundance of 0.0106, the middle of the natural abundance range cited by Meija et al. (2016). Carbon-13 is the only target nuclide for the generation of neutrons by the (α,n) reaction used in both the ORAUT and SC&A analyses. This elevated concentration leads to an increase in the (α,n) neutron flux. However, since this reaction accounts for only ~30 percent of the total neutron flux from the fuel pellet, the net effect is an increase of ~0.8 percent in the flux.

**Observation 6: ORAUT should use the most current value of the natural isotopic abundance of C-13 in calculating the neutron flux from the fuel pellet.**

A different nuclide mix was used to specify the material composition of the fuel pellet in the MCNP input files. The mass fractions of the plutonium isotopes (including $^{241}Am$, which is the

decay product of $^{241}$Pu), and of the uranium isotopes, are listed in tables 1 and 2, respectively. The sum of the mass fractions >100 percent due to the inclusion of $^{241}$Am.

*Table 1. Mass fractions of plutonium and americium isotopes, relative to total plutonium*

| Nuclide | Sources 4C[a] | MCNP[b] |
|---|---|---|
| Pu-239 | 91.0% | 93.52% |
| Pu-240 | 7.9% | 5.90% |
| Pu-241 | 0.9% | 0.57% |
| Pu-242 | 0.1% | — |
| Am-241 | 0.3% | 0.03% |
| Total | 100.3% | 100.03% |

[a] Derived from input to Sources 4C (LANL, 2002)
[b] Derived from MCNP input files

As shown in table 1, the isotopic mass fractions of plutonium and americium derived from the Sources 4C input file, which is listed at the end of the MCNP input file "GB_CRBRNDM.AM.Ns.Carbide.R004.i" and is used for the neutron dose simulation, are similar to those listed by ORAUT (2020, table 6-6). The differences between the two sets of values are due to the fact that ORAUT lists the composition of fresh fuel produced by the Hanford Atomic Products Operations, while table 1 reflects the composition of fuel that has aged for 5 y. As shown in the table, the mass fractions are different in the two input files that are intended to represent the same material.

*Table 2. Mass fractions of uranium isotopes, relative to total uranium*

| Nuclide | Sources 4C[a] | MCNP[b] |
|---|---|---|
| U-234 | 0.132% | 0.000% |
| U-235 | 24.000% | 0.371% |
| U-238 | 75.868% | 99.629% |
| Total | 100.000% | 100.000% |

[a] Derived from input to Sources 4C (LANL, 2002)
[b] Derived from MCNP input files

Table 2 shows the relative mass fractions of the uranium isotopes in the same input files discussed in connection with table 1. Here, the differences are significant. The material used to generate the neutron spectrum included 24 percent enriched uranium: the isotopic composition is identical to that in ORAUT (2020, table 6-7). However, the material in the MCNP analysis contains 0.37 percent $^{235}$U, about one-half its abundance in natural uranium.

Since the elemental compositions of the two data sets are the same (except for the fraction of americium), the disparity in the isotope mix has little effect on the MCNP photon dose analysis, since the cross-sections for photons and electrons used by the MCNP code depend only on the elemental composition. That is not the case for the interaction of neutrons with the fuel pellets—these cross-sections are strongly dependent on the specific isotopes that are present. SC&A performed MCNP simulations of a simplified case with the two different fuel pellet compositions described above. We found that the pellet composition used by ORAUT resulted in a decrease of ~0.2 percent in the neutron dose rates.

**Observation 7: ORAUT should use the same isotopic composition of the fuel pellets in both the Sources 4C and the MCNP analyses.**

We make this an observation rather than a finding because our scoping analyses found only a slight difference in the MCNP results. However, to avoid confusion, the fuel pellet composition used in the MCNP analysis should be the same as that used in Sources 4C to generate the neutron spectrum that is used in the MCNP analysis.

Another issue arises from the following instruction (ORAUT, 2020, p. 40):

> ICRP Publication 60 corrections factors [ICRP 1991] should be applied to the neutron doses in accordance with ORAUT-OTIB-0055, *Technical Basis for Conversion from NCRP Report 38 Neutron Quality Factors to ICRP Publication 60 Radiation Weighting Factors for Respective IREP Input Neutron Energy Ranges*.

The MCNP simulations of neutron doses incorporate neutron fluence to H*(10) conversion factors taken from ICRP Publication 74 (ICRP, 1996, table A.42). H*(10) is an operational quantity which does not embody quality factors. Calculations of neutron doses to specific organs, performed as part of DRs for Carborundum workers, would utilize H*(10) to organ dose equivalent conversion factors listed in NIOSH (2007), which are derived from ICRP Publication 74. The latter publication embodies ICRP Publication 60 (ICRP, 1991) correction factors; consequently, no further corrections are needed. This conclusion is consistent with guidance in ORAUT-OTIB-0055 (ORAUT, 2006, p. 11): “These corrections should be applied to measured dose, missed dose, and dose determined based on neutron-to-photon ratios.” Doses derived from MCNP simulations do not fit into any of these three categories.

**Finding 2: ORAUT (2020) erroneously instructs dose reconstructors to apply ICRP Publication 60 neutron dose correction factors to doses calculated using MCNP.**

### *X-Ray Diffraction Apparatus (Second Operational Period)*

ORAUT (2020) assigned an annual exposure of 1.033 R, due to photons with energies <30 keV, to the operator of the x-ray diffraction apparatus at Carborundum, which embodies a consensus among the WGCC, NIOSH, and SC&A.

### *Second Residual Period, 1968 to 1992*

ORAUT (2020) noted that residual uranium contamination from the first operational period in 1968, the beginning of the second residual period, was higher than that from the second operational period. Since the operations during the two operational periods took place in different locations, workers could not be in both places at once. They are therefore assumed to have been exposed at the site of the first operational period, where the exposures are limiting.

We note an error in ORAUT (2020, p. 42, section 6.2.4): In the first line of the second paragraph, the text erroneously refers to the “first residual period” whereas the data cited are from the second residual period. This appears to be an editorial mistake that should be corrected.

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