MEMORANDUM

TO: Advisory Board on Radiation and Worker Health, Work Group on Carborundum Company
FROM: Robert Anigstein and John Mauro, SC&A
DATE: June 30, 2017
SUBJECT: Final Audit of NIOSH Response Paper and Example DRs

1 Background

On March 2, 2017, Thomas Tomes (NIOSH/DCAS) issued a paper (Tomes 2017) in response to our findings on NIOSH's use of surrogate data in performing dose reconstructions (DRs) for former Carborundum Company[1] workers (Anigstein and Mauro 2016). Tomes also discussed the findings and observations in our review (Anigstein 2016) of the Carborundum Special Exposure Cohort (SEC) Petition-00223 and the NIOSH SEC Petition Evaluation Report (Jessen and Scalsky 2015). An interim status report of our review of Tomes' report was issued on March 12 (Anigstein and Mauro 2017). A document titled "DR Examples 3-2-17," containing summary results of two example DRs based on organ doses to two hypothetical Carborundum workers, along with 22 data files supporting these results, were issued via the DCAS restricted website on March 2, 2017.

The present memo presents an audit of the two example DRs.[2]

2 Example B1

Example B1 was the case of a male worker with an unknown job who was employed at Carborundum from 1943 through 1980 and was diagnosed with cancer of the kidney on December 31, 1992. His period of employment spanned the two Atomic Weapons Employer (AWE) periods, the first residual period, and part of the second residual period. Because his job was unknown, NIOSH made the claimant-favorable decision to assign him doses to an operator, which is the job category with the highest radiation exposures.

We first examined the annual external doses assigned to this worker.

[1] The Carborundum Company will be henceforth referred to as "Carborundum."

[2] An earlier version of this audit was contained in a memorandum titled "Initial Audit of NIOSH Response Paper and Example DRs," that was distributed to members of the Advisory Board on Radiation and Worker Health, Work Group on Carborundum Company, on March 20, 2017.

2.1 External Exposure

Because the kidney was not among the organs for which dose conversion factors (DCFs) for organ doses from external exposure were listed in OCAS-IG-001 (OCAS 2007), the liver was used as a surrogate organ for external dose calculations, as recommended by Siebert (2012).

2.1.1 First AWE Period

NIOSH adopted as a source term for external exposure to penetrating radiation from uranium metal during the first AWE period the 10 uranium slugs that were shipped to Carborundum in 1943. 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 (Allen 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 2,400-h work year, which is consistent with the pre-1951 exposure duration assumed by Allen that is discussed in section 2.1.2 of the present memo. NIOSH prorated the annual external exposures of a uranium machining operator to a contaminated floor and to submersion in uranium aerosols listed by Allen (2011, Table 6.4) to account for the duration of the first AWE period. Since these exposures were listed in roentgens, NIOSH multiplied the values by a factor of 1.42, the ratio of exposure-to-$H_p(10)$ effective DCFs for the liver from 30–250 keV photons, and added these small doses to the dose from the 10 uranium slugs to obtain an $H_p(10)$ dose of 0.210 rem. NIOSH multiplied this dose by the DCF for the liver for 30–250 keV photons to obtain an organ dose of 0.157 rem, which was entered into the IREP (Interactive RadioEpidemiological Program) input file as the median of a lognormal distribution with a geometric standard deviation (GSD) of 5.

We discussed and accepted the NIOSH source term in our previous memo (Anigstein and Mauro 2017). This source term was approved at the March 13, 2017, meeting of the Work Group on Carborundum Company, who voted to close the issue.

2.1.2 First Residual Period

The first residual period extended from September 28, 1943 through December 31, 1958. To determine the external exposures during this period, NIOSH first calculated the areal uranium activity concentration on the contaminated floor. The starting point was an airborne activity concentration of 5,480 dpm/m^3, the geometric mean of the daily weighted average (DWA) of air sampling data from centerless grinding, the process employed at Carborundum, that was listed by Allen (2011, Table 7.5).[3] Assuming a settling rate of 0.00075 m/s and a settling time of 30 d, NIOSH obtained a concentration of 1.07×10^7 dpm/m^2. It then calculated the external exposure rate during the remainder of 1943 (following the end of the first AWE period) and during 1944 by applying the photon DCF for surface contamination listed by Allen (2011, Table 3.10). NIOSH then calculated the airborne activity concentration during this same time period due to resuspension from the contaminated floor, obtaining a value of 106.53 dpm/m^3. It calculated the external exposure rate from this source using the photon DCF for submersion in uranium-contaminated air listed by Allen (2011, Table 3.9). This exposure rate was added to that from the contaminated floor. NIOSH next calculated the annual exposures from these two

[3] Use of the DWA in the breathing zone of an operator leads to a bounding estimate of the contamination level of the floor, since the average air concentration in the room was most likely lower.

sources, assuming an exposure duration of 2,500 h/y. This is inconsistent with the 48-h workweek used by NIOSH to estimate external exposure during the first AWE period, which was based on the annual exposure durations assumed by Allen that are discussed below.

Allen (2011, Table 6.4) presented a matrix of annual doses to workers with various job titles from external exposures to six sources for each of six uranium-metal-working processes. There are three sets of such matrix elements corresponding to three time periods: pre-1951, 1951–1955, post-1955. Comparing the individual values to data for the various pathways presented earlier in this document, one can infer that the annual exposure durations in these time periods are 2,400, 2,200, and 2,000 h, respectively. This conclusion is further confirmed by the annual inhaled and ingested intakes of uranium dust listed by Allen (2011, Tables 7.8 and 7.9), which are broken down into the same three date ranges. This conclusion is consistent with external exposures listed by Allen (2011, Tables 6.2 and 6.3), which are based on 48-h, 44-h, and 40-h workweeks, if it is assumed that the workers work 50 weeks per year, with 2 weeks off.

To calculate the external exposures during 1945–1958, the remainder of the first residual period, NIOSH applied the depletion factors listed by Sharfi (2012, Table 4-2) to the 1944 exposure rates, which were based on an annual exposure duration of 2,500 hours. This is inconsistent with Allen's (2011) assumed work hours during the three time periods spanned by the first residual period.

The organ doses were calculated by applying the effective exposure-to-organ DCFs for 30–250 keV photons listed by OCAS (2007) and were entered in the IREP input file as the median values of lognormal distributions with a GSD of 5. However, in referring to the DCFs for exposure to a uranium-contaminated floor, Allen (2011) stated:

> For this particular conversion factor, 71.8% of the exposure is associated with photons with energies below 30 keV; 17.8% is from photons with energies between 30 keV and 250 keV, and the remaining 10.4% is for photons with energies greater than 250 keV.

Similarly, in referring to the DCFs for submersion in uranium-contaminated air, Allen (2011) stated:

> For this particular conversion factor, 50.5% of the exposure is associated with photons with energies below 30 keV; 28.5% is from photons with energies between 30 keV and 250 keV, and the remaining 21.0% is for photons with energies greater than 250 keV.

To demonstrate the effect of NIOSH's assuming that all the photons were in the 30–250 keV, we calculated the total dose to the kidneys from exposure to a uranium-contaminated floor using the method employed by NIOSH, and compared the results to those obtained by employing the photon energies provided by Allen (2011). In both cases, we used a total worker exposure to a contaminated floor of 0.0500 R during the first and second residual periods,[4] which is the sum of the year-by-year external exposures listed in the worksheet [*Example DR external dose calculations.xlsx]Kidney!*, found on the restricted DCAS website.[5] Table 1 shows a comparison of the median dose to the kidneys calculated by both methods.

Table 1. Calculation of Doses to Kidneys From External Exposure to Uranium-Contaminated Floor

E (keV)	DCF–liver[a] (rem/R)	Fraction		Dose (rem)	
		NIOSH[b]	TBD-6000[c]	NIOSH	TBD-6000[d]
0-30	0.106	0%	71.8%	0	0.0038
30-250	1.064	100%	17.8%	0.0532	0.0095
>250	0.845	0%	10.4%	0	0.0044
Total				0.0532	0.0177

[a] OCAS 2007

[b] Example DR

[c] Allen 2011

[d] Calculated using the energy distribution in the fourth column

The table shows that the method used in the example DR produces a 3-fold overestimate of the dose from this source. This is in addition to the overestimate resulting from the assumption of an annual exposure duration of 2,500 h, as discussed earlier. Although the total median dose from this source in calculated by NIOSH in the present example is only 53 mrem, NIOSH should be consistent in applying Allen's (2011) guidance.

2.1.3 Second AWE Period

The second AWE period spanned 1959–1967. The sources of external exposure during this period comprised uranium operations and x-ray diffraction (XRD) analyses during the entire period, and the fabrication of uranium-plutonium carbide fuel pellets during 1961–1967. Since these operations were performed in separate locations, a claimant should be assigned to the location resulting in the highest doses from external exposures.

Early Years: 1959–1960

For the years 1959–1960, NIOSH adopted a limiting external exposure scenario based on the exposure of an operator to a flat uranium plate, using the dose rate at 30.48 cm listed by Allen (2011, Table 6.1). The organ dose was calculated using the DCF for the liver from 30–250 keV photons listed by OCAS (2007), yielding a dose rate of 0.173 rem/y, which was entered into the IREP input file as a constant

[4] The external exposures during the second residual period are discussed later in the present memo.

[5] This value includes the contribution from air submersion; however, this contribution accounts for only 0.006% of the total exposure rate and thus has no effect on the listed results.

distribution. This is inconsistent with the guidance of Allen (2011, section 6.4), who stated: "Each annual dose value is assumed to be the geometric mean of a lognormal distribution with a GSD of 5." It is also inconsistent with the distribution of doses from external exposure to uranium metal that was assigned to the same hypothetical worker during the first AWE period, which does follow Allen's guidance.

We confirmed that the exposure of an operator to a flat uranium plate produced higher doses than the exposure of an XRD operator to stray radiation from that apparatus; we therefore agree with NIOSH's selection of the limiting external exposure scenario during 1959–1960. This conclusion is not affected by our finding regarding the radiation exposure from the XRD apparatus, which was presented as Issue 1 in our previous memo (Anigstein and Mauro 2017).

Later Years: 1961–1967

The limiting external exposure scenario during the remainder of the second AWE period (1961–1967) was an operator exposed to uranium-plutonium carbide pellets in a glovebox. The $H_p(10)$ photon and neutron doses were calculated by NIOSH, using the MCNP6 radiation transport code. As discussed in our previous memo (Anigstein and Mauro 2017), we had several concerns over the MCNP6 model that was the basis of the NIOSH analyses. These issues notwithstanding, we wished to determine if the MCNP6 results were correctly implemented in the example DRs.

The MCNP6 input and output files are found on the restricted DCAS website; a report of the MCNP6 analyses was presented in Attachment 1 to "Carborundum DR Methodology: July 23, 2015" in the same location.[6] In the course of our previous review (Anigstein 2016), we audited the MCNP6 analyses and confirmed that they correctly embodied the assumptions presented in that report. We also inspected the $H_p(10)$ tally results for photons and neutrons in the various energy ranges that were listed in Tables 7–9 of the attachment and confirmed that they were correctly copied from the MCNP6 output files.

The MCNP6 tallies were compiled in units of pSv/s and comprised doses from a single fuel pellet. Tomes (2017, Table 4) listed annual external doses from photons and neutrons in the same energy ranges to four categories of workers. The source was assumed to be a batch of fuel pellets that contained 100 g of elemental plutonium, the maximum amount of plutonium that could be handled in the glovebox at any one time, according to safety regulations in place at Carborundum at that time. To derive the dose rates to an operator, we need to determine the number of pellets in such a batch. The first step is to determine the mass fraction of plutonium in the fuel—this calculation is shown in Table 2.

Table 2. Determination of Plutonium Mass Fraction in Fuel Pellet

Nuclide	Atomic number density	AW	Atomic mass density	Pu mass fraction
C-12	3.05E+22	12	3.66E+23	
C-13	3.30E+20	13.00335	4.29E+21	
Pu-239	5.76E+21	239.0522	1.38E+24	1.79E-01
Pu-240	3.62E+20	240.0538	8.69E+22	1.13E-02
Pu-241	3.51E+19	241.0569	8.46E+21	1.10E-03
Am-241	1.83E+18	241.0568	4.41E+20	

[6] This document will henceforth be referred to as "DR Methodology."

Nuclide	Atomic number density	AW	Atomic mass density	Pu mass fraction
U-234	1.25E+17	234.041	2.93E+19	
U-235	9.23E+19	235.0439	2.17E+22	
U-238	2.45E+22	238.0508	5.83E+24	
Total			7.70E+24	1.91E-01

The table lists the atomic number density, in atoms/cm^3, of each nuclide in the fuel pellet that was copied from *GloveBox.Pu_U_Carbide.photon.R00.i*, one of the MCNP6 input files. This value was multiplied by the atomic weight to yield the atomic mass density of each nuclide. Dividing the atomic mass density of each plutonium isotope by the total atomic mass density of all constituents of the fuel pellet yields the mass fraction of each isotope. The sum of these mass fractions is 0.191, the mass fraction of plutonium in the fuel pellet. This analysis shows that the maximum batch of fuel that can be handled at any one time was 523 g (100 g ÷ 0.191 ≈ 523 g). *GloveBox.Pu_U_Carbide.photon.R00.o*, one of the MCNP6 output files, listed the mass of one pellet as 1.33355 g, which means that one batch could contain ≈ 392 pellets (523 g ÷ 1.33355 g/pellet ≈ 392 pellets).

We used the $H_p(10)$ tally results at 35 cm for photons and neutrons in the various energy ranges that were listed in Tables 7–9 of Attachment 1 to "DR Methodology" to derive annual external doses to an operator. We first converted the tally results, listed in pSv/s per pellet, to mrem/h, then multiplied these results by the number of pellets in one batch to obtain the hourly dose rate from a batch of pellets. The operator was assumed to spend 50% of his time at the glovebox. Assuming a 2,000-h work year, the operator would have been exposed for 1,000 h/y. We compared our results to the annual doses to an operator listed by Tomes (2017, Table 4). The results are shown in Table 3 of this memo.

Table 3. Annual $H_p(10)$ Doses to Glovebox Operators (rem)

Energy range	NIOSH[a]	SC&A	Δ[b]
	Photons		
<30 keV	1.074	1.108	-3.1%
30-250 keV	2.166	2.235	-3.1%
>250 keV	1.258	1.298	-3.1%
	Neutrons		
10-100 keV	0.001	0.001	—
0.1-2 MeV	0.109	0.113	-3.5%
2-20 MeV	0.183	0.189	-3.0%

[a] Tomes (2017, Table 4)

[b] NIOSH ÷ SC&A - 1

As shown in the table, all the NIOSH doses are approximately 3% lower than the doses calculated by SC&A. Since both analyses utilized the same MCNP6 results, and since the differences are consistent, given the number of significant figures displayed by Tomes (2017, Table 4), we surmise that the difference is due to a difference in the assumed number of fuel pellets in the glovebox. It would be helpful if NIOSH were to present its derivation of the dose rates based on the MCNP6 results so that this discrepancy could be resolved.

NIOSH converted the $H_p(10)$ photon dose rates in the <30–keV energy range to organ doses by applying the DCFs for plutonium listed by Allen (2011, Table 4.1a). (We note that Allen displayed two tables, both numbered 4.1a. The DCFs in question were listed in the first of these tables.) Since these DCFs had

fixed values, the resulting organ doses were entered into the IREP input file as constant distributions. The $H_p(10)$ doses from photons in the 30–250 keV and >250-keV energy ranges were multiplied by the minimum, effective, and maximum DCFs for each energy range. The resulting triplets of doses were entered into the IREP input file as the minima, modes, and maxima of triangular distributions.

A similar procedure was followed for the neutron doses from the pellets. Although six energy ranges were included in the analyses, only doses from neutrons in the 10–100 keV, 0.1–2 MeV, and 2–20 MeV ranges resulted in dose rates of ~1 mrem/y or greater, so only these three ranges were included in the dose assessment. In each case, a triplet of doses were calculated in the same manner as for the photon doses discussed above and entered into the IREP input file as the parameters of triangular distributions.

We confirmed that the NIOSH $H_p(10)$ doses listed in Table 3 of this memo were correctly converted to organ doses, notwithstanding the discrepancies in the $H_p(10)$ dose calculations.

2.1.4 Second Residual Period

The uranium operations during the first and second AWE periods were most likely carried out in separate areas of the Carborundum plant. In the present example, the worker was assigned external doses from the residual contamination from the first AWE period during the years 1968–1980, which end with the termination of his employment. We confirmed that the exposure rates were calculated by applying Sharfi's (2012, Table 4-2) depletion factors to the initial exposure rate during the first residual period. The resulting exposures are higher than those resulting from the residual contamination from the second AWE period; therefore, assigning external doses from the residual contamination from the first AWE period was correct and claimant favorable. The external doses to the kidneys were calculated in the same manner as the doses during the first residual period and entered into the IREP input file as the median values of lognormal distributions with a GSD of 5. As shown in Table 1 of this memo, these doses do not account for the energy distributions of photons from uranium-contaminated air and surfaces listed by Allen (2011), and also reflect the erroneous assumption of an exposure duration of 2,500 h/y, instead of 2,000 h/y that was assumed by Allen for this time period. However, all the median annual doses during the second residual period are <0.04 mrem and consequently do not need to be considered in the DR.

2.2 Exposure to Medical X Rays

The dose from medical x rays was assigned for each year of employment during the two AWE periods as a normal distribution with a mean of 0.025 rem. This is the dose to organs such as the urinary bladder, listed by Thomas (2011, Table A-7), rather than the dose to the liver, the surrogate organ for external exposure to the kidneys, which was used in assigning doses to the kidneys from other sources of external photon radiation. An examination of the anatomical drawing presented by Thomas (2011, Fig. 2) shows that the kidneys are just below the liver and are much closer to the x-ray beam used to examine the lungs than is the bladder, which is much lower in the body and thus further from the collimated beam. The dose to the liver was listed as 0.0902 rem in Table A-7. The standard deviation (σ_D) assigned to this distribution was 0.0075 rem, which corresponds to an uncertainty of ±30% in the mean dose, consistent with the guidance of Thomas (2011). Since σ_D was calculated on the basis the incorrect mean dose, both the mean dose and σ_D need to be corrected.

2.3 Internal Exposure

2.3.1 Intakes

First AWE Period

NIOSH assigned the worker an inhaled intake of natural uranium aerosols of 43,632 dpm per calendar day during the first AWE period, which is the same as the value of 19,654 pCi/d listed by Allen (2011, Table 7.8) for a uranium machining operator prior to 1951. NIOSH likewise assigned an ingestion rate of 895 dpm per calendar day to the worker during this period, which is the same as the rate of 403 pCi/d listed by Allen (2011, Table 7.9) for the same exposure scenario.

First Residual Period

NIOSH used the areal activity concentrations during the first residual period, discussed in section 2.1.2 of this memo, to calculate the uranium aerosol concentrations by assuming a resuspension factor of 1×10^{-5} m^{-1}. NIOSH then calculated the inhaled intake per calendar day, assuming an exposure duration of 2,500 h/y. As stated earlier, this is inconsistent with the assumption of 2,400 h/y used for external exposure during the first AWE period, and with Allen's (2011) assumptions of annual exposure durations of 2,200 h in 1951–1955 and 2,000 h after 1955. NIOSH assigned an ingestion rate of 895 dpm/d to the worker during the first year of the residual period and reduced the rate using the depletion factors listed by Sharfi (2012, Table 4-2), but again failed to adjust for the shorter exposure durations after 1950.

We confirmed that the intakes listed by Tomes (2017, Tables 8–9) were consistent with the methodology described above. The worker in the present example was assigned these intakes during the first AWE period and during the first residual period. The post-1950 intakes were elevated due to the incorrect annual exposure durations.

Second AWE Period—Early Years: 1959–1960

NIOSH based the uranium intakes during 1959–1960, the first two years of the second AWE period, on aerosol activity concentrations measured during two surveys performed by the Health and Safety Laboratory (HASL) of the Atomic Energy Commission in 1959 and 1961 (HASL n/d). Using the regression of order statistics (ROS) method prescribed by Brackett (2005), NIOSH derived a 95^{th} percentile activity concentration of 7.384 dpm/m^3. This resulted in an inhaled intake rate of 48.55 dpm per calendar day by a worker in the general labor category. Twice that value (97.10 dpm/d) was assigned to an operator, which is consistent with the default ratio of intakes by an operator to those of a general laborer specified by Allen (2011). We confirmed that these inhaled intakes, which were listed by Tomes (2017, Table 10), are consistent with the methodology described by NIOSH. Tomes also listed the ingestion rates of the operator and general laborer as 1.94 and 0.971 dpm per calendar day, respectively. As shown in the DCAS file *Carborundum dose calculations_draft 3-2-17.xlsx*, these values were derived by multiplying the inhaled intakes per calendar day by a factor of 0.02. This calculation is inconsistent with the guidance of Neton (2004), who stated: "The amount of activity ingested on a daily basis can be approximated by assuming it to be 0.2 times the activity per cubic meter of air." Applying that methodology to the activity concentrations cited above results in ingested intake rates of 1.01 dpm

per calendar day by the general laborer and 2.02 dpm/d by the operator, approximately 4% higher than Tomes' values.

The uranium intakes were assumed to include contaminants found in recycled uranium, as listed by Allen (2011, Table 3.2). This assumption is consistent with Allen's guidance that uranium processed after 1953 might include such contaminants. The uranium activity concentrations were derived from the HASL sample analyses, while the activity concentrations of the contaminants were calculated by multiplying the uranium activities by the factors listed by Allen and reproduced by Tomes (2017, Table 11). Since the uranium activity was derived from air dust samples that were presumably assayed for total alpha, which might have included the alpha-emitting contaminants, this might appear to be double accounting, since ^{234}U was assigned a multiplier of 1 and the activities of the other radionuclides were added to the mix. However, since it is not known whether the other nuclides were in fact present, and since some of these nuclides may have lower DCFs than ^{234}U for certain organs, such double accounting is prudent and claimant favorable.

Second AWE Period—Later Years: 1961–1967

To determine the source term for internal exposure during the later years of the second AWE period (1961–1967), NIOSH compared the doses from uranium intakes derived from the analyses of HASL samples collected on 11/9/1959 and 4/5/1961 to doses from intakes of plutonium derived from HASL samples collected on 4/5/1961 and 6/7/1961. Tomes (2017, Table 12) listed the intakes of plutonium by workers in the various job categories; he listed the isotopic composition of the plutonium aerosols in Table 13. NIOSH found that the uranium intakes resulted in higher doses to the kidneys and therefore assigned only those intakes in the example DR. We performed scoping calculations in which we multiplied the listed intakes of uranium and plutonium by the respective equivalent dose coefficients for the kidneys at various times after an acute intake, extracted from ICRP (2001). We found that the uranium intakes resulted in doses to the kidneys that were at least 3-fold higher than those from the plutonium intakes, thus confirming the NIOSH finding.

However, we find that it is illogical to assume that the worker was externally exposed to the fabrication of uranium-plutonium pellets, but that his intakes consisted only of uranium aerosols. He clearly would have been exposed to airborne plutonium in the course of his work. However, he may also have been exposed to intakes of uranium. The fact that the fuel pellets contained approximately 80% uranium and 20% plutonium shows that the two materials were handled simultaneously.

According to the NIOSH report of an interview with a former Carborundum workers, [redacted], cited in our previous review (Anigstein 2016):

> 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 2015)

This clearly indicates that uranium contamination was present in various areas of the facility. We also note that the HASL surveys performed on 4/5/1961 measured both uranium and plutonium—the samples analyzed for uranium were collected 20 minutes after the collection of the last sample for plutonium analysis; however, the locations of these samples were not clearly identifiable on the survey

reports (HASL n/d). The plutonium sample sheet has the notation: α – count + chemistry (the last word is only partly legible). This indicates that the plutonium was assayed after chemical separation, so uranium might have been part of the original sample. It is therefore not possible to rule out intakes of both radionuclides by the same worker. As stated in our previous review (Anigstein 2016, section 5.2.2), we recommend that NIOSH assign intakes of both uranium *and* plutonium in calculating internal doses.

Anticipating the use of plutonium intake data in future DRs, we reviewed the plutonium intake rates listed by Tomes (2017, Table 12). NIOSH correctly derived the plutonium aerosol activity concentrations by applying the ROS method, obtaining a value of 1.163 dpm/m^3, as shown in the DCAS file *Carborundum dose calculations_draft 3-2-17.xlsx*. Tomes used this value to correctly derive the inhalation rate of 7.65 dpm per calendar day listed in Table 12. The plutonium ingestion rates were derived by multiplying the inhaled intakes per calendar day by a factor of 0.02, which, as stated earlier, is inconsistent with the guidance of Neton (2004): The ingested intakes per calendar day should be equal to 20% of the activity in 1 m^3 of air.

We also reviewed the assumed isotopic ratios of plutonium and americium in the plutonium aerosols listed by Tomes (2017, Table 13). This table was copied from a table titled "Plutonium Mixture Isotopic to Total Alpha Activity Ratios" in "DR Methodology." In our previous review (Anigstein 2016, section 5.2.2), we stated that

> "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. . . However, according to Strasser and Taylor (1962 . . .), during the period of September 15, 1961 to December 31, 1961, fuel pellets were produced from powder prepared by Hanford Atomic Products Operations.

We found that use of the Hanford fuel isotopic ratios was consistent with the historical record and was also claimant favorable, since intakes with the isotopic composition of either fresh or 5-y-old Hanford fuel led to higher effective doses than those in the plutonium from Dow (Anigstein 2016, Table 1). We had previously recommended that NIOSH adopt either the fresh or the 5-y-old Hanford fuel isotopic mix as the source for both internal and external doses, whichever produces the highest total dose.

Second Residual Period

During the second residual period, residual uranium contamination levels from uranium operations during the first AWE period were higher than those from the second AWE period. In the present example, the worker was assigned intakes from the residual uranium contamination from the first AWE period during the years 1968–1980, which end with the termination of his employment. In this case, it was not necessary to assign intakes from residual plutonium contamination, since such intakes, even combined with intakes of uranium residues from the second AWE period, would lead to lower doses than from intakes of uranium residues from the first AWE period. Since the plutonium contamination was most likely confined to the plutonium production areas, it would not have been present in areas used for uranium operations during the first AWE period. As was the case with the intakes during the first residual period, NIOSH calculated these inhaled intakes by applying Sharfi's (2012, Table 4-2) depletion factors to the calculated intake during the first year of the first residual period, which incorporated the erroneous assumption of 2,500 work hours per year. Similarly, NIOSH calculated the

ingested intakes by applying the depletion factors to the pre-1951 ingestion rates, which were based on a 2,400-h work year, but failed to account for a 2,000-h year after 1955.

2.3.2 Internal Doses

First AWE Period and First Residual Period

We audited the internal doses to the kidneys from the source terms described above by performing independent calculations using integrated doses derived from the DCAL (Dose and Risk Calculation) computer code (ORNL 2010). This totally independent methodology allows us to audit the doses using the same International Commission on Radiological Protection (ICRP) models and parameters that are employed by IMBA (Integrated Modules for Bioassay Analysis). We first compared the internal doses to the kidneys in the years 1943–1992 from intakes of uranium during the first AWE period and the first residual period listed by Tomes (2017, Table 9). These doses were listed in entries 75–124 in the DCAS file *IREP input Carborundum Example_kidney_3-2-17.xls*. We found very good agreement between the two sets of calculations. We next calculated the doses from the intakes during the same period, corrected for shorter exposure durations in the years following 1950: The annual NIOSH doses were up to 3% higher than our values.

Second AWE Period

We also performed independent assessments of the doses to the kidneys resulting from intakes of uranium during the second AWE period, which were listed in entries 125–158 in *IREP input Carborundum Example_kidney_3-2-17.xls*. In order to verify the NIOSH calculations, we based our analyses on the uranium intake rates discussed in section 2.3.1 of this memo, omitting contributions from plutonium intakes that we found should be included in the assessment. We obtained very good agreement with the NIOSH calculations, despite the discrepancy in the ingestion rate. Because the ingested intake is a small fraction of the total intake and the DCF for the kidneys by the ingestion pathway is smaller than that for inhalation, the ingested intakes have only a minor impact on the doses in this case.

We recommend that NIOSH correct the ingestion rate in the interest of consistency. More important, doses from intakes of plutonium, using a revised isotopic mixture, should be added to those from uranium.

Second Residual Period

We performed independent assessments of the doses to the kidneys resulting from intakes of uranium during the years 1968–1980, part of the second residual period, which were listed in entries 176–200 in *IREP input Carborundum Example_kidney_3-2-17.xls*. As expected, the NIOSH values are almost 25% higher than those we calculated, due to the incorrect annual work hours during this period. However, the total median dose from these intakes calculated by NIOSH is ~10 mrem, so the error has little significance in the present example.

3 Example B2

Example B2 was the case of a male maintenance worker who was employed at Carborundum from 1953 through 1980 and was diagnosed with cancer of the lung on December 31, 1992. His period of employment spanned the second AWE period and parts of the two residual periods. Because of his job description, NIOSH assigned him doses to a general laborer.

We first examined the external annual doses assigned to this worker.

3.1 External Doses

3.1.1 First Residual Period

NIOSH calculated the external doses to the lungs during 1953–1958 from exposures to a uranium-contaminated floor and submersion in uranium-contaminated air, as discussed in section 2.1.2 of this memo. The same issues that were noted previously apply in this case:

- NIOSH assumed all photons to be in the 30–250 keV energy range instead of using the energy distributions specified by Allen (2011), cited in section 2.1.2.

- NIOSH assumed an annual exposure duration of 2,500 hours, instead of using a 2,200-h work year during 1953–1955 and a 2,000-h year after 1955, as assumed by Allen (2011).

As was the case with example B1, we were able to replicate the NIOSH dose calculations.

3.1.2 Second AWE Period

Early Years: 1959–1960

In the present example, the limiting external exposure scenario during 1959–1960 for a worker in the general labor category was a technician operating the XRD apparatus. As discussed in our previous memo (Anigstein and Mauro 2017), NIOSH assigned an annual exposure of 0.167 R to a worker from this scenario. Our memo discussed the issues we found with the NIOSH assessment of this scenario. In the present example, NIOSH calculated the lung dose using the DCF for the lungs for 30–250 keV photons of 0.986 rem/R to obtain a dose rate of 0.165 rem/y, which was entered into the IREP input file as a constant distribution. We were able to replicate the NIOSH calculation.

As described in our memo (Anigstein and Mauro 2017), we derived an exposure rate of 1.033 R/y in this scenario. Given a photon energy of ~8 keV, the appropriate effective DCF for the lungs for the <30 keV range, listed by OCAS (2007), is 0.100 rem/R. This results in an annual dose to the lungs of 0.103 rem, less than the dose calculated by NIOSH.

We compared this dose to the alternate exposure scenario during this time period: a general laborer exposed to a flat uranium plate. As listed in the DCAS worksheet *[Carborundum dose calculations_draft 3-2-17.xlsx]External-U Operations!*, the deep dose rate from this scenario is 27.8 mrem/y. Assuming a 30–250 keV energy range, we obtained a lung dose of 19.3 mrem/y. We therefore agree with NIOSH's selection of the exposure to the XRD apparatus as the limiting external exposure scenario during 1959–1960.

Later Years: 1961–1967

The limiting external exposure during the remainder of the second AWE period, 1961–1967, was that of a general laborer exposed to uranium-plutonium carbide pellets in a glovebox. The issues raised in the discussion of the doses to an operator in this scenario, presented in section 2.1.3 of this memo, apply in the present instance. Furthermore, we found an additional discrepancy in two of the hourly photon dose rates to the laborer listed by Tomes (2017, Table 4). These dose rates, from <30-keV and >250-keV photons, were listed in "DR Methodology," as 0.120 and 0.154 mrem/h, respectively, while the values listed by Tomes and used in the example DR calculations were 0.127 and 0.149, 6% greater and 3% lower, respectively, than the "DR Methodology" values.

We used the $H_p(10)$ tally results at 100 cm for photons and neutrons from a single pellet in the various energy ranges, listed in Tables 7–9 of Attachment 1 to "DR Methodology," to derive annual external doses to a laborer in a manner similar to that used to calculate external doses to the glovebox operator. We compared our results to the annual doses to a laborer listed by Tomes (2017, Table 4). The results are shown in Table 4 of this memo. As shown in the table, the NIOSH doses range from approximately 6% lower to 3% higher than the doses calculated by SC&A. However, when we compared our results to those listed in "DR Methodology," we found that the latter results were approximately 3% lower, similar to the comparison of doses to the glovebox operator displayed in Table 3. This reinforces our hypothesis that the differences between our results and those in "DR Methodology" are due to differences in the calculated number of fuel pellets in the glovebox, while the additional differences between our results and Tomes' results for <30-keV and >250-keV photons are due to an error in transcribing the "DR Methodology" values.

Table 4. Annual $H_p(10)$ Doses to Laborer Exposed to Glovebox Operations (rem)

Energy range	NIOSH[a]	SC&A	Δ[b]
	Photons		
<30 keV	0.127	0.124	2.7%
30-250 keV	0.256	0.265	-3.5%
>250 keV	0.149	0.159	-6.2%
	Neutrons		
10-100 keV	0.0001	0.0001	—
0.1-2 MeV	0.0134	0.0139	-3.5%
2-20 MeV	0.0225	0.0231	-2.7%

[a] Tomes 2017, Table 4

[b] NIOSH ÷ SC&A - 1

3.1.3 Second Residual Period

As was discussed in section 2.1.4, the external exposures during the second residual period from residual contamination from the first AWE period were higher than those from residual contamination from the uranium operations during the second AWE period. As in the previous example, the worker was assigned doses from the area with the higher exposures, which end with the termination of his employment.

The external doses to the lungs were calculated in the same manner as the doses during the first residual period and entered into the IREP input file as the median values of lognormal distributions with a GSD

of 5. As shown in Table 1 of this memo, these doses do not account for the energy distributions of photons from uranium-contaminated air and surfaces listed by Allen (2011), and also reflect the erroneous assumption of an exposure duration of 2,500 h/y, instead of 2,000 h/y, which is appropriate for this time period. However, all the median annual doses during the second residual period are <0.03 mrem and consequently do not need to be considered in the DR.

3.1.4 Doses From Medical X Rays

Doses from medical x rays were assigned for each year of employment during the second AWE period as a normal distribution with a mean of 0.0838 rem, which was the dose listed by Thomas (2011, Table A-7) for the lungs, and σ_D = 0.01675 rem, which corresponds to an uncertainty of ±20%. This is inconsistent with the guidance of Thomas (2011, section 8.0), who recommended an uncertainty of ±30%. This discrepancy needs to be corrected.

3.2 Internal Exposure

3.2.1 Intakes

First Residual Period

NIOSH assigned intakes of uranium dust during 1953–1958 to the worker in the present example that were the same as those described in section 2.3.1 of this memo. As discussed previously, these intakes were elevated because NIOSH incorrectly assumed an exposure duration of 2,500 h/y, which is inconsistent with Allen's (2011) assumption of a 2,200-h work year in 1951–1955 and a 2,000-h year after 1955.

Second AWE Period—Early Years: 1959–1960

As described in section 2.3.1 of this memo, NIOSH used uranium aerosol activity concentrations measured by HASL to derive a 95th percentile activity concentration of 7.384 dpm/m^3. This resulted in an inhaled intake rate of 48.55 dpm per calendar day by a worker in the general labor category (Tomes 2017, Table 10). Tomes also listed the ingestion rate of the general laborer as 0.971 dpm per calendar day which, as discussed previously, is inconsistent with the guidance of Neton (2004): The ingested intakes per calendar day should be equal to 20% of the activity in 1 m^3 of air. Applying that methodology to the activity concentrations cited above results in an ingested intake rate of 1.01 dpm calendar day by the general laborer. As in the previous example, the uranium intakes were assumed to include contaminants found in recycled uranium.

Second AWE Period—Later Years: 1961–1967

As in the previous example, NIOSH concluded that intakes from uranium operations during the later years of the second AWE period (1961–1967) produced higher doses to the lungs than intakes of plutonium. We performed scoping calculations in which we multiplied the listed intakes of uranium and plutonium by the respective equivalent dose coefficients for the lungs at various times after an acute intake, extracted from ICRP (2001). We found that the uranium intakes resulted in doses to the lungs that were more than 10-fold higher than those from the plutonium intakes. thus confirming the NIOSH conclusion. However, as discussed in section 2.3.1 of this memo, we find that it is illogical to assume

that the worker was externally exposed to the fabrication of uranium-plutonium pellets, but that his intakes consisted only of uranium aerosols. We recommend that NIOSH assign intakes of both uranium *and* plutonium in calculating internal doses from this scenario.

Second Residual Period

As was discussed in section 2.1.4, the contamination levels during the second residual period from residual contamination from the first AWE period were higher than those from residual contamination from the uranium operations during the second AWE period. As in the previous example, the worker was assigned intakes from the area with the higher exposures during the years 1968–1980, which end with the termination of his employment. As was discussed previously, these inhaled intakes incorporated the erroneous assumption of 2,500 work hours per year. Similarly, the ingested intakes were based on a 2,400-h work year. The assigned intakes via both pathways failed to account for the 2,000-h work year after 1955 assumed by Allen (2011).

3.2.2 Internal Doses

First Residual Period

We audited internal doses to the lungs from the source terms described above by performing independent calculations, as described in section 2.3.2. We compared the internal doses to the lungs in the years 1953–1992 from intakes of uranium during the first residual period, corrected for shorter exposure durations in the years following 1950, to the doses calculated by NIOSH that were listed in entries 64–103 in the DCAS file *IREP input Carborundum Example_lung 3-2-17.xls*. These differences resulted in annual NIOSH doses that were 13%–20% higher than our values.

Second AWE Period

We also performed independent assessments of the doses to the lungs resulting from intakes of uranium during the second AWE period, which were listed in entries 104–137 in *IREP input Carborundum Example_ lung 3-2-17.xls*. We based our analyses on the uranium intake rates discussed in section 2.3.1 of this memo, again omitting contributions from plutonium intakes that we found should be included in the assessment. We found that all but one of the annual doses calculated by NIOSH were 99% higher than our values. Inspecting the DCAS workbook *[CAD_222224_lung U 1959-1967.xls]222224!*, we found that NIOSH had erroneously assigned this worker an inhaled intake rate of 97.10 dpm per calendar day, which, according to Tomes (2017, Table 10), is the intake rate of an operator, rather than the 48.55 dpm/d intake rate of a laborer. In like manner, the worker was assigned an ingested intake rate of 1.94 dpm/d, which Tomes listed as the intake rate of an operator.

Second Residual Period

We performed independent assessments of the doses to the lungs resulting from intakes of uranium during the years 1968–1980, part of the second residual period, which were listed in entries 172–196 in *IREP input Carborundum Example lung_3-2-17.xls*. As expected, the NIOSH values were about 25% higher than those we calculated, due to the incorrect annual work hours during this period.

NIOSH should correct the discrepancies in the intakes used in this example DR.

4 Results and Conclusions

Based on our audit, we found that we understood the methods used by NIOSH and that we could replicate the NIOSH dose calculations with reasonable accuracy. However, we found several instances of errors and inconsistent assumptions in the example DRs.

4.1 Findings

4.1.1 Inconsistent Annual Exposure Durations

The inhaled intakes and external exposures to uranium-contaminated air and surfaces during the first and second residual periods were based on an annual exposure duration of 2,500 h. This is inconsistent with the pre-1951, 1951–1955, and post-1955 exposure durations of 2,400, 2,200, and 2,000 h, respectively, that were assumed by Allen (2011) and that were used by NIOSH to calculate doses during the first and second AWE periods. The ingested intakes during the first residual period after 1950 and during the second residual period were incorrectly based on the pre-1951 exposure durations of 2,400 h/y, failing to account for the shorter durations in subsequent years.

4.1.2 Incorrect Probability Distributions of Doses from External Exposure to Uranium Metal

The doses from uranium-handling operations during 1959–1960 in Example B1 were entered into IREP as constant values. This is inconsistent with the use of a lognormal distribution with a GSD of 5, as prescribed by Allen (2011, section 6.4), and with the distribution of doses from external exposure to uranium metal that was assigned to the same hypothetical worker during the first AWE period, which does follow Allen's guidance.

4.1.3 Incorrect Source Term and Glovebox Model Used in MCNP6 Dose Analysis

Anigstein (2016, Appendix B) presented a critical discussion of the glovebox model and the uranium-plutonium-americium source term used in the MCNP6 assessment of external doses from uranium-plutonium fuel pellets handled in a glovebox. In the context of reviewing the NIOSH SEC petition evaluation report, this issue did not rise to the level of a finding: We determined that NIOSH was capable of performing such an assessment and, in fact, furnished an alternative MCNP analysis with revised input data which could provide the basis for such an assessment. As an issue for present and future DRs, however, this does constitute a finding, since our analysis yielded photon dose rates to the operator that were approximately 50% higher than the NIOSH results.

4.1.4 Incorrect Doses from Medical X Rays

In Example B1, doses to the kidneys from medical x rays were based on doses to organs such as the urinary bladder, rather than the dose to the liver, the surrogate organ for external exposure of the kidneys. In Example B2, doses from medical x rays were assigned an uncertainty of ±20% rather than the uncertainty of ±30% recommended by Thomas (2011).

4.1.5 Workers Externally Exposed to Glovebox Operations Should be Assigned Intakes of both Uranium and Plutonium

We find it to be illogical to assume that a worker who was externally exposed to the fabrication of uranium-plutonium pellets would be assigned intakes that consisted only of uranium aerosols. Anigstein (2016, section 5.2.2) recommended that NIOSH assign intakes of both uranium *and* plutonium in calculating internal doses. In the context of reviewing the NIOSH SEC petition evaluation report, this issue did not rise to the level of a finding: We determined that NIOSH had the data necessary to perform such an assessment. As an issue for present and future DRs, this does constitute a finding, since intakes of plutonium can make significant contributions to internal doses.

4.1.6 Incorrect Uranium Intakes by Laborer During Second AWE Period

NIOSH incorrectly used intakes of uranium dust assigned to an operator during the second AWE period to calculate the internal doses to a worker classified as a laborer in Example B2, which approximately doubled the doses.

4.2 Observations

We have observations on two aspects of dose assessments that have minor impacts on the doses in the present examples, but that are inconsistent with guidance in other NIOSH technical documents.

4.2.1 Energy Distributions of Photons from Uranium-Contaminated Air and Surfaces

NIOSH calculated the doses from external exposure to a uranium-contaminated surface, and the much smaller exposure from submersion in uranium-contaminated air, using fixed values of the exposure-to-organ-dose DCFs for 30–250 keV photons. This is inconsistent with the energy distributions of photons from these two sources cited by Allen (2011), who noted that most of the exposures from both sources are due to photons with energies <30 keV. As shown in Table 1 of this memo, using this method in Example B1 results in a 3-fold increase in the dose to the kidney. NIOSH should either explicitly incorporate Allen's energy distributions in its dose assessment, or discuss why the method used in the example DR represents an acceptable, claimant-favorable simplification. Although this has but a small impact on the total dose in Example B1—an increase of 35 mrem in a total dose of ~35 rem—and an even smaller impact in Example B2, NIOSH should ensure that such an approach, if it were to be used, is applied uniformly in fairness to claimants from other sites.

4.2.2 Estimates of Ingestion Rates Based on Air Concentrations

The ingestion rates in the example DRs during the second AWE period were derived by multiplying the inhaled intakes per calendar day by a factor of 0.02. This is inconsistent with the guidance of Neton (2004): The ingested intakes per calendar day should be equal to 20% of the activity in 1 m^3 of air. The ingestion rates during the second AWE period are approximately 4% lower than those derived according to Neton. This has a very small impact on the total doses, since the intakes by ingestion are much lower than by inhalation, and since the DCFs in most cases are lower for the ingestion pathway. Nevertheless, we recommend that NIOSH be consistent in its intake calculations.

References

Allen, D. 2011. "Site Profile for Atomic Weapons Employers that Worked Uranium Metals, Battelle-TBD-6000," rev. 1. Available at https://www.cdc.gov/niosh/ocas/pdfs/tbd/bat-6000-r1.pdf

Anigstein, R. 2016. "Review of the Carborundum Special Exposure Cohort (SEC) Petition-00223 and the NIOSH SEC Petition Evaluation Report," SC&A-TR-SEC-2016-0001, rev. 1. Available at https://www.cdc.gov/niosh/ocas/pdfs/abrwh/scarpts/sca-carbcosec223-r1.pdf

Anigstein, R., and J. Mauro. 2016. "Review of NIOSH Use of Surrogate Data in the SEC Evaluation Report for Carborundum." Memorandum to Advisory Board on Radiation and Worker Health, Work Group on Carborundum Company. Available at https://www.cdc.gov/niosh/ocas/pdfs/abrwh/scarpts/sca-carbcosec-111016.pdf

Anigstein, R., and J. Mauro. 2017. "Updated Status Report on SC&A Review of NIOSH Response Paper." Memorandum to Advisory Board on Radiation and Worker Health, Work Group on Carborundum Company. Available at https://www.cdc.gov/niosh/ocas/pdfs/abrwh/scarpts/sca-carbcospr0-031217.pdf

Brackett, E. M. 2005. "Analysis of Coworker Bioassay Data for Internal Dose Assignment," ORAUT-OTIB-0019, rev. 1. Available at http://www.cdc.gov/niosh/ocas/pdfs/tibs/or-t19-r1.pdf

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.

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. Available at http://www.cdc.gov/niosh/ocas/pdfs/sec/carbco/carbcoer-223-r1.pdf

Neton, J. W. 2004. "Estimation of Ingestion Intakes," OCAS-TIB-009, rev. 0. Available at https://www.cdc.gov/niosh/ocas/pdfs/tibs/oc-t9-ro.pdf

Oak Ridge National Laboratory (ORNL), Life Science Division, Dosimetry Research Group. 2010. DCAL: Dose and Risk Calculation System, Version 9.4. [Computer software and manual]. Available at https://www.epa.gov/sites/production/files/2016-10/dcalsetup_0.exe

Office of Compensation Analysis and Support (OCAS). 2007. "External Dose Reconstruction Implementation Guideline," OCAS-IG-001, rev. 3. Available at https://www.cdc.gov/niosh/ocas/pdfs/dr/oc-ig-001-r3.pdf

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

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

Siebert, S. R. 2012. “Internal Dosimetry Organ, External Dosimetry Organ, and IREP Model Selection by ICD-9 Code,” ORAUT-OTIB-0005, rev. 5. Available at https://www.cdc.gov/niosh/ocas/pdfs/tibs/or-t5-r5.pdf

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

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

Thomas, E. M. 2011. “Dose Reconstruction from Occupational Medical X-Ray Procedures,” ORAUT-OTIB-0006, rev. 4. Available at https://www.cdc.gov/niosh/ocas/pdfs/tibs/or-t6-r4.pdf

Tomes, T. P. 2017. “NIOSH Evaluation of Carborundum Company: Response to Site Profile Issues and Comments.” Available at https://www.cdc.gov/niosh/ocas/pdfs/dps/dc-carbcosp-r0.pdf